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Bringing Visibility To the Invisible:

Towards A Social Understanding of Nanotechnology

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CHAPTER 1

A Brief Introduction

Hans Glimell and Hans Fogelberg

This report documents a series of preparatory studies mapping out parts of the wide range of epistemological, political, sociological, and cultural issues associated with nanoscale science and engineering. Although assembling them as a collection of papers may give the appearance of a finished work, they are all still very much work-in-progress, spread over the period 1997-2001, and each is carried out on its own terms. Accordingly, the results are largely explorative or indicative, rather than exhaustive or conclusive.

There were several intriguing things about nanotechnology that inspired us to embark upon this undertaking, most of which, appear to have gained even greater relevance since then. In retrospect these can be grouped into five motives arousing our curiosity. *First*, the persistently outlandish nature of the set of ideas labelled 'nano' attracted our interest. In spite of the fact that one of the most reputable American scientists of the post-WW2-period, the physicist Richard Feynman, in a remarkably comprehensive and persuasive way stated the bottomline arguments for those ideas more than four decades ago, they long were doomed to hibernate in an exile relation to the Academy.

Being acquainted with the area of science studies, this observation evoked a bunch of questions concerning the social and cultural construction (cf 'boundary work') involved in establishing scientific credentials; implying the existence of inherently firm, indisputable scientific facts. Tracking 'the nano in exile' (i.e. Feynman's legacy) thus required a detour to the realms of science fiction and to observations of some of the 'gatekeeping practices' which stopped it from returning to its homeland (a theme of *chapters 2 and 3)*.

Second, partly because of having been denied a true academic identity, the nano field appeared to us as something of an open public space with respect to how crucial assumptions are rendered invisible in the discourses and daily practices of everyday science. Phrased in terms common within science and technology studies (STS), it can thus be expected to continue to be relatively transparent for some time as values and epistemic regimes remain to be 'black-boxed'; no 'closure' is attained over competing interpretations and interests among the involved actors. This virgin or greensite status is attractive for the sociologist of science, who often has to work hard to 'deconstruct' such boxes, unveiling the social and political elements which otherwise are obscured through deterministic or essentialistic views taken for granted. *Chapters 5, 6 and 8* resonate with such a ”virgin STS-framing” of the epistemics of nanotechnology.

Further, *third*, ’nano’ struck us as a likely candidate for becoming one of those fairly rare ”shockwaves” that penetrate and re-route substantial portions of the research policy&funding structure, as cherished by most technologically advanced nations. Although perhaps presumptuous, this expectation has so far been largely fulfilled. Like earlier atomic energy technology (in the 50s and 60s), microelectronics (in the 80s) and, more recently, genetic technology, nanotechnology is now skyrocketing in terms of funding while also transforming or being recasted as a separate academic subfieldof first rank. Although having had some early predecessors in e.g. Japan and Germany, the American National Nanotechnology Initiative (NNI) is the most obvious example of this, with Europe now trying to catch up by focusing on ’nano’ in the new EU framework programme (the FP6) underway. A series of questions are evoked by this ”en vogue” status of the field; concerning for example the ”real existence” of any solid epistemological core unifying the many disparate and blurred subfields now suddenly labeled ’nano’, or how new trends or trajectories always are to be situated and remodeled in relation to inherited patterns and constructs of science policies (*chapters 3*).

Fourth, we were driven by our wish that due to its generic character, which implies its broad and profound potential for changing human conditions, not only scientific and engineering expertise but also lay expertise should be given a fair opportunity to have an impact on roads taken and on priorities chosen during the course of development of nanoscale science. One precedent we had in mind here was the set of deliberative exercises called ’constructive technology assessment’ – CRA, which took shape some 15-20 years ago. A little later, through scanning the literature, we learned that such an exercise addressing nano issues, had indeed been undertaken in the Netherlands.

Yet later, the principal idea of inviting a broader range of expertise, even including lay expertise, to have a say on an emerging technology, was brought to the fore by the American National Nanotechnology Initiative (NNI) (announced by Bill Clinton in 2000). This was launched not only as an initiative taking technoscience and engineering a long way towards the perfect or utopian mode of production, but it also encompassed the unabashed policy ambition of ”doing everything right from the start this time’. Hence, by encouraging from the very outset discussions and reflections on the social, economic, legal, and ethical implications of nanotechnology, and heeding them, the founding fathers of the NNI boldly claimed to be able to help the new breed of nanoscientists avoid ”ending up in the same morass of public mistrust as the geneticists and the nuclear scientists”.

Finally, *fifth*, and most importantly: already when we were still merely starting to notice this emerging field rather than studying it in any more detail, we were attracted by its inter-disciplinary and open-ended hybrid character. It struck us as having a particular momentum or potential to challenge several former key boundaries and distinctions shaping scientific practices. A confrontation between the sometimes sharply separate cultures of physics, chemistry, biology, and electrical engineering, with important implications, seemed likely. Also, we sensed the possible erosion or collapse of several former clear-cut demarcations, such as those between theorists, experimentalists and instrumentalists, or those between numerical-textual-visual practices. Although envisioned, of course, not as sudden revolutions but as incremental and drawn-out changes of the mundane everyday practices, we still soon expected enough observable transformation to present a fertile soil for us in our capacity as ethnographers or cartographers of science (cf also motive 2 above).

There's no point in denying, however, that this attraction was also fueled by our fancy for what already at that time was (and is more so now), a ”blossoming bottom-line rhetoric” about the nanoscale (*chapters 2, 7 and 8*). This rhetoric is permeated with a clear 'saviour of mankind-spirit': i.e. in spite of all progress and high-tech, our control of the very structure of matter when manufacturing things remain poor, causing levels of waste and pollution rendering all aspirations for sustainable production impossible. For Eric Drexler and his fellow ”nanoites”, the nano challenge is about once and for all liberating ourselves from this dystopian predicament. Nanotechnology is, he establishes, not primarily about miniaturizing machines, but ”..about making (precise) things *big*”; and it is a necessary and inevitable step to take – ”… a shotgun marriage of chemistry and mechanical engineering with physics as always presiding”. If instead it is phrased in terms of innovation theory, this marriage is about innovation in the true Schumpeterian sense, i.e. as 'the creation of radical new combinations'.

Another reason why the interdisciplinary nature of nanotechnology appealed to us as strongly as it did, resonates with C P Snow's 'two cultures'-argument. To us, the marriage outlined above would not in itself exhaust the potentiality of 'restructuring science'; neither would it secure the future happiness of the couple. One should also, look upon the recasting as a golden opportunity to transcend the divide between Nature and Culture. This touches upon the CRA motive above, but rather than focusing on the importance of widening or democratizing expertise by including other actors through various deliberative practices, it concerns how (natural science) nano scientists and human or social science scientists focusing on nano technology could interact. The radical claim here lies in the initiation of a symbiotic and symmetrical 'on-line relationship', one where the two troops of scientists become each other's critical audience during the very development of a new (techno)science; i.e., as seen from the social scientist's point of view ”informing it while being informed by it”.

CHAPTER 2

Molecular Matters: In Search of the Real Stuff[1]

Hans Fogelberg and Hans Glimell

Introduction

This chapter is organized into three parts. In Part 1, we introduce a fascinating set of ideas about the emergence of an entirely new field within technoscience: nanotechnology, also known as molecular nanotechnology, or molecular manufacturing. We seek to grasp the general rationale and the claims made about the impacts or potential of this technology. That leads us into some of the vivid rhetoric and heated debates characterizing the field. In Part 2, we make an attempt to come closer to the technical principles and solutions involved. It turns out that one has to distinguish between different branches or sub-areas with partly very different definitions and ambitions guiding their work. Among various solutions, the recent discovery of buckministerfullerenes, a specific kind of carbon structure, is particularly noticed. Moreover, some examples of suggested product applications are described.

The aim of the chapter is exploratory. We want to provide a first map of this area of technoscience, as well as some tentative hints as to how to proceed with a more comprehensive social study of the field. This sets the agenda for Part 3. It starts by retrospectively articulating some of the tensions and standpoints reviewed by in the two first parts. After a few remarks on our own plans for the post-Fågelbrohus existence to come, we finish the chapter by proposing some kind of application of the CTA approach within the interesting field of nanotechnology.

The claim: Reinventing Manufacture Through Masterly Molecular Control

> Nanotechnology could have more effect on our material existence than those last two great inventions in that domain - the replacement of sticks and stones by metals and cements and the harnessing of electricity. (Marvin Minsky, Professor of Electrical Engineering and Computer Science, co-founder of the proposition of artificial intelligence)

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[1] Paper presented at the seminar "The Battle at the Bottom: Making The Most of Feynman's Legacy". VINNOVA, Stockholm, April 19th, 2001.

When pressed, no one really claims that nanotechnology, in the sense of molecular manufacturing, actually exists today. And, considering the wide variety of features, characteristics and potential applications that have been suggested as being part of it (some of them mirrored in this chapter), it may well be that trying to proclaim the very moment of its birth would be to fall victim to exactly those traits with which nanotechnology should never be associated: crudeness and arbitrariness. What has been claimed, however, is that for various reasons - whether stemming from some inherent logic of development, the urgent necessity of replacing existing problematic modes of production, or from good old sheer curiosity constantly driving scientists on to new challenges - nanotechnology qualifies as a potentially breathtaking, ground breaking forerunner of a technological trajectory bound to come. In that capacity, as an intriguing *perspective shifter*, it certainly exists already.

So, what is it then, this challenger? In a later section, we will take a closer look at that. For the time being, our focus will stay with the general claims and characteristics attributed to the field, its ”raison d'etre”. Matching that level of description, there is a definition suggested by the most proactive proponent and promoter of nanotechnology, stating that it is *”the precise and purposeful manipulation of matter at the atomic level”*, or, more specificially:

> Thorough, inexpensive control of the structure of matter based on molecule-by-molecule control of products and byproducts; the products and processes of molecular manufacturing.[2]

This definition, or rather vision, is not something that has solely emerged among specialists in the scientific laboratories or among high-tech engineers in advanced industrial R&D projects. It also promises the long awaited answers to a burdensome set of urgent questions or needs in the world, thus addressing global problems persistently plagueing mankind such as pollution, physical disease, and material poverty. From an engineering meta-perspective it has been argued that the roots of those mega-problems are in fact one and the same: *the poor control of the structure of matter*. Seen in this way, the entire range of twentieth-century technologies, once the object of so much pride and spirit of progress, appear as a poor or primitive trajectory of engineering. That then applies for most of mechanical engineering, as well as much of the highly-esteemed medical technology with, among other evils, its extensive use of toxic chemotherapies.

With this disappointing record in front of us, there is only one way to go, the nanoscientists tell us, and that is backwards - ”back to basics”. The solution must be searched for at the only level where full control

[2] Drexler, K.E., *et al.* 1991. *Unbounding The Future: The Nanotechnology Revolution*. New york: William Morrow and Company, Inc p.19.

can be achieved. We have to become masters of matter at its most fundamental level, i.e.where it first materializes and organizes itself into a myriad of constellations: the molecular level. There, on the bottom line of present knowledge, awaits nothing less than another spectacular conquest for the troops of technoscience. Back to basics in fact means going back to nature, in a great attempt to ”pull out” the solutions to our (self made) problems from its tiniest little realms. Engineering must strive to become as clever in monitoring molecular machines as the ordinary tree, that so peacefully and quietly processes carbon dioxide and water into oxygen and molecular building blocks.[3] But it should in fact do even more than that, it should *outdo* those ingenious trees by also learning how to perform this delicate act of cleanliness and precision in a fully preplanned manner, at the pace and scale it decides. A new, naturalised machinery of production will replace the present patchwork:

> Nanotechnology will be a technology of new molecular machines, of gears and shafts and bearings that move and work with parts shaped in accord with the wave equations at the foundations of natural law. Mechanical engineers don´t design molecules. Molecular scientists seldom design machines. Yet a new field will grow - is growing today - in the gap between. That field will replace both chemistry as we know it and mechanical engineering as we know it. And what is manufacturing today, or modern technology itself, but a patchwork of crude chemistry and crude machines?[4]

A Blossoming Bottom-Line Rhetoric

As already indicated, the area is flooded with rhetoric. Although some of it balances on the verge of science fiction, a fair share of the rhetoric is about corroborating the *realism* of the nanotechnology endeavour. It thereby addresses the objection that the crude mode of production we have is there for a good reason (which is that greater precision is both costly and complicated). Approaching the very small, the bottom-line of matter, could, this side argues, lead us into a situation we cannot control (or even be an attempt to violate the laws of nature). This is in fact what is now being discussed within microelectronics, a field that has already travelled a long way along this path (more on that in the next section). But here nano-rhetoric performs its function as a perspective shifter by announcing that it is not at all dense, crowded or chaotic at the smallest level. It just *looks* that way, as long as you employ the top-down

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[3] ”Every tree makes leaves, and each leaf is more sophisticated than a spacecraft, more finely patterned than the latest chip from Silicon Valley. They do all this without noise, heat, toxic fumes, or human labor, and they consume pollutants as they go. Viewed this way, trees are high technology. Chips and rockets aren't.” Ibid.

[4] Ibid, p.20.

perspective that so far totally has dominated our idea of what engineering could be. However when released from that, the spokesmen of nanotechnology assure us, you will on the contrary find that there is plenty of room at the bottom. And to make their claim authoritative, they often attribute the inaguration of the field to a prominent member of the scientific community who outlined its basic idea as early as in 1959:

> The principles of physics, as far as I can see, do not speak against the possibility of maneuvering things atom by atom...Ultimately, we can do chemical synthesis...How? Put the atoms down where the chemist says, and so you make the substance. The problems of chemistry and biology can be greatly helped if our ability to see what we are doing, and to do things on an atomic level, is ultimately developed - a development which I think cannot be avoided. (quoted from the speech ”There’s Plenty of Room at the Bottom” given by the Nobel prize winning physicist Richard Feynman, at CalTech in 1959, introducing the very idea of atomic precise construction).

Thus, the revolutionary thing about this obviously has to do with the point from which you start watching and working. The nano discourse is, at least as it is reflected in these excerpts, about direction; about how to somehow do engineering from the bottom up. But although surely implying a revolution as far as matter-processing is concerned, it is *not* entirely revolutionary. The principal line of argument and the methodology it implies have been applied elsewhere. Again, there is some useful credibility to be gained by reflecting the nanotechnology ideas in something we consider to be as both manageable and impressive; in this case as an analogy with a line of development drawing so much attention lately:

> Digital electronics brought an information-processing revolution by handling information quickly and controllably in perfect, discrete pieces: bits and bytes. Likewise, nanotechnology will bring a matter-processing revolution by handling matter quickly and controllably in perfect, discrete pieces: atoms and molecules. The digital revolution has centered on a device able to make any desired pattern of bits: the programmable computer. Likewise, the nanotechnological revolution will center on a device able to make (almost) any desired pattern of atoms: the programmable assembler.[5]

...and also, in the same vein:

> Today, manufacturing relies on many specialized machines for processing materials; blast furnaces, lathes, and so forth. Molecular nanotechnology will replace these slow, inefficient, specialized (and dirty) machines with systems that are faster, more efficient, more flexible, and less polluting. As

[5] Ibid, p.34.

> with computers, and bits, these systems will gain their flexibility by working with fundamental building

So, according to the above excerpts (most of them issued from the same camp), the nano thing is about learning about the bottom-line, and using that knowledge (that biologists and chemists to a large extent already possess) to start building a brand new sort of machinery with the basic blocks of the material world. For some, this may sound like a form of biotechnology. It has been pointed out, though, that the two are very different, only sharing the fundamental principle of a molecular assembly. Where biotechnology uses ribosomes, molecular nanotechnology uses robotic assembly; further, it uses conveyor belts instead of veins, motors instead of muscles, computers instead of genes, etcetera.[6] Another way to illustrate the relationship is to make an analogy with how the Wright brothers constructed the first aeroplane. Before designing the actual artefact, they made observations of birds flying. Assumingly this inspired them quite a bit. But building an aeroplane was still obviously something quite different from replicating a bird. The biologist does not have the skills or goal to come up with constructions based on what he or she studies; mixing these forms of professionalism up, would therefore be something almost as absurd as asking the expert on birds, the ornithologist, to build aircrafts.

A Shotgun Marriage: Big and Small Becoming a Couple

Although, as has been demonstrated, quite a bit of the rhetoric involved here seems tuned to create an air of realism and mainstream respectability around nanotechnology, it shall not be denied that also *romance* runs deep into its core. We have already met a kind of romance with nature: man is finally about to pay tribute to nature by putting a stop to pollution and instead develop sustainable production in accordance with nature's own molecular preciseness. But there is also another event of almost historical proportions being announced here. We are invited to take part in a wedding, a wedding between parties that for a long time have gone in separate directions, although actually having much to offer each other. The time has come to rejoin those parties, now almost out of sight of each other because of high disciplinary walls and academic rivalry. Here comes the happy couple:

> Nanotechnology is basically a shotgun marriage of chemistry and mechanical engineering with physics (as always) presiding.[7]

Saluting this event is a frequent and logical element in the nanoists[8] repertoire of rhetoric. The close collaboration between the two

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[6] Drexler 1992

[7] Drexler, K.E., *et al.* 1991. *Unbounding The Future: The Nanotechnology Revolution*. New york: William Morrow and Company, Inc., p.80-81.

disciplines (also others such as computer science are welcomed to join the party and become part of the nano family) is absolutely essential. Pure science, particularly research in chemistry and biochemistry, has long been preparing the ground for molecular nanotechnology. Now, all is said to depend on whether she (because there we have our bride), once the honeymoon is over and everyday life returns, will be able to adapt to the habits and life style of the bridegroom. It might not be that easy because to bring realism back in, they are not the same breed of science:

> The development of molecular nanotechnology can keep much of the character of small science, but it will require the addition of a systems-engineering perspective and a willingness on the part of researchers to choose objectives that can contribute to known technological goals. Progress will require that researchers build molecular parts that fit together to build systems, but the necessary tradition of design and collaboration - fundamental to engineering progress - is essentially absent in the molecular sciences today.[9]

So, confronting romance with realism, how deep is the love? Is it deep enough to bridge over the gaps that soon are bound to cause problems for the newly-married? Perhaps they are just too different to make a believable couple in the first place? Well, we'll have to wait and see. But we can notice that not even the marriage broker himself (K. Eric Drexler, that is the name of the 'guru', also called 'Messiah' by scornful critics) whose words and spirit orchestrate this first section - not even he, seems confident on this crucial point. In a somewhat different context, he thus acknowledges that the bride and the bridegroom do talk very different languages. The nanoworld is not one; it can be explored and theorized from many angles, upon which it dissolves and can become very confusing. Indeed, in our reading, Drexler admits that the couple to whose marriage in the foreseeable future he has dedicated his career, may well have *opposite* understandings of what their marriage is all about:

> From today´s viewpoint, molecular nanotechnology looks more like an extension of chemistry than like an extension of miniaturization. A mechanical engineer, looking at nanotechnology, might ask, 'How can machines be made so small?'. A chemist, though, would ask. 'How can molecules be made so large?'. The chemist has the better question. Nanotechnology isn't primarily about miniaturizing machines, but about

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[8] 'Nanoists' has been used as a disparaging term in the debate about nanotechnology, implying that some people in the field are quite fanatic or fundamentalist in their beliefs. We come back to this in the concluding section.

[9] Drexler 1992

> extending precise control of molecular structure to larger and larger scales. Nanotechnology is about making (precise) things big.[10]

The word ‘nano’ is Greek and it means ‘dwarf’. It is also a word that has been allotted a specific place in the arithmetic system, covering a certain range or interval of size (in relation to a given norm, a meter). For many therefore, ”nano” is not at all an object for competing interpretations or negotiating; it already has its fixed meaning. That does not exclude that they may have a clear opinion on whether that is small or big. For example, those who within electrical engineering now try to build new devices scaling them down from the ‘micro’ to the ‘nano’ interval of dimensions, most definitely experience that as becoming very small indeed.

Drexler is, of course, well aware of this when claiming that ‘nanotechnology’ primarily should mean making things big. His motives for taking such a clear stance are plainly political, in the sense that he has appointed himself a spokesman for a specific prefered procedure or trajectory when it comes to developing future technology. He very deliberately, it seems, seeks opportunities to contrast the bright new things to come with the dull old ones residing in many centres of science. He even founded a specific institute called the *Foresight Institute*, to promote the message. Doing all this, he must of course be prepared to face scepticism or antagonism from those representing less propagandistic approaches. Next, we have an example where Drexler was the target, without actually participating himself.

Foresight Institute vs Scientific American: A Heated Debate on the ”Drexlerian Dreams’ (also starring www.)

According to the director of one of the combatants, *Foresight Institute*, the fight lasted four rounds. It started with the publication of a highly critical six-page news story on nanotechnology in the journal *Scientific American*, written by staff journalist Gary Stix.[11] A few days later Ralph Merkle, a researcher at Xerox PARC, Palo Alto, CA., but also active within the Foresight Institute, published a ”complete rebuttal of the full text” on the Institute’s Web site[12] (the major points of which will be recapitulated below). There were in this Round One also some letters sent to *SciAm*, one of them from Carl Feynman, the son of late physicist Richard Feynman who is reckoned as the founding father of the field due to his remarkably far-sighted speech given in 1959. In Round Two, *SciAm* demanded that *Foresight* should stop publishing any quotations from their news story on the Web, upon which the latter replied that

[10] Ibid, p.76-77.

[11] ”Trends in nanotechnology: Waiting for breakthroughs”, in *Scientific American*, April 1996, pages 94-99.

[12] *Foresight Institute* is.....

publication in that media rather should be further encouraged, not restricted, as it represents a valuable contribution to to a democratic debate by giving many parties the opportunity to participate.

The Third Round was more eventful. *SciAm´s* editor-in-chief John Rennie now responded to Merkle´s rebuttal in a letter to *Foresight Institute* (mailed in the traditional way). According to the *Foresight* version, he did so without any ”technical content supporting his negative position on nanotechnology”. *Foresight* published this letter on its web site along with another rebuttal, pointing out Rennies errors in reasoning and logic, as well as his poor standards of science journalism. Perhaps they were after all somewhat attracted by such poor stuff themselves, because when looking back at this, they inform us, the Web readers, that ”We had fun writing this.” In Round_4, Ralph Merkle posted another response to Rennie, and later the same day *Foresight´s* chairman, Eric Drexler did the same, pointing out the complete lack of scientific content in *SciAm´s* position on nanotechnology. Some weeks later, one and a half month after the publication of the article that sparked off the controversy, *SciAm* published a second article that, again according to *Foresight´s* version, ”amounts to a correction of the previous story”. The self-appointed winner concludes its recapitulation by saluting the losing side for having stepped back from its original position, now instead recognizing the growing importance of nanotechnology.

Returning to Round One in an attempt to grasp the essence of the controversy, we ask what it was in Gary Stix' (GS) story that Ralph Merkle (RM) brought up as the crucial elements of this ”unfair attack” on the field? First, RM pointed out that GS had used a deceptive or *misleading definition of the area (1),* namely ”...the manufacture of materials and structures with dimensions that measure up to 100 nanometers (billionths of a meter)”. According to RM this serves as a definition for nano*scale* technologies but not for nanotechnology, which more adequately should be defined as ”a manufacturing technology able to inexpensively fabricate, with molecular precision, most structures consistent with physical law”. A consequence of GS´ irrelevant definition was e.g. that certain problems in today´s lithographic technology quite falsely were taken as an indication that ideas brought up in nanotechnology were not feasible.

The second counterattack from RM concerned what he refered to as the *ad hominem attacks on Drexler (2)* from GS. Drexler himself and his personality had been given unacceptable attention, RM reckoned; there were e.g very peculiar remarks on how he took his tea, which were just insinuations about his character with no relevance whatsoever for the subject of the article. Thirdly, RM struck back on a more fundamental issue, saying that GS in his article made himself into a *spokesman for a purely experimental approach (3)* in developing nanotechnology, an approach which belittles the value of computational and theoretical work, whereas RM and the Foresight Institute instead advocate a mixed approach that encompasses ”the aggressive use of molecular modeling as an integral component of a long range strategy to develop molecular nanotechnology”. To illustrate this, RM recapitulates the way in which GS in the article had commented on his own presentation at the Fourth Foresight Conference in 1995 (around which GS´ story circles). In the same vein, RM later on pointed out that the method of scenario planning which he consider a respectable and established method for gaining certain insights, is dismissed or discredited by Scientific American.

A fourth point given much room in RM´s rebuttal concerns *the idea of self replicating systems (4)*, a crucial idea in the Drexlerian understanding of nanotechnology. GS had in his story presented the opinion that this was nothing but ‘science fiction’. He also quoted a message posted on an Internet bulletin board (sci.nanotech) where Phillip W. Barth, an engineer working with micromechanics at Hewlett-Packard, suggested that the speculative stance within nanotechnology circles on these systems (assemblers) made adherents look like ”a mass social/political movement or a religious faith in the traditions of Marxism and Christianity”. RM here mobilizes several counter-examples, for example the work going on within NASA and in Japan, as well as adducing more theoretical support by referring to the mathematician legend John von Neumann’s ideas on self-regulation.

Much of the rest of RM´s rebuttal is about trying to prove (exemplify) that nanotechnology is not at all as isolated and disregarded as it appears in GS´ story. It is of course an attempt to outweigh the fantasy impression communicated in the article, in which ‘nanopunk’ is mentioned as a follow-on to the cybernetic science fiction written by William Gibson and others; ‘nanoism’ is also talked of as a post-modern form of alchemy. RM mentions a number of professors from various fields to show that the ideas are grounded also in what would be considered to be mainstream circles, and that there is also a growing interest from industry and the boards financing research. He underlines that the scepticism that GS so much emphasizes is concentrated to certain disciplines, whereas others, e.g. computer scientists and computational chemists generally ”grasp nanotechnology quite easily”.

Well, completing our reporting on this public (if you accept www as public) dispute, is it really a matter of grasping nanotechnology? Or is it that there instead are several ‘nanotechnologies’, the one being just as valid as the other. And is it true, what Merkle says here, that professors from mainstream circles do confirm the feasibility of ideas that the Stix article dismissed as nonfeasible?

The Technology: Opening the Door to a World of Buckminister Fullerenes and Molecular Assemblers

The Meaning and Obstacles of a Nanometer Scale Technology

> Things on a very small scale behave like nothing that you have any direct experience about.. ..So we have to learn about them in a sort of abstract or imaginative fashion and not by connection with our direct experience.[13]

As has been demonstrated rather exhaustively by now, there is no simple answer to the question ”What is nanotechnology?”. Nevertheless, there was an unmistakable bias in the first part of our chapter in the sense that we chose as starting points for the introductory discussion of the field a number of claims and characterizations issued in the circles around Eric Drexler. We did that as an acceptance of the recognition of Drexler as the number one proponent of nanotechnology, whereupon we however soon made ourselves and (hopefully) the reader aware of that the drexlerians have aroused at least as much scepticism as enthusiasm throughout their nanotechnology crusade. With the exception of science journalist Gary Stix, the sceptics remained fairly faceless, anonymous.

In this second part, out of the anonymity will step professor Richard Smalley. He will bring a contrast into our story, a useful one we reckon, as he, unlike Drexler, enjoys full credibility in mainstream science circles, confirmed last year by his winning the Nobel Prize in chemistry for the discovery of the self-assembly of nanometer scale carbon structures. In approaching the area for a second time, we will start with another definition of it, one that makes sense to many, but that appear as basically insufficient for those setting the agenda in the preceding sections. It goes like this: *Nanotechnology is everything that occupies the scale of the nanometer*.

And how small, then, is the scale of nanometer technology? If you divide one meter by a thousand you get a millimetre [1mm]. If you take that millimetre and divide it by a thousand once more, you get a micrometer [1µm], which today equals the precision with which one can mass produce metal artefacts. If you then take that one micron, and divide it by thousand again, you will end up on the nanometer scale [1nm], the scale and size (if we may use that term), of molecules and atoms. This is the smallest scale at which it is thought to make sense to try to ”build things”. Three to five atoms side-by-side measure only about one nanometer.[14] Thus, to our present knowledge, the nanometer

[13] Feynman, Richard P. 1965. *The Feynman Lectures on Physics: Quantum Mechanics*. Reading, Massachusetts: Addison-Wesley Publishing Company, p. 1-1.

[14] Smalley, R. ?

scale represents ‘the bottom’ for any prospect of technology. A nanometer technology then naturally deals with the issue of how to control these molecules, atoms, and electrons, and about how this technology might be mass produced. Still, the definition above does not say much about the direction nanotechnology is going. Both Drexler and Smalley use more precise, goal oriented, and also strikingly similar definitions.

Whereas Drexler says that ”nanotechnology is about control of the structure of matter rather than about scale”[15], Smalley says that ”nanotechnology is the art and science of building molecular structures so that they are sufficiently large and complex to function as machines or devices”.[16] While the success of any nanoscale acitivity certainly will depend on the ability to control ‘matter’ on this scale, putting the aspect of ‘control’ ahead the aspect of scale, may lead the practitioners in yet another direction.

The distinction that Smalley make between *devices* versus *machines* is fairly common and lends itself to a distinction between *nanoelectronics* versus *molecular nanotechnology* (or molecular machines). Nanoelectronics is concerned with making *devices* that can perform computation and information storage, whereas molecular nanotechnology is mainly concerned with the manufacturing of molecular *machines*. However, even if this distiction is used here, we should bear in mind that the dividing line between nanoelectronics and molecular machines may be more a difference in interests and aims, rather than in intrinsic properties of technology.

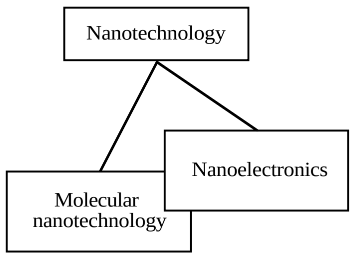

Figure II-1 The two lines of nanotechnology

[15] Drexler, K.E. 1989. ”Critical Path Panel”, Ch. 6, Section E, in the Proceeding of the 1989 NanoCon Northwest regional nanotechnology conference. Dated: February 17-19, 1989, Downloaded on September 25, 1997 at URL http://www.halcyon.com/nanojbl/NanoConProc/nanocon2.html.

[16] Smalley, R.E. 1996. ”Chemistry On the Nanometer Scale”, Introductory remarks by R.E. Smalley at the Robert. A. Welch Foundation 40th Conference on Chemical Research: Chemistry on the Nanometer Scale, held in Houston, TX, October 21-22, 1996. Downloaded from the personal Home Page of Smalley, at URL http://cnrst.rice.edu/NanoWelch.html.

As indicated in the figure above, there is a sort of technological ‘overlap’ between the molecular electronic devices (in nanoelectronics), and the molecular machines (in molecular nanotechnology). This is the small area in which nanoelectronics and molecular machines do meet each other. How? Both need the ability of precise control of ‘movable’ parts of the molecular structure, and both need some kind of replicant function that assembles the molecular structure, either as self-assembled nanostructures (e.g. colloidal grown nanocrystals)[17], or that the structure is assembled by some kind of molecular ‘robots’ (e.g. Drexlers proposal of general purpose ‘assemblers’).

Two Lines of Nano Technology

Nanoelectronics can, in turn, be seen as taking two different routes. One attempts to take the problem of quantum effects which arise with the miniaturisation of traditional micro electronics, as the starting point of solutions which *take advantage* of precisely these quantum effects (see left wing in figure II-2). Even if that technology is certainly new and challenging, it is still in some sense on the same trajectory, as that of today’s semiconductor technology.

Downscaling in microelectronics has, since the invention of the transistor by Kilby in 1958, proceeded at an exponential rate, thus doubling the number of transistors per area unit every 18th month (”Moore’s Law”). The present state of microelectronics uses transistors of about 250-350 nanometers minimum length. An Intel Pentium processor in a modern computer contains about 3.2 million transistors, which each has a minimum feature size on the order of 350 nanometers. However, it is widely believed that a further continuation of downscaling based on traditional technology will run into major problems very soon. With further minimisation, the ‘materials’ will stop behaving as bulk materials and instead start behaving as discrete atoms and molecules, whereupon the bulk flow of current in the transistors will end and instead start to exhibit ‘jumping’ of single electrons (tunneling). When the size of technology approaches that of molecules, atoms, and electrons, the so-called quantum mechanical effects start to ‘take over’. These effects will make it very difficult for the traditional technology to continue its path of downscaling.[18]

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[17] A single electron transistor has been made with this type of self-assemblying structure. See article by Marc Kastner, ”Technology and the single electron”, in *Nature*, Vol. 389, October 16, 1997, p. 667.

[18] Goldhaber-Gordon , D., *et al.* 1997. ”Overview of Nanoelectronic Devices”, in Nanoelectronics Overview, a report Compiled by Ergil Demir, at Chalmers University of Technology. And discussion by Clifford P. Kubiak and Jason I. Henderson, dept. of chemistry, Purdue University, West Lafayette, at the Scientific American ”Ask The Experts: Chemistry” web page, downloaded October 17, 1997, at URL

Nanoelectronics, as an important branch of nanotechnology (if not only for the industrial interest directed towards it), tries to turn this problem into the very solution, and *utilise* the processes of quantum effects for a new generation of computers. If nanoelectronics is feasible *and* manufacturable, it will not only mean that the path of downscaling can be continued, but that a *gigantic leap* can be made in information storage and computational power. A nanometer scale solid state or molecular electronic 'transistor' may be 100,000 times more dense than is presently possible[19]. What does this mean? For example that you could have the library of congress, your desktop files, and all the films at your local video store 'captured' inside a pair of eyeglasses.[20] There are also already technological hybrids between *nano*technology and *micro*technology in transistors, as a step towards a pure nanotechnology.[21]

The other route taken by nanoelectronics is that of trying to control and use molecules as electronic devices for information storage and computation (see right branch in fig. II-2). This route is generally perceived to represent a larger change in technology, and thus also to pose much larger obstacles. Trying to control molecules in nanoelectronics is also what people in molecular nanotechnology want to do, thus narrowing the technological gap between nanoelectronics and a molecular nanotechnology, even if their goal is different. People who work on molecular nanotechnology are thus much more interested in the *engineering properties* of molecules than of their *informational properties*.[22]

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http://www.sciam.com/asexpert/chemistry/chemistry6.html.

[19] Goldhaber-Gordon , D., *et al.* 1997. "Overview of Nanoelectronic Devices", in Nanoelectronics Overview, a report Compiled by Ergil Demir, at Chalmers University of Technology, p. 21.

[20] This is a mind-setting idea of what the supposed dramatic capabilities of nanocomputing may be able to do, proposed Papiewski in, Papiewski, J. 1996. "The Companion", in *Nanotechnology: Molecular Speculations on Global Abundance*. Cambridge, Massachusetts: The MIT Press.

[21] Goldhaber-Gordon , D., *et al.* 1997. "Overview of Nanoelectronic Devices", in Nanoelectronics Overview, a report Compiled by Ergil Demir, at Chalmers University of Technology, p. 24.

[22] Drexler, K.E. 1989. "The Paths to Nanotechnology", Ch. 2, Section E, in the Proceeding of the 1989 NanoCon Northwest regional nanotechnology conference. Dated: February 17-19, 1989, Downloaded on September 25, 1997 at URL http://www.halcyon.com/nanojbl/NanoConProc/nanocon2.html.

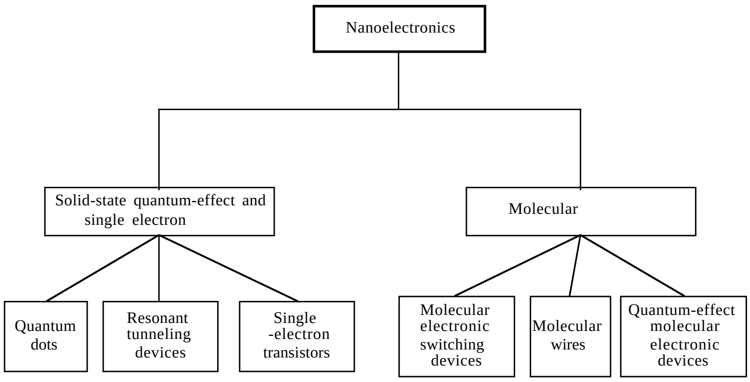

Figure II-2 (above) Different developmental paths in nanoelectronics.[23]

Molecular nanotechnology carries with it the ambition to situate this technology as something new, interdisciplinary, and essentially different in aim and goal, from that of 'pure science' conducted on a nanometer scale. It utilizes 'mind-setting metaphors' to try to keep our minds as open as possible. It displays the search of the 'true character' of nanotechnology. A molecular nanotechnology may, of course, as already described above, be used for building electronic devices such as transistors for switching or amplifying. However it could also clear the way for even more radical changes in technology, as derived from the idea of molecular 'machines', or so-called *assemblers*.

This strange 'machine-molecule' must, in order to do its work as a *general purpose* assembler, be able ”to build molecular structures with any conceivable configuration”.[24] Furthermore a 'true' assembler must ”contain a computer, it must be able to 'see' and make sense of its surroundings, it must be able to propel itself and navigate, and it must be able to handle and bond atoms of various kinds”.[25] In other words, the ambitions are sky high.

Let us contrast this with the view of Richard Smalley, the discoverer of the Buckminister Fullerene, a previously unknown form of self-

[23] The diagram is derived from the outline made in, Goldhaber-Gordon , D., et al. 1997. ”Overview of Nanoelectronic Devices”, in Nanoelectronics Overview, a report Compiled by Ergil Demir, at Chalmers University of Technology.

[24] Crandall, B.C. 1996. ”Molecular Engineering”, in *Nanotechnology: Molecular Speculations on Global Abundance*, B.C Crandall (ed). Cambridge, Massachusetts: The MIT Press, p. 16.

[25] Kaehler, T. 1996. ” In-Vivo Nanoscope and the ”Two-Week Revolution””, in *Nanotechnology: Molecular Speculations on Global Abundance*, B.C Crandall (ed). Cambridge, Massachusetts: The MIT Press, p. 52.

assembling carbon structure.[26] He is pessimistic about the prospects for molecular nanotechnology to overcome the obstacles of building a *universal* assembler, the ultimate goal of a Drexlerian molecular nanotechnology:

> Please realize that most of the extreme dreams for nanotechnology as envisioned by Drexler require that it be possible to build a ”universial assembler”, which is some sort of autonomous microscopic robot which can be programmed to ”build anything”. While I agree that such universal assemblers could very well do most of what Drexler and others dream... ...I am now fairly confident that such universal assemblers are flat-out impossible.[27]

Smalley's opinion on the assembler is that it cannot control all the atoms within a volume of 1 cubic nanometer, and that this poses a major obstacle for a universal assembler. While Smalley acknowledges that a general purpose assembler may work well on a larger scale than the volume of one cubic nanometer, he argues that the chemical reactions are actually settled *within* this volume and that the assembler will have problems in controlling what is going on inside this miniscule volume. The argument is that the movements of *all* the atoms within the volume have to be controlled since the atoms interact with each other. The problem, however, is that the ”fingers” of a Drexlerian general assembler are also made of atoms, and are consequently to big and clumsy to succeed with that delicate task.[28]

But on the issue of societal impact, the differences are not that big between the two. Smalley puts a lot of emphasis on the general potential of nanotechnology to have a *significant impact* on society, given, of course, that his version of nanotechnology will work. Smalley acknowledges that nanotechnology, even in a more modest form of his own nanotubes of carbon, eventually ”may change the future of

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[26] The features of self-assembly into C_{60} carbon structure is discussed by Richard Smalley in his Nobel Prize lecture, ”Discovering the Fullerenes”, December 7, 1996. Downloaded from the personal home page of Smalley, at URL http://cnrst.rice.edu/nobel.html.

[27] E-mail from Dr. Smalley to Richard H. Smith. Smalley's E-mail is cited in, Smith R.H. ”Molecular Nanotechnology: Research Funding Sources”, dated December 6, 1995, downloaded on September 24, 1997, at URL http://hoohana.aloha.net/nanozine/nanofund.htm.

[28] Smalley, R.E. 1996. ”Chemistry On the Nanometer Scale”, Introductory remarks by R.E. Smalley at the Robert. A. Welch Foundation 40th Conference on Chemical Research: Chemistry on the Nanometer Scale, held in Houston, TX, October 21-22, 1996. Downloaded from the personal Home Page of Smalley, at URL http://cnrst.rice.edu/NanoWelch.html.

humankind"[29], and that nanotechnology from chemistry on a nanometerscale "may make even Drexler blush"[30]. In his Nobel prize lecture, for example, he talks very enthusiastically about this:

> Imagine what the impact could be. Essentially, every technology you ever heard of where electrons move from here to there, has the potential to be revolutionized by the availability of molecular wires made up by carbon. Organic chemists will start building devices. Molecular electronics could become reality.[31]

Thus the visions of dramatic change are, it seems, present in all 'corners' of the nanotechnology discussion. Smalley's Fullerenes, the self-assembled carbon nanotubes, can be used in material for storing hydrogen in fuel cell vehicles, to supply bullet-proof vests, for new golf-clubs(!), as conductors, isolators, or semiconductors, and they can withstand the most chemically aggressive milieus.[32] This vision is converging with that of Drexler. Smalley also himself says that "if" we succeed, then nanotechnology will represent a historical turning point in technology and society.

Nanotechnology Applications: Marvellous Devices or New Problems?

> Nanotechnology is a technology destined to change every aspect of our lives. It will allow marvellous new machines and applications, things we can only just imagine, and things we can't imagine at all.[33]

The ultimate goal of nanotechnology is controlling nature at its basic level, which would enable us to be even more successful than nature itself. This is in accordance with the spirit of the modernist project that has accompanied us for a long time now. The *ambiguities* of the contemporary industrial capitalism, here in the form of the environmental problems created by the way we live, serve as one of the starting-points for developing nanotechnology. Somewhat ironically, the huge problems created by the societies resting on modern Western

[29] As cited in *Ny Teknik*, "Små rullar av Kol som förändrar världen", 16/10 1997.

[30] Smalley, R.E. 1996. "Chemistry On the Nanometer Scale", Introductory remarks by R.E. Smalley at the Robert. A. Welch Foundation 40th Conference on Chemical Research: Chemistry on the Nanometer Scale, held in Houston, TX, October 21-22, 1996. Downloaded from the personal home page of Dr. Smalley, at URL http://cnrst.rice.edu/NanoWelch.html.

[31] Smalley, R. 1996. "Discovering the Fullerenes", Nobel-Prize lecture by Richard Smalley, December 7, 1996. Downloaded from the personal home page of Smalley, at URL http://cnrst.rice.edu/nobel.html.

[32] *Ny Teknik*, "Små rullar av Kol som förändrar världen", 16/10 1997.

[33] Chesley, H. 1996. "Early Applications", in *Nanotechnology: Molecular Speculations on Global Abundance.* Cambridge, Massachusetts: The MIT Press.

technology - combined with a crude belief in science and technology as the entire and ultimate solution - now encourage engineers of nanotechnology to propose applications that will be literally *everywhere* (around us, inside us, they will even be ”us”). Thus, the solution to modern technology, as proposed here, is an unlimited amount of new forms of technology.

Among the fairly modest proposals for applications we here find certain instrumentatation for science and medicine, extremely compact and energy efficient computers, strong materials for lighter and more efficient vehicles, and inexpensive solar cells suitable for use in roofing and pavement.[34] These applications can be seen as a continuation and improvement of current technological trajectories. Another traditional area that has been suggested as interesting for an early stage of nanotechnology is bodycare. Expenditures for bodycare are rapidly increasing. Even the most ‘basic’ hygiene products as powders, sprays, perfumes, etc, correspond to an annually world market of about 14-18 billion USD, and the ‘appearance-enhancement’ market is twice as big. Cosmetics is pointed out as one area where molecular engineering can be used on a commercial basis at an early stage: colouring of hair and skin, reducing of skin wrinkles, hair removal or addition, better breath, fat reduction. But new areas may also be explored: self adjusting colouring of fingernails and eye shadow (according to e.g. light angle and mood).[35]

Going deeper into our bodies and also letting the voice of more traditional sciences be heard, targetted drugs and gene therapy are discussed by S. S. David as two biomedical applications. Nanometer sized (medicine) particles can be inserted into our bodies for targeting (i.e accumulation) in a particular organ, cell type, or even a specific area within the cell. Smaller quantities of drugs can be used when they are placed at the location of maximum effect. Negative impacts from having drugs or cytotoxic compounds spread throughout your body, could be avoided. It may, for example, be possible to enhance cancer chemotheraphy by directing the cytotoxic compounds towards the tumour cells only, and thus sparing normal cells.

Such are the promises of nanotechnology in these types of applications. In order to succeed with this task, these particles would, among other things, need to be engineered to evade the immune system. This involves making them able to avoid being identified and captured by the liver. The ‘circulation-time’ thus increases and allows for

[34] Testimony by Eric Drexler on the June 26, 1992, Hearing on New Technologies for a Sustainable World, the U.S. Senate Commitee on Commerce, Science, and Transportation, Subcommitee on Science, Technology, and Space.

[35] Crawford, R. 1996. ”Cosmetic Nanosurgery”, in *Nanotechnology: Molecular Speculations on Global Abundance,* B.C Crandall (ed). Cambridge, Massachusetts: The MIT Press, pp. 61ff.

accumulation somewhere else in the body. The next problem is how to make use of specific mechanisms inside our bodies so that the appropriate accumulation occurs. For this, particles need to have specific sizes (on the order of tenths up to a hundred nanometers) and suitable surface properties.[36]

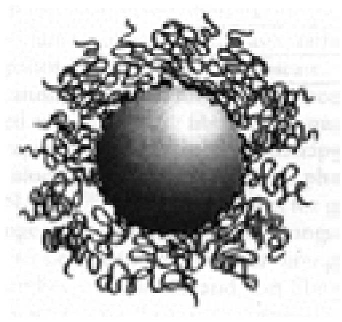

Figure II-3 Example of a nanoparticle coated with polymer.

Figure II-4 Rabbit with targeted 60 nm particle uptake in bone marrow cells only.

Source: Trends in Biotechnology, Vol. 15, Iss. 6, pp.217-224.

For the nanotechnologists, the world of 'the possible' is even larger than hitherto outlined. Consider for example the following imaginative applications selected from a list of proposed, so-called, "early applications":

> Full-wall video screens, full-wall speakers, programmable paint, reprogrammable books, self-adjusting contour chairs, retractable walls and ceilings, walk-through walls, programmable room configurations, ever-

[36] Davis, S.S. 1997. "Biomedical applications of nanotechnology - implications for drug targeting and gene therapy", in *Trends in Biotechnology*, Vol. 15, Iss. 6, pp. 217-224. This idea of having small 'vessels' travelling inside our bodies, doing different medical work, is not new. Neither is it confined to either 'sci-fi' or 'pure sci.', it can be found in both. And Drexler, walking the tightrope between the two, discusses the possibilities of having small machines that sail along our blood streams and 'help' our own immune system to take care of alien bacteria and viruses. Like the nanoparticles described above, but put in more imaginative terms, Drexler also discusses the importance of the 'surfaces' of these vessels in that these "...immune machines could display standard molecules on their surface - molecules that the body knows and trusts already - like a fellow police officer wearing a familiar uniform", in Drexler, K.E., *et al*. 1991. *Unbounding The Future: The Nanotechnology Revolution*. New york: William Morrow and Company, Inc., pp. 207-209.

sharp knives, weapons that change from food to razor blades, mood- and context-sensitive clothing and jewelry, or stationary moving walkways.[37]

The ‘utility fog’ is an example of an application that is not only imaginative, but perhaps even counter-intuitive. The idea is to fill the space, i.e. the free volume between us and the artefacts around us, with an incredible amount of small robots connected to each other in a way that allow them to exert forces in any direction or part of the occupied volume, without causing any harm to us while doing this. It is supposed to behave and look like a fog, which we can see through and walk through. The difference is that this fog can ‘harden’, for example in order to prevent intrusion by burglars into the house, or it could be used for transporting things around, or even ‘carry’ us to the next room.[38]

Less imaginative, but still technologically challenging, is the idea of phased array optics that could produce 3D ‘scenes’ impossible to distinguish from ‘real stuff’. While standing behind a window, looking at a scenic view outside of it, we actually ‘see’ the result of light waves that ‘comes’ from a plane surface (the window). If we then have an extremely high number of illuminating pixels, communicating with each other, these could reproduce such waves whereby we could reproduce the scene outside the widow artificially or have a completely virtual world ‘appear’ in front of us. It is suggested that this would be possible to achieve with nanotechnology and its computational power only, since a normal computer would have problems solving the needed calculations within the life-time of the universe.[39]

Almost all of the applications discussed above are in some sense desirable, or at least not harmful (although they stretch the limits of the possible and our own notions of it). Confronted with the obvious asymmetry of the radical nanotechnological discourse, we had to actively search for where and how the problematic sides of nanotechnology were discussed. Even the nanoites, criticised for making promises they cannot keep, and planting false expectations among people, are not totally unaware of moral concerns. Thus, along with the many propagandistic and futuristic accounts of all the beneficial things that this technology could do for mankind, there does exist a willingness to take part in discussions on its presumingly more ‘ugly’ sides, and its obvious

[37]As proposed in, Chesley, H. 1996. ”Early Applications”, in *Nanotechnology: Molecular Speculations on Global Abundance*. Cambridge, Massachusetts: The MIT Press.

[38] Hall, J.S. 1996. ”Utility Fog: The Stuff That Dreams Are Made Of”, in *Nanotechnology: Molecular Speculations on Global Abundance*. Cambridge, Massachusetts: The MIT Press., pp. 161-184.

[39] Wowk, B. 1996. ”Phased Array Optics”, in *Nanotechnology: Molecular Speculations on Global Abundance*. Cambridge, Massachusetts: The MIT Press., pp. 147-160.

potential of furnishing the forces of destruction and violence with even more power than they have at present.

Drexler, for example, has allotted quite some space in *Unbounding the Future: The Nanotechnological Revolution* to these issues. And at the NanoCon conference in 1989 he said ”we must never build a replicator that is anything like a replicator that could survive in nature”. He criticised biotechnology for ”tinkering with cells that have evolved to live in nature”, which (according to Drexler), ”has the flavour of a dangerous thing to do”.[40] Another representative for the nanotechnologists, B.C. Crandall, shares these basic concerns in *Are Molecules Sacred*?, a ‘flyer’ that he distributed at the nanotechnology conference in Palo Alto in 1991. Crandall draws on the idea that life is essentially just molecular configurations, and that tinkering with molecules therefore is tinkering with life itself. As nanotechnology is in some sense inevitable, he reckons, the development urgently needs to be accompanied by a public process, balancing the risk of being captured by a more ‘closed’ and probably more ‘military biased’ development.[41]

Instead of Conclusions: Sorting Things Out a Little

A Contested Terrain - But What is at Stake?

Whatever it does to you, nanotechnology seems to affect people a lot. And of course hearing (as we now have) about those dizzying, absolutely ingenious things claimed to be the products of future molecular manufacturing, only a stone-age person could remain indifferent. But the excitement is not merely a contemporary version of the well-known fascination for technology. It emanates from professional rivalry or ”territorial tensions”. We started by keeping company with a group of people (gathered around an uncontested leader) who were determined or dedicated to exert a strong influence even on the conceptual framework within which nanotechnology should be approached and theorized. We soon realized that there was a considerable level of distrust of what this group claimed, or, perhaps, of *how* they claimed it. And what this group said about this new technology, though still mainly existing only in theory, was indeed quite amazing. The obvious thing to suspect would be that the people in this

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[40] Drexler, K.E. 1989. ”The Challenge of Nanotechnology”, Ch. 2, Section N, in the proceedings of the 1989 NanoCon Northwest regional nanotechnology conference, February 17-19, 1989. Downloaded on September 25, 1997, at URL http://www.halcyon.com/nanojbl/NanoConProc/nanocon2.html.

[41] Crandall, B.C (ed). 1996. *Nanotechnology: Molecular Speculations on Global Abundance*, B.C Crandall (ed). Cambridge, Massachusetts: The MIT Press, pp. 193-194, fotnoote 3 (Preface).

group were probably not serious, which is why they were often considered to be ”out in space”.

In the second part of the chapter, we set up a little test of that. Let us, compare what the leader of the group has preached, with what an indisputable scientific authority is saying about the same issues. So we invited a Nobel Prize winner to join in with our story, a man rewarded for his work in this particular field. The result was - not guilty. That is, the discredited leader had no doubt produced some wishful thinking or even dubious statements on what one could believe might come out of research (who of us hasn't?), but on the whole he and his fellows definitely not ”up in the blue”? The highly esteemed scientist had in fact claimed very similar things as the discredited one. So, what's the fuss about then? Why this open or half-spoken antagonism? What's at stake here?

To be quite frank: we don´t know, yet. What you have read is so far only a tentative and highly inexhaustive description of a technoscience field. Still, with reference to what we have already covered, we might be able to make some reasonable guesses. A not very far-fetched guess would be that the main problem here could be that the person, around whom much of the fuzz is centered, and those backing him up, are not considered to be 'real researchers'. They may (and we know they in fact *are* most of them) be trained to be scientists or engineers, but they don´t actually work as this. They are ”only” talking, reading and thinking about these nano things, but they don´t really *do* research themselves. And what could we say about that? Well, that it is a ”natural” thing in our kind of society; we group people into professions and seek our identities in belonging to a certain group with its own jurisdiction (authority); then it needs to be 'us' or 'them'. But while that tells us a lot about our society, in this case about how the world of science and engineering works, it doesn't say *anything* for certain about the feasibility of a claim or discourse; not to belong, is not the same as being wrong.

A similar logic of exclusion lies behind the guess that those people labeled 'the nanoites' by some of their critics, are labeled and treated that way because they have placed themselves in ”bad” company. They have not shut the doors properly, thereby letting 'alien elements' in. To be more concrete, the alien element here is the Science Fiction (SF) and/or the Fantasy genre of our contemporary popular culture. Those genres are definitely not accepted by mainstream science&engineering as belonging to their profession, culture, or jurisdiction. And as the nanoites not only let those aliens in, but indeed invite or welcome them as part(ners) in the work on bringing about the future technology, this of course only confirms, in the eyes of the orthodox, that they are not one of us; they are simply not real researchers.

But what then is so utterly wrong about these aliens? One thing is that they challenge or transcend the *form* or *format* within which a decent work of science and engineering documents itself. Science Fiction people are basically promiscuous concerning the media and format through which they appear. Their messages and products are exhibited on numerous different artefacts; apart from books, on films, posters, pins, computer games, t-shirts, graffitti, commercials, body inscriptions, and so forth. And that is certainly a safe way of becoming alien in the current mainstream context; the typical proponent of science and engineering does nothing of the sort.

Further, and part of this, the nanoites' acquaintance with the SF people stirs things up by bringing too much *emotion* into mainstream technoscience. They operate on or exploit the *extremes* of things, squeezing out emotions from our normally well-contained selves. They tease, provoke, seduce and frighten us, and many of us like it (that´s of course why a Smalley report is read by such a small number of people whereas a book by William Gibson, to mention one of the leading SF practioners, is read by millions and millions). To tease and provoke, even to seduce or frighten, could in fact be okey also in the world of respectable technoscience, but then only *on certain occasions* and in fairly *small doses*. Once having violated that norm of moderateness and modesty, which very definetely is what the SF business does with all its excesses, you step out of the community, out of the family, you become an alien. By mingling with those aliens, the nanoites themselves become aliens; a straightforward case of guilt by association.

Why is it that they want to be in that company in the first place? Is it perhaps a part of their personalities that they are attracted to unconventional media and excesses of various kinds. Well, putting the question like that, is of course coming dangerously close to what Ralph Merkle in the *Scientific American-Foresight* debate characterized as 'ad honim attacks' on Drexler. We all have personalities, but there is no need to scrutinize and question personalities particularly when it comes to nanoites or other challenging groups.

Maybe it is not a matter of personalities; maybe it is just that the nanoites share a belief that extremes and excesses are essential elements of how nanotechnology could gain momentum. They may have another understanding of what is required here, that SF stuff like *technopoetry* and *technohorror*[42], are valuable to bring on board. Here one can notice the difference between e.g. Smalley as a representative of traditional science, and the radical nanotechnologists. Even if Smalley also sometimes uses an open-ended language, and talks in visionary terms, this is not integrated in the representation of his scientific work. By contrast, the nanoites attempt to bridge the gap between the manufacturable (which is usually the domain of engineering), the possible (the domain of experimental science), and the *almost* unthinkable (the domain of SF or Fantasy). They hereby 'announce' that

[42] Many nanoites acknowledge *both* these things; as we reported in our section on nano applications, they do not only trade the poetic, friendly and romantic versions of nanotechnology, more than the orthodox side they also have faced possible hidious applications.

new and partly very different practices will be needed for nanotechnology to really come about. They mobilise cooperation as well as confrontation among a variety of actors while striving towards a common goal.

We have yet another piece of guesswork to bring to your attention. That is not about being excluded, or about becoming an alien through guilt by association. No, it is rather the other way round. One of the most important reasons, possibly *the* most important one, for the tensions and controversies developing around the nanoites, is that they (although maybe not always consciously) challenge a paradigm (a paramount one) within the mainstream community of technoscience.

Thus, the *exploratory engineering* (a term suggested by Drexler) that they made themselves spokesmen of, is very different from textbook engineering and experimental science. It is much more heterogeneous[43], theoretical and experimental at the same time; it opens itself up towards rethinking 'the possible' and towards communicating with actor groups usually not addressed by scientists or engineers. They explicitly make use of mind-setting metaphors in order to keep approaches and analyses 'fresh'. Again refering back to the *Foresight* vs *Scientific American* dispute, Merkle brought this up in his rebuttal of the Gary Stix article, saying that its author was an exponent of a "purely experimental approach", belittling the value of computational and theoretical work. He himself and the Foresight Institute instead advocated "the aggressive use of molecular modeling as an integral component of a long range strategy to develop molecular nanotechnology".

How to Proceed From Here

In our partisan reading, nanotechnology appears as a fertile ground for a social study of technoscience. What we have done through this chapter however, is of course no more than a first cursory inspection. From traditional science, we have learned that you need several observations, and that an experiment must be replicated several times. Such basic guidelines still have to be pursued in this case; thus our data are so far scarce and largely arbitrary, perhaps leaving the reader with the impression of a biased account that sympathetically represent the nanoites as a coherent group of heroic men challenging conservative concepts and conventions.

There are many possible directions in which to proceed. We will conclude this chapter by just briefly mentioning five such directions along which a more comprehensive study could be organized:

1. <u>the nano as the next chapter in the Book on Techno-Utopias</u>; claimed to out-compete the two major inventions of man's material culture (the replacement of sticks and stones with metals and cements,

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[43] The term 'heterogeneuous engineering', coined by John Law, is a popular one within certain STS (the social study of Science&Technology) circles.

and the harnessing of electricity; cf quote, p. 3), the nanotechnology rhetoric (also e.g. ”the mightiest machine also the brightiest”, ”a crusade for sustainability and clever engineering”, ”products of unimaginable ingenuity and abundance”) could easily be related to the tradition of technologically driven prophecies (starring Science Fiction and ‘fictional science’) to be traced back at least to the 18th century; in a shorter post-World War II perspective, there is also an interesting Utopia/Disutopia triangular relationship between Vannever Bush’ ultra-optimistic*The Endless Frontier* (1945), Jay Forrester´s deeply pessimistic *Limits to Growth* (1971), and Eric Drexler’s neo-industrial*Engines of Creation* (1986);

2. radical nanotechnology and the ritual demarcation of science; our exploratory study indicates that there is within the nanotechnology field an animated demarcation process (with its specific rituals of exclusion) where the strive for professional (monolithic) control requires that certain phenomena and persons be placed ‘outside’ or made ‘strange’; in an extended study such processes of ‘boundary-work’ and demarcation of science from non-science (cf Gieryn) concerning the nano discourse could be systematically looked at, in comparison with other similar cases documented within the science studies literature;

3. the nano as an epistemological battlefield; related to this (perhaps an integrated part of such a study on exclusion from or demarcation of science) could be an in-depth study of whether concepts and definitions evolving around nanoresearch may be understood as vital resources in a ‘politics of epistemology’ where cognitive authority and political legitimacy are mutually dependent phenomena; obviously, the strategies or moves chosen here, would have a lot do to with your starting point, i.e whether you e.g. approach nano as a nuclear physicist (for whom it promises unlimited energy) or as a bio-chemist or a semi-conductor (quantum) physicist (for who it promises unlimited manipulation of matter); also important here is that the overall status and strength among various disciplines within ‘Big Science’ is being altered by the gradual dismantling of Cold War R&D funding policies and their institutions;

4. an ethnography of nano scientists; an obvious way to go from here is to move from the distant readings on nanotechnology informing this chapter on to a micro-level participant study of the everyday life of a research group active in the field; in addition to observations of the ‘actual work’, i.e. the scientific practise, in the group such an ethnography would also cover its ecology (how it relates to and gets a living from its environment), its social organization (how it structures work, resurces, information, etcetera), cosmology (its knowledge, beliefs, value systems, and so forth), and the group´s representation of self;

5. nanotechnology and ‘society’ - the perfect case for CTA? from a technology policy point of view nanotechnology looks quite troublesome; the area is a too contested terrain to allow for any well-founded interventions: who and what can one put trust? how can you ‘pick the winners’ and gain enough firm ground to make the necessary

priorities of resources? and so forth; however, one could on the other hand argue that the nano trajectory instead represents a rare opportunity for a pro-active role for public officials and authorities involved in technical R&D; its great potential for society at large seems beyond dispute at the same time as much still is 'in the making', leaving room for public debate and participation - perhaps the perfect case for CTA (constructive technology assessment)?; one could here take advantage of the fact that there are many actors and forums through which the nano ideas are processed, ranging from rather conventional (although still perhaps 'high tech') development in well organised industrial circles to plots using nano-tech in SF movies or Fantasy novels; i.e. to sustain pluralism and oppose those demarcations which optimize internal efficiency and rivalry at the expense of a wider reflection on the whole set of social utility and ethical issues also at stake.

CHAPTER 3

The Grand Politics of Technoscience: Contextualizing Nanotechnology[1]

Hans Fogelberg

Introduction: The Big Picture

The work to construct 'nanotechnology' (scientifically, technologically, and politically) includes the argument of science being the primus motor of technological development. Let us begin with a citation from a document that both constructs and summarizes this idea of how science and technology are related:

> Basic research leads to new knowledge. It provides scientific capital. It creates the fund from which the practical applications of knowledge must be drawn… Today, it is truer than ever that basic research is the pacemaker of technological progress… *A nation which depends upon others for its new basic scientific knowledge will be slow in its industrial progress and weak in its competitive position in world trade, regardless of its mechanical skill.* (Bush 1945, p. 19, emphasis in original text)

The citation originates from a report by Vannever Bush, advisor on science and technology to the U.S. administration in the 1940s, who in 1945 submitted to President Roosevelt a report titled *Science – The Endless Frontier* (Bush 1998 [1945]). The basic view put forward by this report was that basic science, or "the freedom of inquiry," as it was and still is termed, is the foundation for new technology. It was, according to Bush, the level of advancement in basic science that determined the long term capability of a nation to keep 'ahead', technologically speaking. The reason why this had gained relevance was that the distance between basic knowledge in science and what had been built as technology was considered to have been dangerously short in the immediately preceding war. The problem was not technical. Artifacts of warfare had been developed at the cutting edge of contemporary science. The problem was that science as a basic resource had been harvested from all its crops. The level of basic science in the United States was considered to have been too weak. Remedying this, Bush argued, was a top priority for the development of a new and more explicit science policy in the

[1] Paper presented at the seminar "The Battle at the Bottom: Making The Most of Feynman's Legacy". VINNOVA, Stockholm, April 19th, 2001.

United States, and he proposed a publicly funded institution for basic science. This was eventually achieved by the formation of the National Science Foundation (NSF) in the 1950. Technical developments have (perhaps always) been part of warfare. However, the world-wars (and especially WWII) situated Science at the core of military strength and national security. The direction of science towards particular technical applications had resulted in many new technological systems, e.g. radar technology, computers, and computer network technology. And a reminder of the strength of this liaison between science and politics is the detonation of the atomic bomb over Hiroshima on august 6 1945 and Nagasaki three days later. The atomic bomb, the result of the so-called "Manhattan Project," was an enormous undertaking, financially, administratively and intellectually. It was also a project in which Vannever Bush had played an important role as a scientific advisor to the Government (Edwards 1997, p. 46ff).

Part of this experience, then, was the feeling among contemporaries of a strong and close link between science and technology. The Bush report on the 'endless frontiers' of science fueled to the notion of science as the origin of technology, which has now become part of the natural political discourses on science and technology. It is also relevant to the present case of the science and technology of nano:

> Our current economy is a reflection of past investments in scientific research… Our current health is a reflection of past investments in research. Our current world leadership in defense is a function of our past investments in science and technology. (Gingrich 2000)

In peace-time science there were new battlefields to conquer. The war to be fought was a "war against disease." However, science and technology remained close to military rationales and discourse for many years to come. The cold war, and what historian of technology Paul Edwards identifies as discourse of a "closed world", created a historically specific environment that in effect has shaped many of the commercial technologies of today (Edwards 1997). The experience of the post cold-war era is that Science and Technology have to seek new discourses and 'allies' that give them renewed meaning and relevance. To explore such 'old' and 'new' discourses of nanotechnology is the purpose of this chapter.

The Very Idea

The origin of nanotechnology is typically traced back to quantum physicist Richard Feynman and his lunch-talk at Caltech in 1959 titled "There is plenty of room at the bottom." Pushing the deductive reasoning of physics to its extreme, Feynman insisted that the principles of physics did not speak against the possibility of maneuvering things, as he said, "atom by atom" (Feynman 1999 [1959], p. 137). The microscopic world - a world that previously had been regarded as beyond the reach of any form of engineering – could be turned into a site for intervention and engineering. If this was possible it would pave the way for the manufacture of new material properties previously not even imagined:

> [a]toms on a small scale behave like *nothing* on a large scale, for they satisfy the laws of quantum mechanics. So, as we go down and fiddle around with the atoms down there, we are working with different laws, and we can expect to do different things. (p. 136)

The technological implications of approaching and making use of the quantum mechanical 'world' would be far reaching, even though Feynman himself had no clear picture of exactly what the manipulation on this scale would lead to in a technological sense:

> What could we do with layered structures with just the right layers? What would the properties of materials be if we could really arrange the atoms the way we want them? They would be very interesting to investigate theoretically. I can't see exactly what would happen, but I can hardly doubt that when we have some *control* of the arrangement of things on a small scale, we will get an enormously greater range of possible properties that substances can have, and of different things we can do…(p. 135)

But what Feynman did realize was that there would be an enormous number of possible new technical applications. Several possible paths towards manipulation were suggested by Feynman, who, in particular, assigned as the task of physics to develop more refined visualization techniques that could reach down to the level of molecules and atoms. Such an instrument, he predicted, would be of great importance also to biology and chemistry.

Among the specific technological applications he discussed was that it might be possible to construct a memory device for computers that was based on data storage using nanoscale bit sizes:

> This fact - that enormous amounts of information can be carried in an exceedingly small space – is, of course, well known to the biologists, and resolves the mystery which existed before we understood all this clearly, of how it could be that, in the tiniest cell, all of the information for the organization of a complex creature such as ourselves can be stored
>
> all this information is contained in a very tiny fraction of the cell in the form of long-chain DNA molecules in which approximately 50 atoms are used for one bit of information about the cell. (pp. 123-124)

In particular, Feynman stressed the possibility and the benefit of making use of and *mimicking* the mechanisms found in biological systems to conduct various tasks at this small scale:

> The biological example of writing information on a small scale has inspired me to think of something that should be possible. Biology is not

> simply writing information; it is doing something about it. A biological system can be exceedingly small. Many of the cells are very tiny, but they are very active; they manufacture various substances; they walk around; they wiggle; and they do all kinds of marvelous things – all on a very small scale. Also, they store information. Consider the possibility that we too can make a thing very small which does what we want – that we can manufacture an object that maneuvers at that level! (p. 126)

Feynman was optimistic about the pace of development in this area, and he anticipated that a new field would emerge in physics dealing with these tasks during the years to follow. He expected that in retrospect:

> in the year 2000, when they look back at this age, they will wonder why it was not until the year 1960 that anybody began seriously to move in this direction. (p. 118)

But while much has certainly developed in science since Feynman's talk in 1959, it is only quite recently that we can identify any "serious moves" in the particular directions he proposed. So our "surprise" today is not that Feynman was so late in proposing this new field of investigation and utilization, but that he was so early. The text he produced in the late 1950s is still surprisingly relevant to the field, and not only as a historical document. Several of his propositions have been turned into paths of actual development in nanoscience and technology. Above all, the major contribution of Feynman was to argue for the plausibility that atoms could be manipulated and used for engineering technical purposes. One obvious problem, which was already pointed out by Feynman, was the lack of sufficiently advanced microscopes by which one could 'see' what one would engineer: atoms. Such an instrument was not invented until more than twenty years later.

Tools For the Task

In was not until the invention of the Scanning Tunneling Microscope (STM) in 1981 that visualization of individual atoms became possible. The STM was invented by Gerd Binnig and Heinrich Rohrer, at the IBM research center in Zürich, an achievement for which they received the Nobel Prize in physics in 1986. The STM takes advantage of one specific property, the tunneling of electrons (which one can think of as the quantum mechanical parallel to the flow of electric current). By this, the STM is limited to the visualization of electrically conducting matter. Other probe technologies 'tuned' to 'sense' other physical properties have been developed (e.g., mechanical and magnetic). One example is the Atomic Force Microscope (AFM) with which one is able to visualize atoms of non-conducting matter as well.

Beginning with the STM, a range of various probe-technologies were developed, leading to a 200 million dollar high-tech industry (Wolde 1998, p. 26). The probe-technologies worked something like a magnifying glass for a hitherto closed world. However, sensing or ‘seeing’ atoms was quite different from actually manipulating them in controlled way. A major breakthrough was when an STM was used, not for sensing atoms, but for moving them in a very precise manner.

Writing With Atoms

Once again IBM played a role in the history of nanotechnology. In 1990, Eigler and Schweizer managed with the aid of an STM to place 35 xenon atoms on a surface of nickel in a pattern spelling the word “IBM.” The probe instrument was now no longer only a device for visualization, it was proven to also be able to manipulate matter in a controlled and precise manner. The probe technique and its extremely high precision engineering had been utilized to position the tip of the probe at an atomic scale, which amounted to one giant leap into the microscopic world. By reversing the process taking place at the tip of the (visualizing) probe, the instrument could be used as a tool for manipulating atoms. By this, specific nanoscale objects could be both constructed and analyzed using the same instrument.

In the Swedish context, the term “atomslöjd” (atom-handicraft) has been circulating in the public debate as a metaphor for nanotechnology as a whole. In a way this is not a particularly well chosen metaphor for its technological endeavor, because ‘handicraft’ is usually associated with the opposite of ‘high’ technology or industrial production. Nevertheless, in the particular case of the work of Eigler and Schweizer in 1990 it is perhaps a relevant metaphor. The manipulation “atom by atom” of an STM is generally not perceived as a practical production strategy for nanotechnology, because this form of manipulation is time consuming in relation to the number of atoms actually positioned. Having the ability to manipulate atoms, novel nanoscale artifacts could be produced by relying on self-assembly mechanisms (the structuring of matter into a lowest-energy configuration). However, the construction and analysis of such objects is still slow and expensive. And as in many other fields of science and technology, the use of computer simulations is gaining increased importance.

More Powerful Computers for Simulation and Visualisation

While probe technologies allow for the analysis and visualization of properties of nanometer-scale objects, it is a time and resource consuming task. The incremental but rapid development of new computer technology intersects with the development of nanoscale resolution microscopes. Together they allow for experimentation both with ‘real’ and ‘virtual’ matter. For macro-world phenomena, e.g. heat transfer in a turbine, the strength of a bridge or the crash-worthiness of an automobile, computer models are usually considered only a rough approximation, due to the vast number of real world variables which a computer model does not take into account. In other words, the epistemic ‘gap’ between the reality and simulation is fairly large.

However, for computer simulation of stable nanometer structures this distance seems to be much shorter. Scientists talk about conducting 'experiments' in the computer, which is more than just a game with words.

Nano Becomes 'Public'

There are several aspects to how nanotechnology became a topic outside science, but a major role in that process was played by Eric Drexler, who conducted a broad elaboration and perhaps most importantly a broad problematization of Feynman's ideas. The major contributions of Drexler are published in popular books on nanotechnology (Drexler 1986, et al 1991). In these books he discusses the limits of possible applications of nanotechnology as well as its potential risks. In particular, he puts forward the concept of 'molecular engineering' and the importance of exploring bottom-up strategies. These contributions are not generally regarded as academic science, and his texts have not been published to any extent in scientific journals.

Drexler's popular-scientific approach placed his contributions in another social setting than that of pure academic science. This was by some seen as a potential obstacle for building a more concerted scientific research effort under the banner of nanotechnology. The work of situating nanotechnology as a purely scientific matter that should be funded by the funding institutions of basic science, required that a demarcation be made between science and non-science. One surprisingly recent example, in which an indirect but obvious reference is made to the "drexlarian" type of publicity, is from a recent biomedical research symposium in the United States. Here in one of the keynote speeches it was said that scientists need to renounce the lunatic fringe of nanotechnology, and leave no room for futurists and dilettantes (BECON 2000, p. 7). However, such strong demarcation efforts are fairly rare today. Perhaps one can say that the successful politics of nanotechnology have altered the balance of power between these two groups. Now the locus of nanotechnology has shifted and its content translated into something more aligned with the traditional scientific community. In sum, it seems that nanotechnology as a concept, practice and discourse has turned out to be a successful recipe for the scientists and science policymakers who believe it to be the key to future technology. The successful policy process of the recent large federal US nanoinitiative especially seems to have eased up these rather tense relations.

Nano Becomes 'Political'

The academic scientific community of the 1990s worked towards situating nano-science and technology on the political agenda: The sciences of the nanoscale had to be translated into a technology of the nanoscale; the technology of the nanoscale had to be interpreted in terms of a technology on the macroscale; and this technology had in turn to be translated into specific artefactual, economic and social outcomes. During such ‘construction-work’ of nanotechnology as a political concern, many different resources need to be mobilized. While ‘politics’ is often referred to as alien to both scientific work and to technology (and the market), politicization is still highly relevant, and, I would argue, very much a normal element of modern technoscience. Politicization is simply one of the resources available for ‘entrepreneurs’ of science and technology when they want to transform their ideas and visions into material objects and commercialized products.

The US Policy of Nano[2]

The US has since the 1980s, through funding from NSF, evaluated foreign developments in science and technology. For many years the focus has been on the developments in Japan. More recently, the scope has been widened to also incorporate the monitoring of the more concerted research policy activities of the EU. Such foreign technology monitoring was facilitated by the establishment of the NSF founded, World Technology Evaluation Center (WTEC), at Loyola College in Maryland. When, in 1991, the Ministry of International Trade in Japan initiated two 10-year nanotechnology programs (the 185 million USD Atom Technology Project, and the 40 million Quantum Functional Devices Project), it became obvious that nanotechnology had become part of the strategic considerations that a policy on science and technology had to deal with. But nanotechnology did not follow the usual pattern:

> This situation is unlike the other post-war technological revolutions, where the United States enjoyed earlier leads. The international dimensions of nanotechnology research and its potential applications implies that the United States must put in place an infrastructure that is equal to that which exists anywhere in the world. (NNI 2000, p. 26)

A range of studies and activities had been conducted during a short time period. The NSF asked the WTEC to perform an assessment of developments in nanotechnology in the world, and to compare these developments with those of the United States. As part of that study a workshop was conducted in 1997 on the *R & D Status and Trends in Nanoparticles, Nanostructured Materials, and Nanodevices in the United States* (WTEC Workshop 1997). The aim was to help the United States to “capitalize on emerging opportunities and optimize allocation of R&D funds… [by the analysis of] …the state of the art and benchmarking U.S. activities” (Ch. 1). The outcome of this workshop was, among other things, the establishment of a principal nano-policy actor in the United

[2] Web portals for US policy on nano: www.nano.gov, www.itri.loyola.edu

States called "the Interagency Working Group on Nanoscience, Engineering and Technology" (IWGN).

The final report of the NSF funded WTEC study was published in 1998 in the report *Nanostructure Science and Technology* (WTEC Panel 1998). The report aligns itself with what by the mid and late 1990s had turned into a chorus of voices reinforcing the significance and potential of the field:

> Panelists had seen the tip of the iceberg or the pinnacle of the pyramid before starting this study, but only since undertaking the study do we fully appreciate just how broad the field really is and begin to understand what its exciting potential and impact may really be. (WTEC Panel 1998, p. 4).

The report also defined the locus at which this potential may be released and turned into a technology. This locus concerns the appreciation of something that many had witnessed before, but which now had emerged as the very basis and core of the field as a whole, typically summarized by the terms 'inter-disciplinary', 'multi-disciplinary' or 'trans-disciplinary':

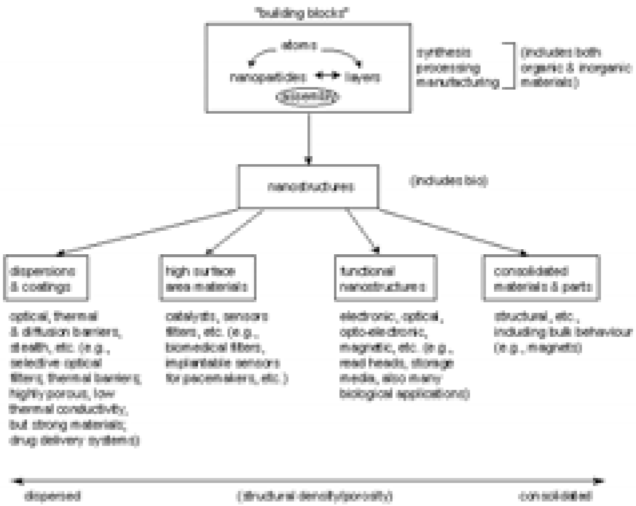
> The rapidly mounting level of interdisciplinary activity in nanostructuring is truly exciting. The intersections between the various disciplines are where much of the novel activity resides, and this activity is growing in importance. (WTEC Panel 1998, p. 5)

The driving forces of the field are (perhaps surprisingly) seen as 'technological'. It was a 'technology-driven' process, due to the confluence of three streams of technology developments: (1) new and improved control of size and manipulation of nanoscale building blocks, (2) new and improved characterization of materials at the nanoscale, and (3) new and improved understanding of the relationships between nanostructure and properties, and how these can be engineered. Thus we may add a characterization of the field that pertains more to the science-technology axis: the characterization of nanoscience as a technology-driven endeavor, and the characterization of nanotechnology as a science-driven endeavor.

The WTEC study and its report were designed with a hierarchical layer-model, mirroring how the complexity of nanotechnology was perceived. This assumed a vector of innovation, and a time-axis. These layers of nanotechnology are: particles (the nanoscale building blocks), structures (the materials built by such blocks), and devices (the functional technical devices built using such material). See the figure below:

Nano

Nanostructures



(organizational chart of the WTEC study, adopted from WTEC Panel 1998, Ch. 2)

Scanning the science and technology policy of Japan and Europe, the study found that what from a distance had seemed to be quite different policy strategies (Japan funding large national programs and the US and Europe funding small research groups in competition), on a closer look turned out to be research activities which in practice were dominated by individual researchers whose 'network' was based on personal or professional contacts (p. 9). Given that the field really is interdisciplinary, this interdisciplinary character was only (at best) mirrored at the level of research groups, and not at a higher organizational level (e.g. that of the level of multidisciplinary networks between laboratories and between universities).

To deal with these more strategic questions was the purpose of the workshop following up this report. The IWGN workshop on Nanotechnology Research Directions (IWGN Workshop 1999) discussed the ramp-up and coordination of resources to the field, and more importantly, it developed a first proposal for a national initiative on nanotechnology:

> The initiative proposes doubling the Federal investment in nanotechnology and founding a cooperative grand alliance of government, academia, and the private sector to promote U.S. world leadership in nanotechnology. (IWGN Workshop 1999, p. iv)

The actors relevant to this initiative were defined as: academics (who need to reorganize so as to take into account the transdisciplinary character of the field which is considered as an inherent feature of it), the private sector (which cannot afford to just wait-and-see, but needs to actively and selectively engage and take part in the development), the government R&D laboratories (which are a US-specific policy actor that could function as nanotechnology 'incubator'), the government funding agencies (such as NSF, DOD, DOE, DOC, NIH, and NASA, which should support this expansion and focus), and finally the professional societies (of scientists and engineers who need to establish forums for communication, both national and international).

The implementation plan of this proposal, the "National Nanotechnology Initiative" (NNI 2000), was supported by the president's Committee of Advisors on Science and Technology, which contemplated the historical and strategic dimension of the proposal. In a letter to the president, the committee says that:

> Nanotechnology is the first economically important revolution in science and technology (S&T) since World War II that the United States has not entered with a commanding lead. Federal and industrial support of R&D in the United States for this field already is significant, but Europe and Japan are each making greater investments than the United States is, generally in carefully focused programs. Now is the time to act. (NNI 2000, p. 114)

The NNI was supported by the president, who used as a rationale of this effort what in the NNI had been termed as the 'grand challenges' of nanotechnology:

> My budget supports a major new Nanotechnology Initiative, worth $500 million. …the ability to manipulate matter at the atomic and molecular level. Imagine the possibilities: materials with ten times the strength of steel and only a small fraction of the weight – shrinking all the information housed at the Library of Congress into a device the size of a sugar cube – detecting cancerous tumors when they are only a few cells in size. Some of our research goals may take 20 or more years to achieve, but that is precisely why there is an important role for the federal government (cited in NNI 2000, p. 13).

Its implementation is structured along five lines of activity: (1) long-term fundamental nanoscience and engineering research, (2) grand challenges, (3) centers and networks of excellence, (4) research infrastructure, and finally, (5) ethical, legal, and social implications, and workforce education and training. The three major funding agencies are National Science Foundation, Department of Defense, and Department of Energy. Activities 1 and 2, receive the major share of the total 495 million USD (NNI 2000, pp. 14, 31).

One result of the collaborative aim of NNI is the establishment of a strategic California based research institution, the "California NanoSystems Institute" which is a joint effort between universities at Los Angeles and Santa Barbara, with the California silicon and bio-related high-tech firms. Their aim is to learn how to produce nano-systems that incorporate both biological and electronic nanostructures (CNSI 2000). But while such explicit work of trying to merge 'bio' with 'materials' is taking place, and while the importance of bio-nano is stressed in most policy related documents, little seems to have actually been achieved. A reason might be that:

> Two things must occur if the potential of nanotechnology for medicine science is to be best realized. First, the biomedical community must be made aware of, and urged to participate in, this emerging field. Second, biomedical scientists and engineers must communicate effectively with each other and understand that biological systems provide excellent models for the development of these new technologies. (BECON 2000).

While the NNI program stands on two legs — the drastic increase in nanotechnology funding and the streamlining and more efficient 'managing' of resources of the research machinery — it also incorporates a quite new element that is more directly linked with a social scientific appropriation of nanoscale science and technology. The 'fifth element' of the NNI proposal (funded at approx. 28 million USD in FY 2001), addresses issues that are typically not present this early on innovation. The 'chroniclers' of science and technology, be they historians, sociologists or other academics typically deal with or take as a point of departure for investigation, a social problematique that has emerged as a result of technoscientific innovation (and commercialization).

The European Scene of Nano-Policy[3]

One theme that emerges from various national nanotechnology activities and their evaluations is an aspect of the science-technology research-development problematique I here choose to call 'irregularities'. With the emergence of a shared notion of nanoscience and technology as being composed of a variety of disciplines and of certain strategic research foci, it has became possible to perceive the national research agenda in terms of it being aligned or misaligned with a perceived trajectory of nano development, and of it being behind or ahead of this development. National studies often refer to such irregularities, and policy studies at the federal US level and EU level describe their role as one of correcting such irregularities, so as to make the machinery of research and development more efficient and effective.

An example of this at the national level is a report on the UK developments, *Making it in Miniature – Nanotechnology, UK Science and its applications* (Hirst 1996). Here, it is noted that while the UK was early to recognize nanotechnology (by e.g. the "National Initiative on Nanotechnology" in 1986, and the LINK Nanotechnology Program beginning in 1988), the foresight-derived priorities of the 1990s tended to

[3] Web portals for EU policy on nano: www.cordis.lu/nanotechnology

miss or downplay the recent increase in the technological relevance of nano:

> nanotechnology (and possibly other 'cross-sectorial' technologies) may have 'slipped between the cracks' of the sector-based panels [of the UK technology foresight studies], and thus not be seen as priority areas for government support…. [in which] the omission of nanotechnology means that scientists face an uphill struggle for funding. (Hirst 1996, p. 37)

Another example is the Finnish Nanotechnology Research Program. Contemplating the fact that the program (that stretched from 1997 to 1999) was not granted an extension, the scientific evaluation panel stressed that:

> [s]cientifically, technologically, and economically it is extremely important that Finland have a strong activity and international presence in at least certain aspects of nanotechnology research (TEKES 2000, p. 3)

A subsequent innovation policy analysis of nano developments in Finland, *Hurdles on the way to growth. Commercializing novel technologies: The case of Nanotechnology* (Meyer 2000a), extends the scope, and compare these developments with nanotechnology internationally. Meyer maps out what he calls systems of innovation of nanotechnology in Finland, Sweden, Germany, UK and the US. One important indication of this study is that 'irregularities' in the sense described above can arise from differences in national styles of innovation, styles which in turn tend to be aligned with the industrial infrastructure of nations (p. 108). He also identifies three different types of nanotechnology policy, which he terms: general nanotechnology programs (in which a number of often very different projects are carried out under the label of nanotechnology), specific nanotechnology programs (aimed at incremental development in one specific field of nanotechnology), and finally, umbrella programs (which use general themes as a guiding principle) (p. 111).

The Dutch technology foresight study, *Nanotechnology: Towards a Molecular Construction Kit* (Wolde 1998), makes little contribution to the issue of current and future Dutch nanopolicy. However, it is one of the more comprehensive descriptions currently available for non-specialists on the scientific and technical characteristics of 'nano'.[4] It also provides an overview of relevant scientists and research centers in the Netherlands in relation to nanotechnology. One more specific contribution is that it more explicitly than what is common in similar documents, puts in the foreground the 'tools' of nanoscience and technology. It defines nanotechnology in terms of four important but

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[4] Another larger study (which unfortunately due to my shortcomings in the German language will not be described here) is the study *Innovationsschub aus der Nanokosmos* (Bachmann 1998).

interdependent areas: nanoelectronics, nanomaterials, molecular nanotechnology, and nanoscale-resolution microscopes.

Documents more directly addressing the issues of nanotechnology as a European endeavor have also been published, here represented by two reports from the technology policy analysis institution, the European Commission Institute for Prospective Technology Studies (JRC/IPTS). The report *Overview of activities on nanotechnology and related technologies* (Budworth 1996), indicates that the first step towards a European Nanotechnology Initiative was already taken in 1996 (p. 8). The analysis of the state-of-the-art of European nanotechnology concludes that:

> The broad picture which emerges from the available information is that the EU taken as a whole is reasonably well placed in the various branches of nanoscience. The European effort is, however, fragmented by discipline and by nation…. It would be possible to improve its position by taking actions at the EU level (Budworth 1996, pp. 8, 52)

These actions, however, needs to be adapted to the European culture of innovation, perceived to differ from that of e.g. Japan:

> The extent and ambition of the nanotechnology work in Japan is impressive, but the prospects for emulating it in the EU do not seem good. The Japanese long-term approach, its combination of competition and collaboration, and the readiness and generosity with which industry will fund R and D are unique to it. In seeking to promote the development and application of nanotechnology, the EU must adopt approaches which suit its own culture and mechanisms. (Budworth 1996, p. 68)

A similar conclusion emerges from the second report, *Nanotechnology in Europe: experts' perceptions and scientific relations between sub-areas* (Malsch 1997), where interviewed experts stressed the need for initiatives in nanotechnology at the EU level.

The United States had embarked on its journey towards nanotechnology in the belief that Japan already had such programs, and then later also further motivated by the belief that there was competition (even!) from Europe. This belief propelled the United States towards launching what already seems to be a historical turning point for a technology of nano, the US/NNI. The policy process of the NNI was in turn a major reason for European policy-actors to start developing similar efforts. US and EU used one another in a reciprocal way for building the argument that "the other" is moving ahead in science and technology. However, this reciprocal definition of EU and US as major competitors is not the only relevant axis of competition. These two regions now also join to strengthen their mutual position in relation to Asia (and in particular Japan). The European Commission and US/NSF organized a workshop in late 2000 to collect the nano-experts' view of where and how US and Europe can join in research projects on nanotechnology (CORDIS Focus, November, 2000).

The new and sixth framework program (FP6) for research and innovation is presented as a program that will change the situation for nanotechnology in Europe, elevating it to a European priority for increased funding and coordination:

> Lying at the frontier of quantum engineering, materials technology and molecular biology, and one of the forseeable hubs of the next industrial revolution, nanotechnologies are attracting considerable investment on the part of the EU's competitors (500 million dollars of public funding in 2001 in the United States, i.e. twice as much as current spending there and five times as much as Europe spends at present). (CEC 2001, p. 21)

As part of a total of 17.5 billion EUR research and innovation program at the European level, nanotechnology is for the first time made an explicit research topic (at that level).

The large framework program for science and innovation for the year of 2002-2006 make "nanotechnologies, intelligent materials, and new production processes" one of seven priority areas. If closely related research activities, or areas where nanotechnology is generally perceived to make a big difference are also included, one can perhaps say that at least three of the seven research themes relate to nanoscience and technology. The explicit research theme for nanotechnologies is funded at 1,300 million EUR for this period, which together with the two related relevant priority themes "genomics and biotechnology for health," and "information society technologies" total 6,900 million EUR. (CEC 2001, pp. 38).

Themes and Patterns

There are no stable, precise or generally agreed definitions of nanotechnology, the reason for this being that it is:

> one of those 'generic technologies' which may be crucial to many industrial fields, but which is not a single science in itself and more a collection of different disciplines and areas of expertise (Hirst 1996)

Many reports start with a discussion of the definition of nanotechnology. However, apart from some very vague definitions, there is as of yet no consensus on any precise definitions (Malsch 1997). There is also little reason to believe that its definition will stabilize, considering that the term 'nanotechnology' is mostly used by nano-experts and policymakers when they communicate with each other, where it is used mostly as an abstract metaphor. It is a conceptual abstraction similar to 'science', or 'technology'. More to the point, trying to provide nanotechnology with a definite logical definition will probably fail due to the natural heterogeneity of modern technoscience. Nevertheless, the attempts to demarcate within nanotechnology can be made a topic of analysis since they tell us about the actors and their different worlds.

Among the relevant dichotomies expressed by nano-experts are those between: inorganic and organic materials, top-down vs. bottom up approaches, scientific or industrial orientation, and narrow or broad definitions. Other themes that emerge from the different characterizations of nanotechnology are:

1. *Scale*. This is the definition of the least common denominator of scientists. The nanometer is the unit of definition. Here the range of the relevant scale begins at 0.1 nm (representing the size of a hydrogen atom) and goes up to about 100 nm (representing the approximate size where 'bulk' material properties become important). Sometimes the range is said to be 1-100 nm, and sometimes it stretches above 100 nm. One reason is that the fabrication of a 100+ nm structure requires control of matter below the 100 nm range. So 'scale' needs to be related to whether it is the size of objects, the material structures built with these objects, the resulting functional devices, or their methods of fabrication.

2. *Technical application* (e.g. in electronics, materials or biotechnology). The association of the term nanotechnology with a current or proposed technical application directs the attention towards the commercial products and industries, or in other words, towards the particular systems of innovation already in place. Lessons learned from the history of technology and from innovation studies then suggest that 'nanoelectronics' has to be understood in the context of the present semiconductor and computer industry.

3. *Interdisciplinarity*. Another theme is to characterize nanotechnology as an inherently interdisciplinary field, in which physics, chemistry, biology, and materials science are the disciplinary branches on which a science and technology of the nanoscale is to be built. This directs the flashlight towards the disciplinarity of science, and the need to develop new interdisciplinary networks and collaborative efforts. The view that interdisciplinarity is an immanent feature of nanotechnology is indeed a common theme of the nano-discourse. While the nanoscale dimension is by no means foreign to science, with the term 'nanotechnology' a much more intense and advanced communication between chemistry, biology and physics is demanded. This, then, directs our attention towards differences in knowledge cultures (or epistemic cultures). At the same time as the various disciplines would remain intact, they would give birth to a new super-discipline, the science of the small. This view suggests that the problems and possibilities of the nanoscale dimension are intrinsically similar and that therefore all sciences conducting work on the nanoscale dimension will (have to) merge into one large nanoscientific field, and would have more in common with each other than with their respective earlier disciplinary affiliations.

4. *Methods of fabrication*. Another characterization is more associated with a notion of a basic approach or strategy for the fabrication of nanostructures: e.g. top-down vs. bottom-up. The top-down strategy starts with a sample of 'bulk' materia and removes matter from this

sample using various techniques. This can be done via 'ultra precision machining' (mechanical or via lasers), or by using lithography, familiar to the semiconductor industry, but here in a further developed form, to produce smaller feature sizes. This type of description directs our attention towards the tools of nanotechnology, or more generally, its material culture.

5. *Particular nanoscale objects or phenomena* Another type of demarcation is related to more narrow nanoscientific communities that cluster around particular nanoscale objects or phenomena deemed so important that they lead to the establishment of research paths in their own right. As the field of nanotechnology matures, it is plausible to expect that such specific areas of focus will grow in importance. Presently this concerns the investigation of particular molecules that exhibit interesting properties, in particular the so-called fullerenes or buckey-balls, or the investigation of properties of so-called 'clusters'. Clusters are objects at the boundary between the micro- and macroworld, which is what makes them interesting. Clusters of atoms are objects too large to be considered molecules, but still too small to exhibit the properties of bulk material.

In addition to foresight studies and other more explicit policy documents on nanotechnology, there are academic studies of science, technology and innovation. One methodological stream of work which has been early to recognize nanotechnology as a topic worthy of attention is bibliometric studies. In bibliometric studies of patent applications and of the scientific publications they cite, it is implied that these patents are a representation of technology, and that the scientific papers cited in patents are a representations of science (Narin 1995, Schmoch 1997, Meyer 2000b). The expectation is that streangth in scientific publication goes hand in hand with streangth in technical innovation, particularly in so-called high-tech areas.

The number of scientific publications that explicitly mention the term "nano" in their titles grew exponentially during the first half of the 1990s (Braun et al 1997), indicating that nanotechnology may become a 'discipline' of its own. A further exploration of this growth was conducted by Meyer and Persson (1998) in a study of both scientific "nano"-publications and "nano"-patents in the U.S. between 1991 and 1996. They found that "nano"-publications had an exceptionally large degree of boundary spanning and interdisciplinarity, which indicates that nanotechnology is developing as an interdisciplinary field (the largest relative growth rate was found in the chemical and physical sciences, while materials and life sciences lost some ground during the period). However, they found little support for the view that the science of the nanoscale relates to technology (in terms of useful and commercialized artifacts) in any clear way. This was interpreted as an indication that studying the dynamics of nano science and technology requires a more fine grained analysis.

One such study was carried out by Meyer in a paper published in *Research Policy* (Meyer 2000b). His qualitative analysis of ten recent U.S. patents in nanotechnology is interesting. Earlier statistical studies had indicated national differences which were hard to explain. Moving beyond the statistical methods, he analyzes patent by patent, interviewing the innovators, and another picture emerges. This undermines the notion of scientific citations in patents as being an indication of a direct science link. The reason was that individual researchers acted as both scientists and technologists:

> researchers seem to integrate scientific and technological activities increasingly by working on one subject-matter… generating scientific papers as well as technological outputs (patents) (Meyer 2000b, p. 422).

A similarly intertwined relationship between 'science' and 'technology' is indicated by Gupta (2000), who studied the specific nanotechnological field of carbon nanotubes. Gupta found that researchers within industry are leading both in the field of patenting and in publishing in scholarly journals (Gupta 2000).

Postscript: The Question That has No Answer: Is a Distance Between Science and Technology Fruitful or Not?

Heinrich Rohrer of the IBM Research Division in Zurich and co-recipient with Gerd Binnig of the Nobel Prize in Physics in 1986 for the invention of the Scanning Tunneling Microscope (which made a technology of the nanoscale possible), argues that nanotechnology is not presently at such a developed or 'mature' level that it will benefit from being channeled into research of particular technical applications. In an article in Microelectronic Engineering, "The nanoworld: chances and challenges," Rohrer (1996) argues that linking science too closely to the development of new technology will hamper possible future developments. In his comparative-historical argument he draws a conclusion similar to that of Vannever Bush 50 years earlier. Rohrer compares nanotechnology with the historical developments of microelectronics, and argues that the existence of a 'distance' between science and technology was a prerequisite for the early developments in microelectronics. The risk Rohrer now warns of is to rush towards technical applications too early in nanotechnology. That would have the effect of putting the science of the future technology of the nanoworld in a less developed position compared to what was the case for the technology of the microworld in electronics.

We can from this brief survey of the discussions of nanotechnology only draw the conclusion that the metaphor of science as the origin of technology remains important to the field, and that the idea of a 'distance' between science and technology are seen as beneficial to both science and technology. Returning to the notion of 'technoscience', however, we can still appreciate these concerns from the field, but only when we do not take science and technology for granted, or think of them in terms of logical definitions. Scientists and engineers of nanoscience and technology are above all doing technoscience of nano, producing both scientific and technical objects.

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CHAPTER 4

A Nano Narrative: The Micropolitics of a New Generic Enabling Technology[1]

Hans Glimell

The Joint Appropriation of a National Interest

Overture: Just One of Those Meetings

Some twenty years ago, in August 1980, there was a meeting in Stockholm arranged by the National Board for Technical Development - 'STU'. There were lots of meetings like that one, and many more were to follow. This was so since STU at this time was working very hard to establish an alternative mode of science and technology planning; a new mode or regime one could label a 'collaborative technoscience intelligence', whose smallest 'social cells' were talks, discussions and an institutionalized sharing of responsibility.

In this context, as well as in the Swedish public administration circles more generally, words like 'conflicts' or 'controversy' usually make people feel very uneasy. Yet those attending that August meeting would all admit that consensus or mutual understanding was not exactly what it developed into. This came as no surprise to the organizers. STU knew what it had put on the agenda, and also that that 'something' was part of a 'wider something' bound to become controversial. There was, as one participating researcher remembers it today:

> a major tug-of-war going on, concerning how one should address science (Interview 21; *I-21)*.

But STU had made up its mind. Although 'its' in this case certainly disguises a mixture of people and priorities, frequently ending up on different sides of disputable issues, it now as a joint body had decided to revise and gain control of the terms on which that tug-of-war was going on.

The story to be told here is about the complex course of actions emanating from this intention, thus offering the reader a slice of contemporary science and technology history. More than that, however,

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[1] Paper presented at the seminar "The Battle at the Bottom: Making The Most of Feynman's Legacy". VINNOVA, Stockholm, April 19th, 2001.

the story narrates how a certain troop of scientists staged a stunning performance which not only empowered them as practitioners of their own scientific subfields, which at the time were lagging behind, but also rocketed them to the level of sought-after promoters or officials of science and technology at large. Several of them have indeed ended up in top positions of the Swedish university system.

There is no way they could have achieved that without establishing a close and long-lasting association with those of the STU staff struggling assist in the birth and stabilisation of a new technoscience intelligence order; and vice versa – the two were mutually dependent processes. Notwithstanding these ties (strikingly illustrating the phrase ’the irony of history’), at precisely the stage when that up-and-coming troop of scientists departed for their ’nineteen-ninetees tour of triumph’, their bed-fellows were disconnected from the subsequent phases of the process to become, almost overnight as it were, merely remnants of an obsolete species of science policy servants.

But thirdly, and most of all, this technoscience narrative is about how these people in symbiosis (before facing such different destinies), made a lasting ”nano-imprint”. That is, when ’nano’ right now is signing up as one of the key denominations of international science policy, our story claims to have something to say about current nano prospects in Sweden. Regardless whether the choice for good reasons will be to join the US and some other nations in launching a national nano initiative, or if, for equally good reasons, there will be a nano-no-decision, it seems like a sound policy investment to take a look at what kind of foundation we have here. Thus, the mix of elements to appear – ambitions, policies, relationships, humans, artefacts, etc – has gradually emerged into a heterogeneous network issuing the authorized mappings of the area (its what, where and how), at the same time as also controlling ’the national track’ for materializing and sustaining them. That is therefore what we should stick to and mobilize if we want to keep operating in the direction crystallizing for some 15 years now. And that is what has to be transcended or even dismantled, if we instead want to do something quite new or different.[2]

Under the Surface

So then, - what was that meeting more than twenty years ago all about? Well, the keywords were ’surface sciences’. On the table in front of the

[2] This narrative is about th*e conception and birth* of the nano discourse in Sweden; in our framing dating appr. from 1980 to 1991. Phrased in the ’nature vs nurture’-dichotomy, it is ’nature’ – the genetic heritage – which is being focused on (the intellectual and social foundations, or moulds, of nano research). Although not being part of the narrative, ’nurture’, i.e. the environment in which the child grows up, is of course also quite important here. It is variously made account of in other texts or seminar presentations produced within our pilot study. (”Technoscience in Transformation: The Case of Nanotechnology”)

participants there was a report written by the physicist Birgit Jacobson who recently had returned to Sweden after spending three years at Stanford on a scholarship. Back home she was asked by some STU officials, who had approved her the grant, to make an outline for a research programme titled ”The Physics and Chemistry of Surfaces” (sw. Ytors fysik och kemi, YFK). This task was right in line with what she had been involved with in the US. It offered her a golden opportunity to synthesize and propagate the many great things she had found to be building up a new cross-disciplinary field: ’surface sciences’.

Her sheer enthusiasm for the importance and potential of this new frontier in the making, was not shared by all the participants. On the contrary, several of them, based in industry or in some of the Collective research institutes which were operating in close conjunction with industry, were quite upset. ”This is not what we talked about”, they said, referring to what they saw as an early draft of a programme presented the year before. First, what struck them was the general vagueness of Jacobson’s report, it noticably lacked concrete and applied qualities, being too theoretical, esoteric almost. And then, there was in the current report a very strong emphasis on surface physics, whereas colloids chemistry that was part of the earlier proposal had been heavily played down.[3]

Jacobson replied that compared with what was now evolving in the major universities overseas, her approach was still relatively narrow and down-to-earth. Thus, it was justified and essential to move towards the broad and the visionary here, as there had been real break-throughs lately in science. Due to rapid technological development – ultra vacuum technology (a spin-off from the Space Programme), opto-electronics, electronics&computer science – the situation for science engaged in the surfaces of materials were fundamentally being altered. She could here cite a crucial passage from her own report:

> For the first time ever we now have access to experimental methods to fabricate and analyze purified materials sensitive enough to detect signals from very small samples on a surface with a resolution high enough to distinguish signals of the surface layer from signals from the bulk. (STU-protocol YFK-meeting, 1980)

For the STU officials attending the meeting, these were well-known words, being almost identical with the claim of a recent report from the Department of Physics at Chalmers Institute of Technology (Weinberger 1997:442). They may have agreed tacitly but were careful not to reveal it too much, having in practice already decided in favor of Jacobson’s

[3] A parallel reading of Jacobsons’ report and a STU-report issued two years earlier – ”Surface- and colloid science in Sweden”, STU-information nr 89, 1978 - corroborates that there was a substantial difference in scope and character developing in a few years; with the adjectives ’visionary’ and ’useful’ depicting the divide.

outline, and therefore now wanted to gloss over rather than exacerbate the irritation of the proponents for industrial utility. An attending professor of physics, however, rallied to the support of his colleague by advocating that representatives of industry should not be allowed to stop the programme underway to get, as he said and repeated in a latter written to STU shortly afterwords, ”a broad and generic knowledge-enhancing profile”.[4]

YFK was far from the only Framework Programme (FP) whose shaping was accompanied by heated discussions like this one, neither did the disputes come to end once the programmes were launched. There was for example one FP starting up in the area of catalysis, and another one in combustion technology, both being made the objects of dispute. When the pilot study of the former was published, some of its contents, was characterized as ”…having an unmistakable smell of good old transistor and vacuum tube technology” (I21). Certainly, this was not just a case of being a bit sharp in a ’business-as-usual’ battle rhetoric starring on the side the short-term utility interest and on the other the proponents of visionary long-range research. This was a piece of blunt impertinence, or of academic arrogance.

What elicited it? What was at stake here? Because after all, there must have been high risks involved. STU was not in principle the body to turn to with the most visionary and even arrogant academic stuff since it in the first place was there to see to the interests of industry, i.e. applied research and development. There should then have been a limit to what sort of ’contestant debates’ the research community could process through STU without burning its boats; and this looks close to reaching that limit. The challengers, in this case as well as in several others in the years to come, to a noticeably great extent came from the same branch of the physics science community. How come? Did mere chance have it that there was a disproportionately high share of hotspurs or madcaps in that particular branch?

Of course not, chance had nothing to do with it. But there were other ’actors’[5] to be taken into account here; actors present during that

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[4] Weinberger, in his exhaustive work on STU’s contributions in science&technology policy, points out how one from inside science regarded what was happening as a ’historical event’. In doing this, his phrasing ends up close to one of the seminal criteria of what soon was to be labeled ’mikronik’ and now is ’nano’: ”From the scientific disciplines’ point of view, what was happening can be described as a fusion or an amalgamation of scales since surface physics started to incorporate increasingly more complex ’chemical systems’, at the same time as the traditional surface chemistry started to strive towards more microscopic-atomic descriptions.” (Weinberger 1997:445)

[5] In this narrative, the word ’*actor*’ is used in the open or non-prejudiced sense as it has been developed within ’STS’, Science and Technology Studies, and in particular in its *Actor Network Theory* (ANT) offshoot; with Bruno Latour and Michel Callon as its leading scholars. In an ANT-understanding, ’doing science’ or ’making science policy’ are both human endeavours where ’actor’ could be many

meeting on Jacobson's report when the practitioners' utilitarian reading of 'surface' clashed with the scientists' visionary-reading of the same term, and actors who although anonymous were among the signers of that outspoken letter on catalysts of the past. One such actor had a grandiose (today perhaps less so) name: national interest.

A Vacant Key Position

According to the historians, the years 1978-80 stand out as a watershed in the European development of post-second-world-war science and technology policy.[6] For several years there had been signs on the macro-economic level of stagnation in comparison with "the Golden Age" of the 50s and 60s. For many politicians and policy makers it became more and more obvious that the solution to this problem was to bring about or 'catch up' with a new wave of industrialization, a reindustrialization erected on a pronounced high-tech basis (Rothwell& Zegveld 1985; Freeman&Soete 1987). Only by taking advantage of this, which meant succeeding in the escalating worldwide technological warfare, could one escape the threats of recession. Caught up in the struggle for hegemony among the Great Powers, with Japan increasingly challenging the US supremacy[7], and the Europeans ever so worried of lagging even further behind, small countries too had no other option than to join the new "Picking the Winners" game (Irvine &Martin 1984, Katzenstein 1985).

Within a few years, several of them, including Sweden, were to launch new national technology initiatives (Glimell et al 1988, Arnold&Guy 1986).

For STU, this international refurnishing came very timely. Already in the mid-seventies, after having existed for only five years, criticism was

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different things: humans; non-humans like a Scanning Tunneling Microscope, an algorithm, a silent agreement, a public policy, dreams, desire, etc. These actors do not just add up to an incalculable mess of things. Through a series of activities referred to as '*heterogeneous engineering*', they are being enrolled (mobilized), integrated, disconnected, reintegrated, and so forth, evolving into a *network* having (although not in any essential, permanent way) some kind of '*agency*'. The links or relations between the actors are continuously being (re)shaped by the phenomena of *translation*; through which the character, ´size´, potentiality or agency of the various actors belonging to a network, are altered.

[6] Confronted with such statements, one must always be on one's guard, as reshuffling the cards representing events and trends to fit an invented before-after dichotomy, belongs to the most common tricks by which social scientists try to catch the attention and communicate with the rest of the world. However, in this case, even a sceptical cynic must admit that the evidence of something like a major divide, looks extraordinarily strong and unanimous.

[7] For example with the 5th Generation Computer Programme coming up, along with numerous other strategic technoscience initiatives from the widely recognized MITI administration.

raised concerning the role it was developing. In brief, there was an empirical and a theoretical dimension to this. The projects which STU supported had little connection to each other, and were typically fairly small. Springing from the ambition to promote industrial development, many of them were also quite conservative; yet applicability or usefulness turned out to be a much more far-fetched quality than expected. Theoretically, this was cast as being too much trapped in the logics and philosophy inherent in the so called linear model of innovation[8]. In addition, there also lurked behind the scenes a faction within industry that took every opportunity to publicize its ideological disapproval of STU's existence on the whole.

In hardly no time at all, it seemed, in the year of 1979, the Swedish planning intelligentsia was swept off its feet by the new international trend in science and technology. Three parallel official reports were produced; with STU, The Academy of Engineering Sciences, and the Ministry of Industry as initiators. They all presented very much the same analysis and conclusions, thereby forming a sharp contrast to what one had been used to in the seventies, when issues on technology and industry were regularly (ritually even) contested. At this point of a sudden consensus, STU was on the way to identifying a new role for itself. In its in-house policy work-shops, prototype development of two new tools had started: the monitoring device 'STU-perspectives', and the Framework Programmes (FP).[9] None of these were genuine STU brands; the first could partly be traced back to technology assessment activities applied elsewhere in the Administration, whereas the FP's were an "import" from The Natural Science Research Council ('NFR') via new recruitment, although hardly yet being put in practice there.

The topic for the three reports published in 1979 was 'the industrial future of Sweden'. On top of their agendas was the traditional trade structure and the increasingly obsolete technological basis upon which it rested. They did not go into the situation within the universities to any particular depth, yet that was very clearly a crucial part of the problem. Everyone knowledgeable in the field was aware, for example, that the industrial structure largely was replicated within research by the intimate links between industry and the engineering sciences. A government agency keeping track and addressing that relation used to be the Council for Technical Research ('TFR'), however that had been closed down as part of the formation of STU in 1968. Therefore, the analyses now

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[8] As early as 1977, when most people within innovation research circles still seem to have held this model in high esteem, a government committe evaluating STU seriously called it in question. See Weinberger, p.419-421.

[9] A nano cosmos analogy would perhaps be that STU-perspective was supposed to be something like a TEM (Transmission Electron Microscope) helping to characterize materials, whereas the Framework Programmes were more like an AFM (Atomic Force Microscope) that with its tip could lift, move and rearrange the atoms (groups of the research community) around a little.

circulating might have supplied STU's radical critics, those opposing it in the first place, with compelling arguments. It did not, however, because neither the critics nor anyone else had what STU at least was on its way to get access to: an outline or chart of exactly the gaps and industrially relevant strongholds of conservativism which now were becoming a national interest 'to cope with'.

A quite ordinary survey was important here, a survey distributed to all Natural and Engineering Sciences Faculties. On the basis of the material it provided, covering data from several hundreds of departments and research groups on what areas to give priority for future funding, STU, in cooperation with NFR, organised a number of conferences with leading university representatives. Certainly, the overall pattern and concrete suggestions evolving here, were just as relevant for NFR, in its capacity as the larger research funding agency of the two. But there was (and is) a built-in problem here. The NFR-structure attributes great influence to delegates from the research community itself, reassuring its access to the appropriate expertise, though always at the risk of solidifying the current power structure. Hence, NFR was here hardly the independent forerunner a new national strategy badly required.

On the other hand, STU wasn't exactly that either. Its legitimacy was not to be rooted primarily in basic research circles, but in industry and its technical development, that so much was part of the problem. So there was a "gap", a much-in-demand position not fitting in with the existing profiles. At least one of the two agencies had to reroute, and re-root, its central line of business. Given the identity problems recognized both from the inside and the outside, and the void left behind after TFR, STU was the one of the two having the strongest motives for change. There was not a bed of roses ahead. A task which the vacant position demanded of its future holder obviously was to "be harsh on industry", to challenge it with regards to its conservative science strategies. Not even academic arrogance could perhaps be excluded from the elements one would have to mobilize, to get that off the ground. The charter that the new national consensus provided even authorized it.

At the same time, one would quickly run into problems if new initiatives and reframings were 'let loose' without any restrictions or norms of conduct. The new 'scientific-ized' innovation behaviour that one wanted to fertilize, had to be 'tamed' or domesticated somehow. To succeed, such a process must regulate a two-way traffic, as there were two parties and rationalities to confront, without letting them violently crash into each other. STU faced the challenge of transforming the national mission –"we must re-industrialize Sweden", into a new commitment for itself – "bring more 'fresh science' out to criss-cross the old ruts of technical development". It thus had two tasks to balance: on the one hand constructing socially acceptable forms along which one could 'be harsh on industry', because that was necessary; and on the other hand to develop tools and practices injecting (that is the doves' version – the hawks would have it ’re-assuring’) a certain dimension of industrial relevance to the visonary, ’curiosity-driven’ science.

Indeed, Weinberger (1997) has identified exactly this – creating, as he puts it, ”an institutionalized (compulsory) place of negotiation”[10] – to have been one of two constituating roles for STU’s activities during the nineteen-eighties. It was one of the pillars for its overall function or rationale, labeled ’the network entrepreneur’.[11] The introductory ’just one of those meetings’ about YFK offered a snapshot what it could be like, and it was parallelled and followed by numerous others in the close to 20 FP’s which were initiated, negotiated and implemented during this decade of attempts to ’restore’ technoscience.

Being an entrepreneur in a demanding situation like this one, with its inherent claims of breaking new ground, one would welcome “running into” a troop which for some fundamental reasons had the potential of becoming a future showcase example of the new brand of science policy in the making. The well-attended meetings which STU and NFR organised in 1979-80, showed that many were willing to be enrolled, or instead themselves be the ’enroler’, in the formation of ’something different’. After all, new funding and a new form of long-term funding

[10] More specifically defined as: ”to construct a set of rules regulating how two parties and two social systems, the university world and industry, can negotiate research programmes where internal academic criteria can be successfully combined with the need to produce industrially relevant knowledge”. (Weinberger, p.468)

[11] ’Entrepreneurs’ are primarily not associated with long-term plans or strategies; rather they improvise, take advantage of opportunities, and materialize in creative ways on the spur of the moment. Some readers may sense that the direction this Nano Narrative is about to take, is incompatible with such an understanding. Indeed, as the narrator, I may have caused or encouraged such a reading by implying a given, ’black-boxed’ character to the events or actions retold. For example, the debate on ’National Interest’ coming out as a ready-made ’context’; or the actions of the ’network entrepreneur’ or ’the arrogant academics’ or others, as emanating out of comprehensive and well thought-out ’strategies’. If I did, my narration is in danger of developing into a ’vulgar sociology’ (or history of technology), as there are no ’contexts’ or ’strategies’ here. In principle confessing to an ANT-approach (*cf note 3*), I contest the idea of actors being *in* a context; instead contextualization is fabricated and negotiated like everything else, through the continuous interacting or ’networking’ with combinations of humans, ideas and non-humans. Not everything, or alls things equally, are penetrated or affected by some essentialistic ’context’. The same applies for ’strategies’. Actors don’t *have* them; they populate their ’little world’ with other actors, and artefacts, which they endow with an array of qualities (such as a past, visions, targets, limits and ’agency’ of some kind). Talking in terms of strategies, one might miss the richness, contradictions and multiplicity of these locally situated processes; doing poor work of sociology or history. For more on this, see Latour (1996); e.g. pp. 133-138, 142-143.

were envisaged. But there was one troop in particular looking capable of acquiring just those extra qualities that…

The Perfect Partner

Via Jacobson's outline for YFK and via The Arrogant Letter and via several other documents, the message was being voiced: it is within Physics that the new, visionary research of great societal interest is being born. Especially, to be more accurate as to its location, on 'the surface of things' where physics bumps into chemistry. Of course, one would expect most people in science to claim that their discipline in general, and what they themselves do in particular, are visionary, and there is no easy way of deciding whose claims are the most justified. Pointing at specific breakthroughs allowing genuinely new observations, is not a bad thing to try though, to persuade others. And quite a few physicists, eventually also some chemists, did that. There was now, they argued, not only an accomodation of instruments based on laser technology (awarded a nobel Prize already in the late 50ies), but also major progress in e.g. opto-electronics, computing, materials fabrication technology, and in microscopacy, where a new invention 'in the pipeline' soon was to attract much attention.[12]

As a whole, physics was at the time a comparatively well-off part of science, being amply represented in the NFR scientific committees for example. But not all of physics was so; some subfields were distinctly less visible and less favoured when it came to funding, than others. Judging by the much-in-use criteria of publishing, one such subfield was solid state physics, or condensed materia physics. In the beginning of the nineteen-eighties appromixately 40% of what was published in the leading physics journals belonged to this field, whereas it in Sweden was allotted some 20% of the funding. At the same time, all monitoring activities, the ones carried out in the parallel picking-the-winners investigations of 1979 as well as the early reports from 'STU-perspectives', unanimously pointed out microelectronics as the motor of innovation and industrial competitiveness for years to come. And although there is not always the clear-cut relation between basic science and technology that one once imagined, microelectronics is very much applied solid state physics.

This situation then strikingly seems to have illustrated the deep worries which were at the heart of the 'national interest mobilization'. In spite of its major industrial relevance, and the fact that this strand of

[12] Only a few years after their achievment, the inventor of the Atomic Force Microscope (AFM; in 1981), a physicist, was awarded the Nobel Prize. He however shared the prize with a chemist who pioneered the Transmission Electron Microscope as early as in the thirties, thus having to wait almost 50 years for his full recognition. (For the 'positions' of AFM and TEM in the material culture of nanotechnology, see Fogelberg 2001.) Perhaps one can see this as symbolic for where the spots of scientific fame for long had been directed.

physics still was relatively inexpensive (in comparison with high energy physics and several other areas where one single instrument could cost something like half the budget of a social science faculty), it was lagging behind. One could have expected that its intimate links with the industrial success story par excellence, would give it a glory-by-association effect, but obviously it hadn't. Not yet.

Of course for those on their way to reform or transform STU, this could be seen as a clear or conspicuous indication that one was setting out in the right direction; a confirmation that there was a ”holy” mission to be fulfilled here. In addition, very much the same evidence was being made available on the international science policy arena. In 1982, in pursuit of the technological warfare announced a year or two earlier, several European countries launched national initiatives focusing on microelectronics and information technology; with the Alvey Programme in Britain setting the example.

If one then had looked into the rear view mirror, a Swedish version of such a programme would not have stood any chance of raising the necessary political support. Yet, after a short and largely opaque preparation process, Riksdagen in 1983 approved to a National Microelectronics Programme (NMP). The initiative was driven by an STU official in close cooperation with a consultant who had spent several years in the semi-conductor industry of Silicon Valley and a fellow official at the Defence Procurement Agency (Glimell et al 1988). Its profile as well as size, deviated significantly from anything previous, reflecting and materializing a new spirit and framing of science and technology policy.

The bulk of NMP's budget was assigned for an upgrade of the VLSI silicon technology used in production by one of the two domestic semi-conductor manufactures. For this part, NMP4, a 50-50 funding quota with industry was stipulated. On a substantially lower level of financing, there was however also a long-term research module (NMP2; later called 'submikron-programmet'). This can be traced back to a meeting in Göteborg arranged by the Committe for Physics at NFR in 1982, 'new research perspectives on semiconductors'. The response was overwhelming; NFR received many more applications in the area than there were resources for. As they were considered too important to be rejected three members of the Committe, two physics professors and one industrialist, composed a separate super conductor programme. There it lay dormant until it was picked up by STU in setting up its NMP proposal.

Although certainly important, this takeover was only one of many examples of the new traffic now opened up in between the two agencies. It was running in merely one direction, it seems, with STU importing from NFR demands not satisfied there, or science planning procedures which then were adapted to fit its own emerging toolkit for monitoring and negotiating. For several cohorts of ambitious young solid state physics people (mainly in Göteborg, Lund and Linköping), this was the opportunity to start climbing from having been in a Cinderella situation:

> …Our only chance lay in juggling with the border areas in-between STU and NFR, although most of what we then got, we got from STU (*I-15*).

Less than a year after having successfully launched NMP, in mid 1984 STU initiated yet another process. A second major questionnaire was constructed, issued to some 600 research groups. They were asked to respond with what they reckoned were strategic opportunities as well as threats for Swedish industry within a 5-10 year perspective (STU-information 532, 1986: pp.56-58). One of the main features in the material gathered, was the future importance attached to the interconnections between different scientific areas. Three conferences, co-organized by STU and IVA, were organized to take this a step further.[13] Soon, four areas characterized by being both strategic and situated at the border or interface between several disciplines, were identified.

Conceptualised as part of an expanding techno-political networking endeavour, this allowed another ”ally”, an academic element – ’interdisciplinarity’ – to be enrolled along with the already incorporated ’national interest’, which also had the potential of furthering new flows of traffic. And again, some of the most open-minded solid-state-physicists, sensed the opportunity that was popping up. By making public statements such as the one to follow, they not only expressed their full agreement that the new role STU was constructing for itself was a real and crucial one, they also – adding to the fertile borderland between NFR and STU – expanded their own operational ’funding recognition space’:

> If *X* is to become a strategic area of research, attitudes as well as the procedures for allocation of funds, have to be altered. It is unsatisfying to define research as ’physics’, ’chemistry’, or something else, without having at one’s disposal resources for interdisciplinary work (ibid, p.2)

Dressed for Success

A Nano Precursor and a Quantum Leap

The STU/IVA meetings connecting strategic importance with the potential of interdisciplinarity, resulted in the identification of four areas, for which further meetings with researchers were organized. One of the areas was our ’X’ from the last quotation: micronics. It has been described as:

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[13] These meetings and the work surrounding them has been characterized as something of a forerunner of ’Teknisk Framsyn’ carried out in 2000. (*I-23)*

a continuation of microelectronics, in relation to the programmes in that area it can be regarded as a kind of spin-off to other systems and properties (I-2), [also as] “the true spearhead of ’nano’” (I-18).

STU introduced the area officially in an appendix to its budget application in 1986 where it in general terms was described as:

technology for the fabrication of components and systems whose functions are based on a combination of extremely small geometrically fixed structures with varying biological, chemical and physical properties (STU-information 570-1986, p.1).

Later in the same report (p.3), the micronics concept was tightened up by the requirement of tailoring structures from the molecular level in all ’three dimensions’ (in many other material science contexts only one dimension has to be ’nano’). According to one interviewee involved:

..micronics is the same as what one today talk of as ’nano’, it is just we didn’t then have the instruments we have today (I-23).[14]

Micronics was introduced as a brand new frontier of technoscience, possibly of the same importance for the nineteen-nineties as microelectronics had been for the preceding decades. Much of its essence and potentialities were linked to the notion of interdisciplinarity or amalgamation of ideas and science areas; it appeared as limitless and seamless, coming across almost as the ’ultimate concept’ Close to fifteen research fields were mentioned as directly relevant. There was a ’micron-oak’ whose branches illustrated this multiplicity; a five-pointed star made up of Physics-Chemistry-Biology-Electronics-Mechanics, and then in the middle of that cosmos: micronics. In practice however it was people from physics and chemistry who responded most strongly. Out of 58 applications for the Micronics Programme, upon its announcement in 1987, only around 10 came from outside physics or chemistry university departments.

Notwithstanding all articulation around the concept, the importance of being flexible as regards its application came out strongly in the announcement of the programme. It was pointed out that several of STU’s FP’s already had some micronics in them, and that a new program should link up with those in order to further strengthen groups which already had gained an international reputation. Such a flexiblibility also seem to have been put in practice by ’the network entrepreneur’. Several researchers have testified how they could ’manoeuvre’ favourably in-between programmes. For example, the groups from solid-state-physics

[14] As a concept, ’micronics’ did not last long. On the one side there was the terminological focus on ’material science’ sweeping many things together under a broad label; while on the other micromanufacturing side of the spectrum, the terminology has gone towards micro systems technology (MST; in Europe) and micro electronic mechanical systems (MEMS; in the US). source: I-8

which came to capture a considerable share of the micronics programme, were doing similar things in e.g. YFK, the submikron programme or the FP on Bio-Compatible Materials (an offshoot from YFK, giving some of its participants the chance to expand their areas in parallel).

This is not to say of course that possibilities for 'surfing' came by themselves. They required a lot of hard work and administrative (as well as 'political') skills on the part of the researchers. A lot of time had to be spent in meetings or conferences away from one's actual research, a legacy of the collaborative and interactive modes of planning which STU promoted (cf 'institutionalized negotiations', extensive monitoring with the active involvment of researchers, etc). Indeed, a hidden prerequisite or implication of this, without which the strategy most certainly would fail, was that the leading spokesmen of research had to go a long way towards becoming truly professional partners (co-producers) in the manufacturing of science policies.

Also, there may be demands building up in 'the other direction', in relation to one's research group. Thus, if you build up Big Things – a great reputation, a large staff, big laboratories – you are mentally and socially soon under the 'slavery' to sustain it. To cope with such a post-entrepreneural predicament, you better become a first-class grant performer (a ”grant acrobat”), which implies educating yourself as a multi-skilled science policy interventionist.

Thus, in addition to being production sites for the making of new creative research concepts, the historical settings we have peeped into, were market places and training camps for the trading of communicative and social skills. Naturally, the bonds of friendship you establish with STU officials or other agency representatives, are ever so important here. And the other way around; the networking mode of action that STU seeked to foster encompassed not only arranging institutionalized negotiations between parties, but relied also on quite informal contacts on an ad-hoc basis. As the management philosophy was to develop a flat organisation with few levels of decison, several of its officials had their own ”pocket money”; which if you saved it up for a while added up to more than just that. It could for example be quite helpful in filling in ”gaps” along the logistics of building up the research infrastructure; a piece of microscopy or lithography equipment missing in otherwise up-to-date lab facilities, a quick response to a sudden request to go abroad to participate in the announcement of a breakthrough in micro accentuators, etc. A selective, ”fine-tuned” and direct (although often hidden for others) support integrating sponsorship, spokesmanship and fellowship, was being developed.

This was of great help to many ”semi-established” research areas seen as having great potential, and condensed materia physics is the clearest example. It seems to have taken full advantage of the combination of big open-competition grant money and smaller portions of informal pocket money. No doubt, it needed both of them. Because the Nano Narrative, tracing as we here do the Swedish nano-roots, is among other things a story about a research field that within a short period had a spectacular growth. It entered the eighties as a very small subfield of physics, and it left it up-sized many times over:

> During the eighties physics went from being a low-budget branch of physics to becoming an expensive one. The rise in device prices, due to its rapid sophistication, uplifted it almost to the level of e.g. nuclear physics. From the level of perhaps a few million up to the level of 30 or 40 million SEK. …This was almost like a quantum-leap: in hardly no time at all, one went from being at a merely innocent level to becoming a grown-up. (I-16)

At the Treshold of Triumph: Clouds Building Up

When it comes to launching a new mode or regime of action, as when STU dedicated the best of its skills to changing the planning of technoscience, there are no such things as a final victory or a sheer success. Rather, this is a human endeavour concerned with how to keep a fragile network together, hopefully adding some new resources or allies to it, but always being aware it might collapse the very next minute. Nevertheless, there was, in the case of STU, some feeling of triumph in the late 80s. After all, compared to 1979 when one initiated the transformation towards a more active and mission-oriented role, there were some achievements. With the FP's, one now dealt with 'project kits' in key areas, selected after careful preparations and mobilizing the very best of expertise; not just separate projects, remaining very much what they were as incoming applications. The FP's rarely ran smoothly on track. There was typically laborious work, frustration and controversy involved. However, after a decade one had somehow learned a little about how to handle it; and in fact, in 1988, one was getting ready to set out on yet another journey.

But not everything was rosy for STU. At the same time as it was gradually gaining recognition from earlier sceptics (e.g. IVA and NFR) for its contributions to technoscience policy, it was still a potential target for others' scrutiny. In certain research policy circles, consisting of critics inside the universities as well as people from politics and industry, a 'backlash' against the doctrine much cherished in the nineteen-seventies – sectorial research – was launched. Despite not being a clear-cut example of a sectorial agency, and although numerous government interventions worldwide had been launched, STU's ambitions to become a pro-active spokesman for a national industrial interest, were here framed as an unhealthy state corporativistic intervention policy. The research councils, founded already in the 1940s, still represented within these circles the only appropriate and legitimate form for govenment funding.

When, in this spirit, suggestions were made in the mid-eighties to re-establish the Council for Technical Research (closed down in 1968), it first seemed like STU would succeed in putting them in the shade. Very swiftly one installed such a council oneself, as an in-house body. In doing so, the claims could be ”domesticated”, so as to fit in with and add a new dimension or option to the networks already in existence. From the researchers’ point of view, i.e. for those already involved in e.g. the FP’s, this was good too, as they could take advantage of the ’social investments’ made in learning how to interact.

However, not all external threats were disarmed. The eighties was also the decade when the neo-liberals ’infiltrated’ in the government administration. Serving their overarching purpose of cutting down public spending, they were in particular looking out for authorities or agencies which had a corporativistic flavour to them. If they also were operating fairly close to other agencies impaired by problems or signs of decadence even, so much the better…

Baptizing the Beautiful Baby

Rumour has it that in 1987-88, when the preparation of a new funding concept, going beyond the framework programmes, was initiated, the idea of the STU official being its primus motor, was ”talked down” by a few researchers (I-9; I-10; I-15; I-16). The new concept was envisaged as one essentially founded on the good experiences one had gathered, however it took them a step further by expanding the single-dimension common denominator normally required so far, into a more comprehensive set of objectives or criteria. Whereas the FP’s once had meant going from financing projects to financing ’project kits’, this one – the research consortium – was to propel a concerted action under a firm and professional, yet decentralised, leadership. Those who are said to have talked someone down, had all been engaged in the FP’s, while at the same time holding responsible positions in the physics committes of NFR.

The achievement here attributed to them was in fact twofold. First that thanks to them, the coming material science consortia, developed into something more future or long-term oriented:

> …one had at first thought of them as something more traditional, with linkages e.g. to the steel industry; (I-15),

and secondly that physics, in practice condensed materia physics (a term used alternately to or rather like ‘solid state physics’) , was greatly upgraded:

> There is no way that NFR could have extended condensed materia physics without this initiative, and I am sincerely grateful to STU for having made this possible. But just as much for the scientific orientation inscribed into it; of course STU wanted us to get in touch with every

existing industry, but basic science had become recognized and accepted once and for all. (I-10).

Certainly, with today's knowledge of the success which was laying ahead for the concertia, it may come naturally to (re)present actors framing it in heroic terms. According to the earlier tellings of this Narrative, there had been many a negotiation throughout the 1980s over the 'optimal balance' between utility- and curisosity-driven research; and in retrospect this particular one – taking place when the 'Project Kit'-model was about to become transformed to the mightier 'Consortia model' – may appear as the Final Negotiation, settling the long-lasting matter. It, according to this understanding, was the ordeal coming up, the decisive 'trial of strength' for the competing parties. To be noticed, however, it was STU and the research representatives having these talks; the former assumingly acting as the spokesman for industry and practicability.

But – our needs for heroes and crucial single events taken aside – how much really speaks in favour of this trial-of-strength-interpretation? What options could one have expected? How much discretion should one 'socio-logically' re-attribute to these talks, this 'negotiation'? What was separating, unifying and regulating the relations between the mixed set of actors – all the humans, devices, inscriptions, financial flows, expectations, etc – populating our story?

As accounted for, there here seems to have been a development of a network not guided by some major plan, but emerging out of multitudinous interactions between elements, connecting them to a shared mission and knitting them together (although perhaps not lastingly or irreversibly). Thus, there was e.g. the networking evolving around the construction of 'A National Interest', another around 'The Making of the Perfect Partner', and a third on 'Progress Through Interdisciplinarity'. In-between these there were links, or translations, not logically following any clear-cut order, but produced within complex patterns of social interaction (many productions fail of course).

As 'networking' is conceptualised here, it simply does not "allow" any human actor just to remain a party solely housing an infrastructure, or a forum for others' actions and interactions; something that the early discussion on STU establishing 'institutionalized places of negotiation' might have suggested. Although doing exactly that may provide the necessary impetus to the many interactions, negotiations, translations, etc which make up the network, you can still never stop there. The very minute 'something social' is starting up, you cannot escape from being part of it. In lots of ways, some more shallow but others profound, you become addressed, calculated, interpellated and integrated somehow. And it is not just the others that pull you in. Also you yourself, being a social creature and not only paint on the wall, start fulfilling a lot of functions, most of which you neither could know of in advance and plan to do, nor plan not to do; some, in fact, you are not even aware of doing.

The researchers asked to assist in developing the consortia concept, had been ’net-workers’ all during the STU-endeavour to create ’a collaborative techno-science intelligence’. With them, long-standing relations and commitments were etablished. There were at this point all kinds of commitments, personal bonds and investments (in time, labs, organisations, human capital, friendship, and so forth) involved. While some spokesmen for the universities at an early stage, when e.g. YFK was being negotiated, may well have displayed some academic arrogance or youthful insolence, they were now maturing men of science, professionally speaking for a rising cohort, empowered as they were not the least by STU itself. This is not picking up the hero-role, just re-locating it to STU; it had its own interests in this, and just as much as it may have helped or empowered others, those others did so in return. It is just to say that donors and receivers had long practised Perfect Partnering, and therefore did not emerge as very trustworthy contending parties at the end of the road.

So, of course the Academics were ”winning”; as they had done already at that August meeting on YFK some 7 or 8 years earlier, and frequently thereafter. They were winning not by proving to be extremely forceful or smart in a trial of strength (which doesn’t say they might not have been that too), but because losing was never an option. It had been excluded long ago. There had been a fusion of men (mostly) and machines and ideas and perhaps even of personalities. And ’STU’ was not the ’STU’ it used to be, because one part of it now was an amalgamation between NFR and STU. When the new ’model’ – the research consortium – was released (in 1989) its bulk or chassis was identified as an unmistakable NFR-make. The consortia were to be funded to 90% by STU and 10% by NFR, which then may look like a 100% robbery. But this was a gradual thing; perhaps in 1981, when STU ’allowed’ Jacobson and other researchers to ’be harsh on industry’, it was already 20 or 30% NFR; and later, at the time of the Micronics FP (with its start 1985-86), it may have been 50 or 60%. Accordingly, the academics invited here were not performing a robbery. They were just doing what was expected from them at this point; a job for which STU had ’trained’ them.

What we then in fact have here is a ’family event’. It may have looked as if another ’negotiation’ had been set up, but really ’confirmation’ or even ’celebration’ seems more to the point. It was time to baptize the nice-looking baby, to announce her arrival, and to furnish her with the clothing and the additional gifts she would need to do well in life. However, for one of the parents, hardly was the christening over, before the baby was being…

A Rather Pathetic Attempt at Recapture

In spite of STU’s attempt to harness the external demands for a Council for Technical Research by installing it in-house, there was a political decision to have it re-established in 1990. This affected the territory of technoscience policy production, the realms of this Narrative. The borderland between NFR and STU, the one that the solid state physicists saw as their historical chance to exploit, was no longer that 'open space', as there now was a third settlement in that area – the new TFR. Soon upon this, an even more thorough reorganization followed. Three agencies were merged – STU, the National Energy Administration (STEV), the National Industrial Board (SIND) – into a new combination called 'Nutek'. To make a long story short, this even more radically altered things as the traditions and 'policy making cultures' of STEV and SIND had little in common with the 'network entrepreneur mode'.

This introduced a very strange situation to those in our cast. Their Great Programme (anthropomorphized as 'The Beautiful Baby') – the result of many years of joint fabrication of new research planning tools and of new reciprocal relationships between research officers and policy officers – was at the wrong place! All by a sudden, its homeland was gone, transforming it into an anachronism within the distant and foreign Nutek federation. So after having enjoying a place at the centre of things, it was turned into an alien, or intruder, playing at someone else's backyard. What would now happen to this favourite baby, coming out from her christening looking so smart and confident?

Well, those owning the house in whose backyard the baby now suddenly found herself to be, stared at her and said: "You have to pass a test, if you want to play with us at our place". The Great Programme, before actually even having got started, had to go through a 'rite de passage', an 'obligatory point of passage', because some of the people rapidly getting Nutek-ified wanted to recapture a baby that had developed in a direction which perhaps made sense a year ago, but now didn't. New values had to be disseminated to pave the way for a new regime. As regards the consortia, a thorough re-negotiation was out of the question. Accepting this, but still eager to take some action, one decided to inflict a checkpoint upon the eleven consortia just getting started. The thing to be especially checked here, was whether the existing agreements guaranteed the industrial use or usefulness of the consortia; the practical feasibility of those science squads.

The first in a row of consortia evaluations to follow had this focus, and it concluded that usefulness was discriminated and had to be better re-assured. As a result, in the years 1992-93 Nutek exerted some pressure on the consortia, issuing certain new guidelines or recommendations for their work. The effects of this early intervention have been estimated as rather limited (I-7; I-11; I-22; I-23; see also Persson 2001, forthcoming). A few projects with a strong theoretical orientation, or addressing materials unknown to industry, were removed or terminated prior to plan. Soon, however, everyone involved appears to have realised that the measures taken merely turned into empty gestures or asides, with little bearing on what was at the core of the typical consortia course of action.

The reason of course was that the consortia had for years been rigged for sailing in another direction. In addition, we know that their captains were no ordinary seamen but well-trained commanders, perfectly capable of repelling everything they regarded as unnecessary or unjustified interference. Although perhaps not being impregnable forts, several of them were amply equipped (if there was 'a trial of strength', this was it). Also, of great importance, those negotiating (or, as it were, 'baptizing') the terms or moulds for the consortia, made sure, making use of an international trend for their own best interest, that the peer review tool was stipulated as the major legitimate source of intervention. Sticking to this, shortly after the industrial relevance evaluation, the first peer review on the scientific standards of the consortia was initiated by the consortia administration. And indeed, it had some quite positive things to say, which, according to those involved (I-14; I-22; I-23) took the sting out of any remaining criticism. From that moment, it seems, it was quite clear that the material science consortia was "dressed for success".

She could now get on with life, although living in her first exile (there would be a second one). In fact, in this as well as in her next accomodation she was taken care of very well, by people who had known her from her very first breath. The rest of Nutek simply had to swallow the bitter pill, realising that recapturing their former baby was not a realistic thing to do. It now belonged to someone else, and was part of something different, although to whom, and of what, still was very unclear. For every peer review (and there were many of those), she looked like a safe success, but to no use for Nutek. There, one had to start all over again, with the not very enviable task of coming up with new concepts out of much less resources than there used to be. And at "the threshold of triumph", there was for some of its officials not glory waiting on the other side, nor even a fair recognition of their efforts and dedication, but only oblivion.

But the Micronics Programme ('MP'), the "Nano Precursor", was still there. She was not in a terribly good shape though. She was missing something very dear and important: her sister. Already at the conception of MP, it was stated that she was meant to live quite close to her sister. Her name was 'YFK'. The two were to be seen almost as two coordinated arms of the one and same body. The recent remarkable development of scientific instrumentation, it was declared, has now spurred a "a revolution in physics and chemistry". And then, to explain how from that common footing, the two siblings were related:

> It is today and in the future possible to understand processes and structures on the atomic or molecular level, so that genuinely new perspectives as regards tailored material- and structure-fabrication now can be discerned; and in addition it will become possible to manufacture it by means of modern production technology. … 'YFK' was earlier established to serve the first of these areas, whereas from this year and onwards, 'MP'

will cultivate the second. (Excerpt from Foreword, STU-information nr 621, 1987.)

’YFK’ was no longer ’YFK. She had found for herself a new identity, the Materials Science Consortia, a policy concept all ”Dressed for Success”. At the point where this Narrative tells its last tale, she was still living in the same building as her younger sister ’MP’. Only that the two of them didn’t meet all that often…

CHAPTER 5

Dynamics of the Emerging Field of Nanoscience[1]

Hans Glimell

Introduction

The following is a selection of aspects considered important to the ”dynamics” of nanoscience and nanoengineering (NSE). They reflect my understanding of what counts in the community of NSE, while addressing approaches which social science could adopt to account for and stimulate reflections on the ”multi-faceted technoscience endeavour” preoccupying that community. Although I myself set out by organizing these aspects into three categories - cognitive, social and culture dynamics - the implied research agenda to emerge defies rather than advocates such a classification. In the concluding paragraphs, it is suggested that perhaps only by playing down another resistant demarcation in our society, namely the one separating professionally authorized expertise from lay expertise, will it become possible to envision and exploit the entire dynamics of nanoscience.

Cognitive Dynamics

a. Obviously, the expansion of nanoscience and the very idea of an emergent nanotechnology emphasize the need for interdisciplinarity. In spite of the positive response that challenge often invokes, the practice tends to be different. There is a long tradition within academia of the single discipline as the core entity of organization. Even in areas where external forces have exerted strong pressure to transcend them, disciplines have proven amazingly persistent.

Within the field of science and technology studies (STS), Thomas Gieryn in the mid ’80s introduced the notion of *’boundary-work’*. Scientists sustain the epistemic and cultural authority of science by constantly drawing and redrawing maps or spatial segregations highlighing contrasts with other kinds of knowledge, fact-making methods, and expertise. Since then many forms of boundary-work

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(expulsion, expansion, protection of autonomy...) have been shown to apply also to how credibility and cultural authority *within* science is being contested. When future cartographers will try to come to grips with the many negotiations and redrawings of maps that we could expect to be a salient feature of NSE in the years to come, this is a vein of the social study of science to be consulted.

b. When research foundations launch a new 'brand' on the R&D funding market - like now, when 'nano' has entered the front stage through NNI - they also fuel a lot of new boundary work. The rules of the game are changed, and those who want to play it had better start depicting the new landscape (borders, barriers, shortcuts) and the emerging criteria which may give them access to it. At least two risks deserve our attention here. One is that a lot of resources go into the re-presentation and re-labelling of ongoing work, which nevertheless remains very much the same (it may also leave researchers with the bad feeling of having been forced to make promises they cannot fulfil). The second risk is that one succeeds in pulling new research into the field, but fails in securing for those new elements a sufficiently high quality. In Sweden, as an example, the dynamics of a major national energy research initiative launched in the early '80s, were soon severely hampered by the disrepute of its quality deficiencies.

c. Several historians of science have brought our attention to the "sequential pattern" of the evolution of a scientific field. For example, from his thorough studies of the history of physics, Galison concludes that when there has been a breakthrough in *one* of the three innovation arenas he distinguishes - i.e. theory, (methods of) experimentation and instrument making - the other two stay stable until the new element has become fully assimilated in the scientific practices.

If such results are taken seriously, there should be implications here not only for historians but also for future-oriented policy makers, when e.g. they take on an emergent field such as NSE. Although, of course, aware that the above model is, for analytical reasons, a simplification of a much more interwoven reality, it can still draw attention to a choice they face. They could choose a liberal or laissez-faire type of strategy, largely leaving to the research community to 'make a bet' on where the next incremental change will occur. Or they may choose an interventionist strategy where funding is steered towards the arena they believe will generate the next major innovation impetus. Looked at from the individual research group's point of view, the strategic choice becomes one of either trying to encompass all three arenas or competences, running the risk of allocating insufficient resources (i.e.: no excellence) for everybody, or go for excellence in merely one of them, at the risk of not having picked the winner.

d. In addition to laboratory studies (or ethnographies of the everyday practice of science) and historical case studies, there is within STS a field that elaborates *controversy analysis* as a fine-tuned methodology with which the micropolitics for winning cognitive or epistemological credibility and hegemony is studied. As NSE in many respects represents a juvenile area, it is likely to see the emergence of several scientific controversies. Some of these, if carefully studied, could become rich sources of knowledge on how the main demarcations and topography (cf 'boundary work' above) of the nano-landscape is evolving.

Social Dynamics

a. Controversy studies do not merely shed light on the internal consistency or credibility of the scientific claims under study. They also point at how those claims are embedded in, or proactively 'mobilize' various social and cultural factors. By basically broadening the symmetrical analyses used on controversies, there is by now an extensive body of research on the "anatomy" of the wider societal networks constituting and chanelling innovation. One here finds the studies informed by the actor-network theory (ANT; or the "Paris school" founded by Bruno Latour), in which a 'follow-the-actor-methodology' guides the analyst, and where 'science' or 'technology' take the shape of heterogeneous networks blending humans and non-humans, facts and fiction, 'the technical' and 'the social', 'nature' and 'culture'.

b. Given the generic character of NSE, the close monitoring that ANT and similar approaches set in motion are useful in articulating the diversity beneath that homogenous surface. Consider for example molecular electronics compared with bio-nano (or the interface of biological and organic nano materials). The actors, nodes and connections appearing in the extension of these NSE subareas obviously constitute two very different networks of innovation. Nanoelectronics is being negotiated and moulded in between two camps - the conservative mainstream of the microelectronics industry with its scepticism towards anything popping up as a challenger to the three decades' old CMOS technology trajectory, and the camp committed to a scenario where that trajectory might come to an end within some five years from now. As different and even antagonistic as those two camps may be, they are still very close from a cognitive point of view; i.e. they are perfectly aware of what the other is up to and why.

The bio-nano case is not like that. The corresponding dual relationship is here the one between the bio-nano scientists with their "wild ideas" of new hybrid materials to be applied in bio-interfaces and bio-implants, and the mundane health care sector with its clinics. There, the practitioners usually have great difficulties in at all grasping what the other party is so concerned about. A gap in terms of knowledge and everyday experience rather than one of different assessments of the technology, here separates the two.

It is by no means clear which of these two makes the better partner in bringing radical science towards applied innovations. What should be clear, however, is that only with a thorough knowledge of the often very different actor-actant-networks in action in various regions of the nano territory, the chances of 'tailoring' initiatives, interventions and resources to the crucial nodes or points of communication and social interaction will improve.

c. A very crucial point of exchange, where the different character of nano networks matters a great deal, is where "government money" should be shifted over to "market money". Obviously these two imply very different expectations, rationalities and infrastructures. But interestingly, in some regions of the "nanoscape", Science with government money is doing what Industry normally should be doing; while in other regions, Industry with its market money is producing what Science should deliver. Within NSE, in its premature state, many such "imperfections" will occur. Economists have studied some of these (e.g. in venture capital studies), but the tools they offer are at the same time too narrow and too crude to account for the complexity, importance, and *social* dynamics of these points of exchange.

Cultural Dynamics

a. The nano endeavour is in profound ways culturally embedded and relevant. It is inspired by the grandiose idea of man becoming as brilliant as nature in building things (materials, devices, artefacts, products), a truly utopian idea within a long standing tradition of man's fascination with the prospects of science and technology. The "nano" is a lot of laborious work, but also nothing less than the ultimate challenge; the "wet dream" of any dedicated engineer. It's no surprise then, that it is well etablished in popular culture. Long before it reached presidential committes or NSF, it flourished in science fiction movies, in the Fantasy literature, and in groups of radical 'nanoites' organizing themselves to meet in VL or RL to discuss nano.

For at least a decade, the scientific community did boundary work to keep the demarcations towards this radical popular version of nano straight. In lacking some of the formal qualifications that make up the credentials of this community, and, even worse, in refusing to keep his distance from the non-scientist nanoites, Eric Drexler, of course, had to remain unauthorised 'on the other side'. By "demarcating" like this, one avoided both the worst "technophilia" and the "technohorror" of the nano discourse. In doing so, however, one missed the opportunity to conquer determinism by suggesting more modest or reflective understandings, in exactly the way demonstrated by John Seely Brown and Paul Duguid when they at this workshop take issue with the 'tunnel vision thinking' guiding Bill Joy in writing his widely recognized *Wired* article. (By the way, illustrating the above demarcations, ten years before Joy's article, quite a similar analysis was presented without much notice at a Foresight Institute conference).

b. One of my informants, a nano-bio scientist, recently told me how he believes that an extended interaction with people from the Social Sciences and Humanities at early stages of the research process, would make it possible for us to ”get ahead of ourselves”. He belong to those (still a clear minority I reckon) who would give full support to a meeting like this.

Fine, but any cultural analysis worthy of the name, should encompass reflexitivity. Thus, come to think of it: what does it really *mean* that we - a mixture a people from industry, government and universities - gather here for a few days to discuss ’nano’ before we know what actually will become of it? This is an important question, as we from the very moment we start discussing (and even from when we started to prepare ourselves by writing statements like this one) can be pretty sure of (without thereby aggrandizing ourselves) affecting the development of ’nano’. How? We don’t know, and we cannot know. The answers to most of the questions to be raised during our workshop, can only be answered by future historians of science&technology. We will affect things, but we are not ourselves able to recognize our impact even when we see it. As once expressed by Jorge Luis Borges: *”Time is a river, that pulls me along, but I am the river.”*

Beyond Business As Usual

Although I, together with everybody else, share the predicament described by Borges, my concluding words will still have an activist flavour. I do think that one of the most thrilling things about this workshop, is that we might well be involved in something ”historical” here. Ten or twenty years ago an event like this didn’t happen. There was certainly a debate on the societal and ethical implications of technology in general, and there were foresight or scenario activities taking place, but the idea to actively try to integrate at a very early stage of a new emerging technoscience area also the perspectives and experiences of social scientists, is to my knowledge a new one.

Herein, lies perhaps the real challenge and dynamics of the nano initiative. It could well be that NSE develops into something of a ”public expertise field”, where the vital research ahead of us becomes the concern of the ’many’, without of course thereby lessening the importance of science in the traditional sense. The vivid debate on the genetic technologies during the last few years has shown that the ’public’ may be prepared, and often increasingly *well* prepared, to take a greater responsibility for the science and technology underway (taking what is often referred to as the ’public understanding of science’ a step further). We don’t know; perhaps the molecular biology revolution will turn out too strong to give room for ’nano’ as another major issue in the debate. But also, this will greatly depend on how the spokesmen for and members of the growing NSE community respond to the possibility of planting ”their” science and technology in the wider realms of the public.

Reference

Conversations with Professor Magnus Willander, Physical Electronics and Photonics; and Professor Bengt Kasemo, Chemical Physics; Chalmers Institute of Technology, Göteborg; and members of their staffs.

CHAPTER 6

'Science' and 'Technology' as Knowledge Cultures[1]

Hans Fogelberg

Introduction

The field of nanotechnology can be approached at many different levels. The investigation can begin at the level of national research policy agendas, to be analyzed in relation to what, in policy documents, are described as three major competitive regions: The U.S., Europe, and Japan. One can analyze the different research programs on a national level, or in the case of Sweden, research consortia or large laboratories. Such research foci would deal with the familiar social and political environment (or context) of science. Moving closer to the scientific content of nanotechnology, we may enter the research institutions, laboratories or research groups working on specific research topics, presumably occupied with narrow and esoteric aspects of physics, chemistry, biology or material science. At this level we may find probe techniques (scanning probe microscopy), and techniques for constructing atom-thick layers on surfaces (e.g. molecular beam epitaxy). There is one level of research foci below those earlier mentioned consisting of the very content of nanoscience and nanotechnology, namely the nanoscale objects as they are described by scientists through concepts, theories and measurements. I would argue that all levels need to be addressed. The important strategy would then be to find a research focus that does not prescribe or 'rule-out' a particular level at which nanotechnology is approached.

The purpose of this chapter is to analytically address the various concerns of a study of 'nanotechnology', taking into account the fact that it is difficult to imagine any new technology that can compete with nanotechnology as to the degree and depth of esoteric and abstract science-content. By touching ground in historical and sociological studies of science and technology on the one hand, and on the other hand relating these discussions to different characterizations of nanotechnology — as they are presented by natural scientists,

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[1] Paper presented at the seminar "The Battle at the Bottom: Making The Most of Feynman's Legacy". VINNOVA, Stockholm, April 19th, 2001.

policymakers, science-technology analysts, and in media — this chapter aims at identifying several strategic issues for a study of nanotechnology.

The Political Rhetoric of Nanotechnology

Many of the policy documents that have been generated emphasize the possibilities and the desirability of generous support for nanotechnology. In these documents a link is forged between the funding of nanometer scale basic natural science and the various successful artifacts this will provide us with. The result will be a more efficient technology with less environmental impact, providing us with better health, greater prosperity, and increased national security. Nanotechnology is, in other words, represented as the technical 'fix' of the future.

While most analysts of technical change have long since abandoned the 'technology as applied science' model, it is still present in the science policy discourse, where it long has served as a legitimating device for allocating resources for basic research in natural science. It has done so despite the fact that the model is mostly used without providing evidence of its appropriateness (Barnes and Edge 1982, p. 148). This link between science and technology is close to what is typically referred to as 'technical determinism', the idea that there is some form of logical line of development which new technology follows, and that this new technology will have a profound impact on society. In a kind of 'worst-case' determinism, science unravels nature's secret, the technology of the 21st century will emanate more or less directly from these basic scientific principles, and finally, the development of nanotechnology will have such a dramatic impact that it will profoundly determine the future of society. What is revealed here is simply that to study nanotechnology one needs to explicitly deal with issues of technical determinism, and for this we need to consult some relevant literature.

A Non-Hierarchical Conception of the Science-Technology Relationship

The notion of science and technology as separate cultures has long since guided the analysis which has sought stable patterns in the relationship between science and technical innovation. Analysts have asked questions like "what is the context of what? What comes first, stands above, and explains?"

In his historiographical assessment of articles in *Technology and Culture*, Staudenmaier (1985) found a range of different positions among historians of technology in this respect. While not all different views were seen as equally plausible by historians, Staudenmaier's analysis still indicates that there is no emerging consensus about one major form of relationship between science and technology. The historian's route, what Mayr (1982) call the 'empirical-inductive' method, tends not to yield any simple patterns of a science-technology relationship from which historians could generalize. In other words, well crafted and insightful historical studies did not support the kinds of conclusions that would be needed for the analytical endeavor of managing science and technology.

Mayr notes that this lack of generalizations leads to a state of frustration, directing analysts of technology to another route of conceptualization more aligned with a philosophical approach of formulating (prior to the study) a logical definition of the relation between science and technology. It is this 'logical-deductive' method of approaching science and technology that gives rise to something of a 'mirror-image' model (Mayr 1982), in which we tend to see science and technology as mutually exclusive to each other. It was then not a long step to consider these two parts in terms of a hierarchy, giving birth to the long-lived 'hierarchical' model of science and technology, in which science mostly, but not always, was placed in a 'higher' position than technology. It is from this basic conception that Barnes and Edge (1982) identifies the 'lag-model' of technical innovation, which has certain implications for the assessment of science policy in relation to technical innovation. Because if it is true that the hierarchical model is embedded in the discourse of science policy and technology policy, then the 'lag-model' looks like a method to evaluate how well the system or 'the machinery of innovation' works:

> To apply the 'lag' theory one takes a technological innovation and works backwards along the lines of cultural change which terminate in it, noting particularly those points at which a scientific discovery or some part of the knowledge of pure science was involved. One then selects one such discovery, preferably the most recent discovery encountered, and accounts the later technological innovation as the logical consequence of that discovery. The innovation thus redounds to the credit of basic science, and the 'lag' between the discovery and the innovation which it 'implies' serves as a measure of the competence of technologists. (Barnes and Edge 1982, pp. 148-49)

This lag model exemplifies the close relationship between the history of technology and innovation studies. While the analytical interest goes in different directions along a time scale, themes of interpretation overlap. Because, turned on its head, this model suggests that the production of scientific papers has something to do with the possibility of making a certain technology into a technical and commercial success. But the logic of technical innovation implicit in the 'lag' model is problematic. It matches a well known pit-fall in historical analysis of innovation termed "Whig history," i.e. historical accounts that chronicle technological success stories as the inevitable outcome, here as the result of scientific events.

The failure of the empirical-deductive route to arrive at a consensus about the boundaries of science and technology and of their relationship, and the equal failure to give empirical evidence in support of the logical definitions, is according to Barnes and Edge (1982) only natural. They argue that within our culture one may choose to identify one sub-culture as ‘science’ and another sub-culture as ‘technology’, but that this does not mean that there is in itself anything profound in these terms, only that when we do choose to use these conceptualizations, we need to treat them on a par with each other in a non-hierarchical and symmetrical way which traces interaction, rather than prescribing one as the context to the other. As Barnes and Edge carefully point out, neither is there anything profound in the ‘interactive model’. One benefit remains, however. The lack of consensus among analysts on what is ‘science’ and what is ‘technology’ will not prevent agreement on a more basic level, i.e. that science and technology always interact.

From a policy perspective such a conception connects to more recent streams of thought in technology policy that emphasize the communication and interaction between scientists and technologists. From this brief outline of the science policy of nano, however, such interaction is presently only facilitated among a narrow group of actors in different scientific fields. Hence it indicates that science policy, on some general level, is still aligned with the ‘old’ hierarchical model of treating nanoscience as the context of nanotechnology. The question of hierarchies is basically a question of contextualisation.

Social Contextualisation in the History and Sociology of Technology

The rejection of the ‘applied science’ model as a myth is central to the history of technology. Earlier forms of history of technology emphasized the narrow technical knowledge about the internal workings of technical artifacts. It did so without framing or explaining how and why a technology works with reference to a broader social context. This position, called ‘internalism’, has today been abandoned by most historians of science and technology. One reason is that following the logic of internalism, one is bound to embrace technological determinism in one form or another. To the extent that social factors enter as explanatory resources, they do so only to explain technological failures, reducing the role of historical accounts of technology.

This tendency to utilize non-social (and therefore non-historical) factors to explain the birth and development of a new technology became problematic for the development of a history of technology as an analytical endeavor. Unsatisfied with this state of affairs, historians of technology sought to integrate the social context into the analysis of artifacts and analyze how this context shaped and was shaped by artifacts. This line of investigation, termed by Staudenmaier (1985) as ‘contextualism’, has since been the guiding star and mark of a good history of technology.

In an analysis of how historians of technology followed the contextualist theme, Smith and Reber (1989) found that contextual analysis of technology tended to divide into two streams: one that kept the internal workings of artifacts as the main object of investigation, through a focus on technical knowledge in a rather narrow sense, and another of making the social context itself the main object of investigation. By this, technology and its social context tended to become integrated in only two very specific ways. In the first case the social context was added as a kind of background description in which the narrow technical development unfolds. What then is lacking, according to Smith and Reber, are the specific links between this broader social context and the technical details under scrunity. In the second case, the stories told are characterized by the opposite, a lack of technical detail, relegating artifacts and their workings to the periphery of the story. What these two contrasting types of contextualisation have in common is the remaining lack of integration of technology and its social context within the analysis.

A parallel concern was expressed by Trevor Pinch (1996), assessing how one particular form of social contextualisation (termed social constructivism) has managed to provide social contextualisation of aspects of technology that had not earlier been contested or approached with historical analysis. The aim of the social constructivist approach to technical change was to push back, with the ultimately goal of overcoming, the technical determinism that prevails when technology remains as a 'black box'. When looking back on the work conducted under the constructivist banner, Pinch argued that much work did not in practice come to grips with artifacts in this originally conceived 'radical' way, but more often tended to avoid questions of the workability of artifacts (which is very much the same as the second type of contextual contrast found by Smith and Reber). If we believe in the benefits of a *non*-hierarchical model, as argued above, we ought to benefit from an approach that tries to integrate facts and artifacts, science and technology, in one and the same framework and study.

There is one obvious candidate for such an agenda. The suggested research program for the integrated study of facts and artifacts of Trevor Pinch and Wiebe Bijker (1984) aimed at a reversal of the tendency to separate the social study of science and the social study of technology. However, the inertia of established practices and the development of overlapping yet distinct academic communities that saw themselves as students either of science *or* technology, forced this research program to gravitate towards the technology pole. In what is now known as the Social Construction of Technology approach (SCOT), Pinch and Bijker comb the constructivist science studies for methodologies and analogies to be applied to the case of technical change. The integrated study of science and technology, which would satisfy analysts of both technical change and science remains to be carried out.

Tracing the Sub-Cultures Within Science and Technology

So far this discussion has treated science and technology as homogeneous entities or cultures, even though it is noted that in conducting empirical studies, the boundary between the two often gets blurred. Here I move somewhat closer, both to science and technology, with the aim of considering one of the main questions of the present 'nano-discourse', namely the problem of how various scientific disciplines, each relying on different objectives, methodologies, theories and concepts, begin to communicate with each other and form a field of nanoscience and technology in its own right.

From the point of view of science studies, Karin Knorr Cetina (1999) suggests that rather than treating scientific disciplines *per se* as the objects of inquiry, we should use methodologies and concepts that allow us to see the difference in 'epistemic cultures' in science. By expanding the notion of the 'laboratory', as compared to the tradition in laboratory 'bench' studies which tended to focus mainly on scientists and the processes of establishing scientific facts, Knorr Cetina suggests the possibility of instead considering instead how different epistemic cultures function as 'machineries of knowledge', consisting of "entire conjunctions of conventions and devices" (Knorr Cetina 1999, p. 11). Notions introduced by Knorr Cetina for this comparison include, when, how and where scientists use a technology of, 'correspondence', 'intervention', or 'representation' (Knorr Cetina 1999, p. 33).

A related analytical ambition can be found in technology studies. Wiebe E. Bijker, shifts along a parallel axis of analytical focus towards a more aggregated level of analysis, as did Knorr Cetina. Bijker introduces the notion of 'technological frames' to account for how and why a particular local culture, conceives, designs and uses artifacts in a certain way (Bijker 1987, Bijker 1995). A technological frame is composed of the concepts and techniques employed by a particular community for solving technical problems or developing new technology (Bijker 1987, pp. 168ff). It is compatible with the notion of a social group that shares a set of basic meanings attributed to a particular technology or artifact. In this it is not confined to the social groups of engineers or scientists only, but also incorporates other groups such as consumers. The technological frame describes the materiality, concepts, theories, and practices of a local culture, and how these jointly structure the way meaning is attributed by providing a "grammar" for how members of a group interact (Bijker 1987, p. 173).

Bijker's conceptualization of 'technological frames' is, within the context of this study, utilized to legitimize the extension of Knorr Cetina's notion to include what I would like to call the "epistemic culture of technology." I do not consider this a controversial step to take, since technologies have always been present in laboratories. This presence, however, has in 'science studies' typically been treated in a way that sustains a split between historians and sociologists of science and those of technology. The former have tended to focus on theories and concepts, and to relegate technology to the outskirts of science rather than placing technology side-by-side with science.

The validity of extending Knorr Cetina's notion will be measured by the degree to which one can demonstrate that there are boundaries parallel to those of the institutionalized laboratory, or scientific sub-discipline, that encapsulate a certain epistemic culture of technology. Following the discussion above by Barnes and Edge, this can be done by placing all sub-cultures, scientific and technical, on par with each other, and seeking answers as to how all of them interact. In relation to the conceptualization of the interactive model of science and technology, this would be the task of seeking the interactions in a more fine grained analysis of a particular strategic set of sub-cultures within science and technology.

The technological frame argument suggests that we are likely to find many different epistemic cultures of technology. The wider the range of social groups considered, the wider the range of technological frames. It will also depend on various levels of aggregation: national differences, technology branch differences, differences between technologies or artifacts, and differences between or within companies.

The attempt in recent science policy initiatives to create a 'cross-cultural' interaction to allow 'nanotechnology' to grow will thus not only depend on mitigating differences in the epistemic cultures of science, but also those of the involved technologies and industries. Two examples, arguably only tentative ones at this point, are that it is plausible to expect that nanoelectronics will have to accommodate or position itself in relation to the technical culture of the semiconductor industry, and that the development of a technology of nanotubes for hydrogen storage will have to relate to other forms of energy technologies and industries. This means that 'cultural differences' will be important not only for the integration of different epistemic cultures of science, but also for the differences in epistemic cultures of technology. The various epistemic cultures will have to merge in channels of specific technological applications. How can this be both understood and facilitated?

Transgressing Concepts That Attempt to Bridge and Link Sub-Cultures

The notion of 'boundary-objects', as suggested by Star and Griesemer (1989), accounts for how a link can be forged between various and highly differing communities of actors allowing them to cooperate. Star and Griesemer analyze how various heterogeneous groups like amateur naturalists, professional biologists, the general public, philanthropists, conservationists, university administrators, preparators, taxidermists and animals — all representing different social worlds — utilize boundary objects as a way to communicate and collaborate, allowing a natural history research museum to be founded. To qualify as a boundary object, it must in some sense inhibit the multiple social worlds it is supposed to link:

> Boundary objects are objects which are both plastic enough to adapt to local needs and to the constraints of the several parties employing them, yet robust enough to maintain a common identity across sites. The are weakly structured in common use, and become strongly structured in individual-site use. These objects may be abstract or concrete. (Star and Griesemer 1989, p. 393)

One recent example of the application of Star and Greisemer's concept comes from mechanical engineering. Techniques of representation, computation and simulation can exhibit this nexus function of boundary objects, as shown by Henderson (1999) in her analysis of visual representations in mechanical engineering. Here drawings, sketches and models work as boundary objects. Since mechanical engineering is very much a visual culture, such visual representational objects as 'drawings' allow different groups within a company to communicate, cooperate and take action towards a common goal.

Joan Fujimura (1992) argues that this 'plasticity' of boundary objects helps facilitate the coordination and management work across different social worlds, but is less helpful for explaining fact stabilization in science, where one particular actor group's view needs to become stabilized at the expense of those of the other actors. Fujimura situates herself between one more machiavellian (or Latourian) approach focussing on fact making processes, and another which emphasizes collective work (Star and Griesemer). For this purpose Fujimura proposes a notion of 'standardized packages', which is a concept aimed at representing a more confined locus where fact stabilization can occur while still functioning as an interface between different social worlds.

Conclusion

Given the empirical nature of the field of nanotechnology, several traditional issues and themes of science and technology studies need to be addressed. In this chapter it has been suggested that there are several fruitful concepts coming from both science and technology studies that deal with the relevant issues, but also that work remains to be done in merging the two lanes of techno-science studies. Nanotechnology seems to me as one relevant and strategic research site for such an endeavor.

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CHAPTER 7

The Material Culture of Nanotechnology[1]

Hans Fogelberg

Introduction

The material milieu of research and development in nanoscience and technology could be the strategic focus for a social scientific research program on 'nanotechnology'. Interviews with Swedish researchers in nanotechnology programs make it clear that they regard new instruments and methods for studying nanoscale objects and phenomena as essential for the field as a whole. The precise control of fabrication, 'seeing', and characterization is essential for even speaking about 'doing technology' on this scale. Without the advanced material culture of nanotechnology the field would cease to exist or would be pointless by definition. And without progress in this area it is hard to see how it will ever assume the prominent role as the core of future technology that many believe it has the potential to be.

Historical, philosophical and sociological studies of science have focussed on the material cultures of science, in particular of particle or high-energy physics (e.g. Pickering 1984, Traweek 1988, Galison 1997, Knorr Cetina 1999), and biology (e.g. Latour and Woolgar 1979, Latour 1987). But there are, to my knowledge, as of yet no published works on nanotechnology. This chapter outlines what I believe to be relevant to a social-scientific research appropriation of the material culture of nanotechnology. The chapter is organized in the following way. The first section deals with the fabrication and characterization of nanoscale structures. This is meant just to provide a very brief introduction to some of the technologies and methods currently used in nanotechnology. It is by no means a comprehensive or inclusive description of all the varieties of instruments available. There are of course a vast number of scientific and technical textbooks that describe the functioning of these instruments, and such literature would be of interest in a more detailed study. But since we still lack a firm understanding of how these instruments are actually integrated into the practice of nanotechnology, a more relevant and comprehensive overview will have to wait. The purpose here is merely to flesh out the argument that these technologies

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[1] Paper presented at the seminar "The Battle at the Bottom: Making The Most of Feynman's Legacy". VINNOVA, Stockholm, April 19th, 2001.

are at least important for the understanding of current nanotechology, and perhaps also for understanding some of the problems and possibilities associated with the reinvention of these technologies in the context of industrial production.

In the section on models and simulation the situation is similar; there is very little social scientific description available of nanotechnology. Simulation is sometimes mentioned in policy documents and foresight studies but very little has been written on this topic. At the same time there is no difficulty finding scientific papers on this topic, but as argued above, at this point we can merely suggest that such data can be useful in a more detailed study of what nonoexperts actually do with these modeling and simulation tools. Therefore the topics of models and simulation are approached by a discussion of related literature in science studies. Models have long been of interest to historians of science, and in this sense its younger ‘sibling’, computer simulation techniques, are part of a continum of research interest. However, because of its increased importance in many fields of science, it has become a topic of investigation in its own right.

The section on visualization is separate from the first two sections because visualization is an end product of both experiment and simulation (and of theory, through the construction of models that can be visually interpreted and understood). Hence the argument put forward in this section is that the visual culture – as part of an overall material culture of nanotechnology - deserves separate attention. The reasons for this are manifold. One is that the visual aspect are under-researched in science studies (while perhaps less so in technology studies, see e.g. work of Ferguson 1992, and Henderson 1999). Another reason is that images are used when different groups need to communicate, and images can function as a ‘wordless’ language that facilitates this communication. The question whether this role is relevant only to the ‘laboratory-bench’ work, or if it also has some relevance outside of the normal scientific context, is one important topic to explore. Because if the latter is true, it might be the case that visualization is a crucial activity for mediating the interaction between abstract science and the public.

Fabrication and Characterisation

From interviews with nanotechnologists and from the tracing of a nanoscience discourse in the literature it becomes clear that the experts of nanoscience regard their instruments in the nanolaboratory as highly important for any form of scientific endeavor at the nanoscale:

> [t]o work in nanoscience, it is a prerequisite to be able to fabricate and characterize nanostructures: to make rabbit stew, one must first catch a rabbit. (IWGN Workshop 1999, p. 7)

The following section tries to give a short-hand impression of the role of instruments in the material culture of nanotechnology, focussing on what it takes in terms of instruments to "catch a rabbit" in nanotechnology.

Current work in fabrication aims at developing:

> [m]ore reliable means of controlling nanostructure size and placement, with an end view of being able to scale up the production of such materials while maintaining the control over the nanostructure (IWGN Panel 1999, p. 19).

To this end there are many different techniques relevant to the fabrication of nanostructures, but here only the most common ones in the literature will be touched upon. In fabrication of nanostructures one typically differentiates between "top-down" vs. "bottom-up" approaches. In the top down approach the idea is to 'sculpt' a nanostructure using bulk material as a starting point. Obvious technologies are various forms of lithography and etching techniques, which is both an extension, but more importantly, a reinvention of the technique familiar to the semiconductor industry. Another method in the top-down tradition is mechanical attrition, described as 'ball-milling', producing nanoscale building blocks which can be assembled into new bulk materia. In the bottom-up approach one assembles a nanostructure using nano-sized building blocks. Relevant techniques here are chemical synthesis, powder and aerosol compaction, and perhaps in the future, various forms of bio-related techniques. One typically differentiates between fabricating the basic building blocks of nanocomponents (by which one need to control their size and composition), and constructing materials using such components (by which one need to control their interfaces and distribution) (WTEC Panel 1999).

It is clear that (so far) physics has had a leading role in nanotechnology, and in fabrication as well. Of particular relevance here is the extension, or perhaps we should say the "reinvention" of the lithography technique of the semiconductor industry, to now allow the fabrication and control of structures at the nanoscale dimension. Nanolithography, as this area is sometimes called, includes a whole class of techniques. It also typically includes special facilities exhibiting clean or ultra-clean milieus. Another stream of techniques for fabrication seems to originate more from chemistry, including various technologies for synthesis (as e.g. the vapor deposition technique for the production of carbon fullerenes). To take the step from 'fabrication' to 'manufacturing' is by no means something that will come easily. This is one important point at which 'bio-nano' is expected to make a difference. Nanobiology holds, on the one hand the promise of providing new and more refined tools for the advancement of biotechnology, whereas on the other hand the 'biogenic' strategies may be an effective way to produce nanostructures *en masse.*

Microscope technology is essential to the characterization of nanostructures. Relevant to nanotechnology is the common distinction between ‘probe’ vs. ‘optical’ microscopes, or more precisely, between Scanning Probe Microscopes and Nanoscale-Resolution Optical Microscopes. Important examples of the probe microscope class are the Scanning Tunneling Microscope (STM) and the Atomic Force Microscope (AFM). Important optical microscopes are High-Resolution versions of the Transmission Electron Microscope (TEM) and the Scanning Electron Microscope (SEM).

The material culture associated with these instruments is characterized by much criss-crossing between instruments and practices. For example, the probe microscope can both visualize and manipulate. The manipulation capability of probe microscopes has been combined with the high-resolution optical microscope, producing an integrated fabrication tool. And probe microscopes have been used as tools for fabrication in lithography (Wolde 1998). In sum, the material culture of nanotechnology is characterized by a rapid development of new instruments and new combinations of earlier instruments.

Hence, while there is a clear ‘logic’ dividing line between fabrication and characterization, a less clear-cut picture emerges when we take the instruments of nanotechnology as our point of departure. Several of the important instruments actually work as tools for both fabrication and characterization. Not only can one instrument exhibit such ‘reversible’ features that make it useful for both, but two or more instruments are sometimes combined and built together. Several of these instruments are produced on a commercial and industrial basis, but there are also indications that one important aspect of the material culture of nanotechnology is the ability to build (tinker with, or modify) or in other ways improve or specialize the instruments on one’s own. Such alterations of instruments for more advanced fabrication and characterization should be seen as part of the dynamics of the field. In this vein, it has been suggested that the advancements in nanotechnology come from a process in which fabrication, characterization, and theoretical understanding, are linked together in a cyclical way, by which improvements in one area facilitate and stimulate advancements in the other (WTEC Panel 1999, p. 18)[2].

Models and Simulations

Modeling, computer simulation and the use of computer graphics are commonplace in contemporary science.[3] The trend is that the

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[2] Note that this view of Evelyn Hu accords with that of Galison (1997). A remaining difference, however, is that in Galison’s model the stepwise advancement in theory, experiment, and instrumentation, need not occur in a repetitive cycle but can be more random.

[3] Its increased relevance to industry has also been reported upon, especially for drug discovery, homogeneous catalysis, computational thermochemistry and semiconductor bandgap engineering (see home page of the NSF funded international technology monitoring program at www.itri.loyola.edu).

importance of such tools increases over time. If this might be a general trend in science, it seems particularly true for nanotechnology. The reason has to do with phenomena which are not well understood due to their complexity:

> A critical issue for nanotechnology is that the components, structures, and systems are in a size regime about whose fundamental behavior we have little understanding. The particles are too small for direct measurement, too large to be described by current rigorous first principle theoretical and computational methods, exhibit too many fluctuations to be treated monolithically in time and space, and are too few to be described by a statistical ensemble (IWGN Workshop 1999, p. 17).

It is here that modeling and simulation provide guidance for both theoretical work and experimentation:

> [the] critical challenge in developing successful nanoscale technology is development of reliable simulation tools to guide the design, synthesis, monitoring, and testing of the nanoscale systems. This is critical for nanotechnology because we cannot "see" the consequences of experiments at the nanoscale. (WTEC Workshop 1997, Ch. 9, Section "Nanoscale Theory and Simulation")

The making of functional devices will require a vast number of tests on structures. These tests would be much more effectively conducted in an artificial setting, since the "[o]ptimization of nanoscale materials or devices will require exploration of thousands of design alternatives prior to synthesis." (IWGN Workshop 1999, p. 18). Here, the use of simulation tools is expected to vastly reduce the number of possible structures suitable for further exploration and manufacturing. However, increasing the importance of simulation in nanotechnology requires several other improvements, such as:

> [a] better basic understanding of the connection between structure and properties at the mesoscale… new algorithms to carry out calculations of mesoscale phenomena... [and] improved ways to communicate mesoscale information in appropriate graphical representations where the relevant elements for designing new systems can be visualized and manipulated. (WTEC Workshop 1997, Ch. 9, Section "Nanoscale Theory and Simulation")

In practice, such simulation work encompasses a wide range of approaches and methodologies that differ in terms of the time scale of interest, the length scale of interest, and properties of interest:

> Among the methodologies, we note particularly those based on classical and quantum molecular dynamics (MD) simulations, where the appropriate (atomistic) equations of motion for a system of interacting particles are integrated, and the resulting phase-space trajectories are analyzed (numerically as well as in animated form). In classical MD

> simulations the interatomic interaction potentials are constructed using semi-empirical data and/or fitting to quantum-chemical calculations. More recently first-principles molecular dynamics (FPMD) methods have been implemented, where the interactions are evaluated concurrently with the atomic motions through self-consistent solution of the many-electron Schrödinger equation. Such FPMD techniques extend our capabilities to investigate systems and phenomena involving electronic rearrangements and chemical transformations, as well as allowing studies of electronic spectral and transport properties. Other simulation methodologies include classical and quantum Monte Carlo techniques and methods for structural optimization (simulated annealing and genetic algorithms). (WTEC Workshop 1997, Ch. 9, Section "Simulations and Modeling for the Nanoscale")

Examples of areas in nanotechnology where modeling and simulation have been used include lubrication, electric and mechanical properties of carbon nanotubes, quantum dots and their electrical connection, kinetic aspects of DNA, and electrical properties of polymers (IWGN Workshop 1999, pp. 21-30).

Moving now from the characterizations of nano-experts, towards the social-scientific appropriation of this work, there is some relevant literature to consider. Recent work in the philosophy and sociology of science on theoretical models and computer simulations (henceforth models and simulations), places models and simulations in the position of being much more important and interesting than envisioned by many previous accounts. The traditional view of models as mere 'simplified' theory is rejected because it tends to underestimate the much more proactive role they play in contemporary science. This is put forward in two recent contributions, one philosophically oriented anthology *Models as Mediators*, edited by Morgan and Morrison, and one sociologically oriented special issue of Science in Context, "Modeling and Simulation," edited by Sismondo and Gissis. While the philosophical contributions tend to focus on models, and the sociological accounts on simulation, both argue that models and simulations can no longer be seen as subordinate to 'theory' and 'data' in the production of new scientific knowledge, but have to be approached as a topic of investigation worth attention in its own right (Morgan and Morrison 1999, p. 36).

A central thought is that models and simulations are part of theory and the world, yet remain partly independent of both. A 'classic' example of what it means to have a model is the case of the 'mathematics' pendulum. The pendulum model links to theory via Newtonian force laws (which in themselves say nothing about pendulum motion), and links to the 'world' by representing a visually analogous (however idealized) case of a physical pendulum (Morgan and Morrison 1999). This partial dependence and independence is also their source of strength; they are the "monsters necessary to mediate between worlds that cannot stand on their own, or that are unmanageable." (Sismondo

1999, p. 258). This partial independence creates a space for learning: for learning more about the model, its underlying theory, and the world. It is this strange partial dependence and partial autonomy that make them useful for exploration in both theory and data. They can at times be used as black-boxed entities, allowing for interaction in very much the same way as with technology or instruments. It is this feature that makes simulation occasionally resemble experimentation. This does not mean that scientists generally believe that what is in the computer is analogous to nature. The point is that interacting with a simulation as if this were so, allows for an explorative mode of knowledge production.

This ability to mediate and relate to theory and experimentation makes it particularly interesting as a facilitator for communication and interaction between groups of scientists. It can under certain circumstances create a quite substantial platform for communication between diverse scientific disciplines (e.g. chemistry, physics, mathematics, engineering) and between scientists from different epistemic cultures (e.g. theorists, experimentalists, and instrumentation experts). The establishment of such temporal but sometimes also longer-lasting platforms of communication, or 'trading zones', in which scientists and engineers meet is the focus of *Image and Logic,* Peter Galison's extraordinarily rich history of the material culture of microphysics (Galison 1997).

One large section of this book deals with the history of the "Monte Carlo" simulation technique (pp. 689-776). Galison describes how this simulation technique was initially developed after WWII for the work on the thermonuclear bomb, for which experimentation appeared impossible. He describes the history of a technique that now has become part of the everyday practice of physics. The Monte Carlo work was facilitated and carried out in a context of extensive mixing of different scientific disciplines, which was a new form of task-oriented collaborative tradition that developed in the U.S. during WWII (p. 775). In such collaborative trading zones local trading languages and practices develop that build on a local agreement on meaning, 'agreements' which may not necessarily hold outside that specific context. A metaphysical dimension of the Monte Carlo simulation was that it linked the world in a specific way. Not only could simulations be used for the numerical solution of equations (which have no known analytical solution), but the Monte Carlo simulation itself had an unexpected similarity relationship with the world of atoms and particles. There was:

> a purportedly fundamental affinity between the Monte Carlo and the statistical underpinnings of the world itself. In other words, because both Monte Carlo and nature were stochastic, the method could offer a glimpse of a reality previously hidden to the analytically minded mathematician. (p. 739)

The historical interest in models points to, on the one hand, the relation between theory and models, and on the other hand, the relation between models and the world. While computer simulations are in some strictly logical sense merely the application of a model, recent studies of science tend to assign them a much more proactive and interesting role. The peculiarly in-between status of models, which relate to both theory and the world while preserving some form of autonomy, seems to become even more interesting in the case of simulations. The degree of 'artefactual' status, so to speak, increases when we move from models to simulations. In conclusion, then, it seems that an interesting topic for further research is the question of how the tools and practices of simulation relate to the production of new scientific knowledge.

Visual Representations

The use of visual argument in contemporary scientific practice is so common that we do not reflect on the fact that there is nothing inevitable in this, or the fact that our particular way of using images in science may depend on a more general visual practice of a culture and time (Kemp 1997, p. 362). Kemp distinguishes between two forms of images: those directly associated with the subject matter of scientific investigation (see app., image 3, 4, 5, 6), and those more related to the pursuit of science (image 1, 2, 5). He identifies both continuity and discontinuity in visual practice. The use of perspective images and observational points has been practiced since the fifteenth century, while new representational practices have emerged around the need to visualize n-dimensional 'objects'. Another difference is that advanced microscopes seldom use the visible spectrum of light. What is conveyed is, in that sense, nothing visible; what we see are 'shadows' or interference patterns. Probe 'microscopes', when scanning a surface, produce data that can be processed so as to provide an image of a phenomena. Hence, 'seeing' is to be understood as something highly mediated.

There is also another aspect of the probe microscope that can become an interesting subject of further study. Using a scanning tunneling microscope to visualize atoms of conducting matter, scientists manipulate the images by processing the numerical data in the computer and using software for its visualization. In for example the Transmission Electron Microscope:

> raw data contain combined information on the sample filtered by the microscope itself. The information on the sample can only be retrieved by suitable interpretation and retrieval techniques. Useful image interpretation requires numerical image processing and computer simulation of the images, using the dynamic *theory* of electron diffraction and *experience* with crystallographic aspects that can give rise to special effects on images and diffraction patterns. (Wolde 1999, p. 187, emphasis added).

Scientists build the structures they then visualize. Manipulation (and mediation) goes all the way from a beautiful image of a corral of atoms with electron 'standing waves' within the corral (see app, image 3), down to the very building of that corral in the first place. There is a kind of 'blurred' boundary where seeing meets manipulation.

The philosopher of science, Ian Hacking, rightly asks: "Why do we believe the pictures we construct using a microscope?" Pointing to the fact that the visual display of microscopy has a remarkable history of robustness, and immunity to changes in theory, he argues that this should be seen against a background of experimental practice of microscopy, which has a long history of using 'non-theory' approaches to differentiate artifacts produced by the microscopy from the real thing (Hacking 1983, p. 200). As I understand it, what Hacking means by the 'real thing' is that which we see in the microscope, and which we can confirm to exist by reproducing the same structure with other types of microscopes (p. 208).

Hacking gives an example of how scientists can – on the basis of a theoretical understanding of the scientific content of an image - use even highly counter-intuitive methods of visualization. In his example from crystallography, researchers look at images of crystal using both our (everyday) perceptual space conception, but also a quite different 'reciprocal space', in which "near is far and far is near" (Hacking 1983, p. 207). This may be an example of what Galison means by working with 'controllable images'. Galison argues that the century-old ideal of objectivity, presumably embodied in the chemical photograph, is today complemented by the manipulated image, which is seen to provide no less evidence (Galison 1997, p. 810). Scientists decipher the images by a familiarity with the intentions of a particular image. But the manipulated image is by this no less valuable and no less 'true'. Quite the opposite. The images that has been manipulated through 'filtering', or coloring, works perfectly well in scientific publication. This means that saying that something is 'mediated' or 'manipulated' should not be understood as an argument against it being 'real'.

Visualization is also relevant to different contexts. Consider the fact that modeling, simulation and visualization are carried out in a local scientific context, aimed at communicating very specific scientific content. Results generated within this narrow context are then typically confronted by a wider scientific community. Here, scientists use images in articles, posters, and in other forms of presentation to communicate with a broader (and more heterogeneous) scientific community. In regarding this step it is valuable to think of the images as representations for which it is allowed to use particular forms of manipulation by computer graphical techniques. A third form of context in which images appear are when used as graphic representations in a public context, as 'icons' of nanotechnology.

This means that the 'model-simulation-visualisation' practice of the local context, scatters in specific ways into new contexts, representing not precisely the same thing, but neither something totally different from that of its original content. As the 'model-simulation-visualization' assemblage move into a public discourse, theoretical simulation considerations move into the background, leaving the images as icons in the front. With an integrated framework we need not change our register as we move out of the local scientific context to consider also the public representations. In other words, if 'art' matters in the public context, it also does so in the narrow scientific context. If an epistemological perspective is relevant for the narrow scientific context, it is also so for the broader public context.

While there are no sharp lines to be drawn, it has nevertheless here been suggested that the philosophy of science emphasizes models whereas the sociology of science emphasizes simulations. Common to both the philosophy and the sociology of science, however, is that they make fairly modest inroads into the field of visual practices of science. Interest so far have been part of a focus on instrumentation and experimental practices, but these do not seem to have drawn much on insights gained in e.g. cultural studies of media or art. This is only mentioned here as an indication that the available tools for studying visual representations in science may be much richer than originally conceived. However, this is as far as I shall go here, wishing to merely indicate that a larger study should consider making use of these tools as well. Here I remain aligned with the 'tradition' of science studies, but add a theme from technology studies, which is a field more rooted in and familiar with analyzing highly heterogeneous situations.

Henderson (1999) addresses visual representations and their ability to facilitate communication among engineers in a case study on the use of computer-graphics techniques in American high-tech engineering. She shows how computerized drafting technologies (CAD) facilitate and link tacit and non-formal knowledge with formal knowledge in the development of new technical artifacts. However, her study does not include the uses of computers for the calculation, simulation, and subsequent visualization of such calculations. In this area of engineering work, computers and computer graphics are used for the simulation and visualization of static or dynamic processes in the artifacts or technical systems to be designed (using e.g. finite element methods to visualize static or dynamic stress, strain or heat transfer). There is reason to believe that, while simulations conducted in an engineering context may not be the same, neither are they something completely different than those in use in science. It seems plausible to argue that what Henderson found in engineering design — that visual images facilitate an apprehension of the already known and the yet-to-be-made-explicit knowledge — is an insight worth taking seriously in a study of nanoscience and technology.

Questions for Further Research

To summarize, while there seems to be a solid belief among scientists that the very existence of nanotechnology relies on its instruments, and especially its tools for visualization, these aspects that relate to the 'material culture' of nanotechnology remain novel to the academics of science studies and technology studies. In this basic sense, one could draw the conclusion that any study of the material culture of this new technical paradigm of nanotechnology will be relevant and worthwhile. However, since there is a large degree of reflexive awareness among active scientists, and since e.g. scientific visualization has now even been institutionalized in Sweden through a professorship, and has for many years been part of a science-art axis of collaboration, I believe it beneficial to relate to and communicate with these activities during a study.

Research topics can be divided into three areas of focus: The first is the local context of science, in which the main research question is how do models, simulation, and visualization form a part of the local context of nanoscience? The second relates more to the broader scientific and technical context. How is this knowledge translated into the context of a broader scientific (and techno-scientific) community? The third topic relates to the public context. How are the findings communicated to the public and policymakers?

Appendix: Examples of Visualization of Nanotechnology

(Images are adopted from IWGN Workshop 1999, and its subsequent 'outreach' folder)

Image 1: Public Outreach

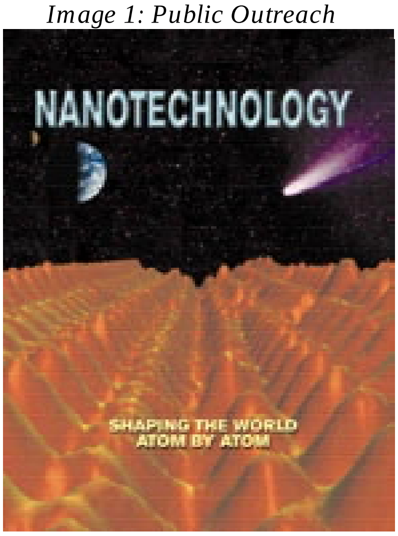


Image 2: Context of Nanoscience

www.stanford.edu/
group/quate_group/

Image 3:Content of Nanotechnology: Quantum Corral

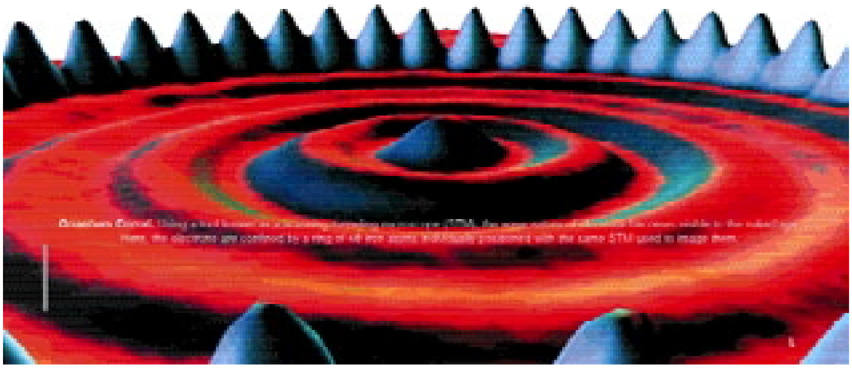
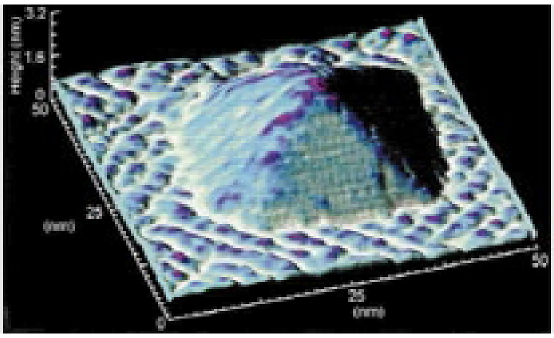


Image 4: Content of Nanoscience



Modern Pyramids. This nanoscale pyramid of germanium atoms—one kind of quantum dot—formed spontaneously atop a ground of silicon. It could help researchers develop new generations of tinier electronic devices that are governed by quantum phenomena.

Image 5: Linking Content with Context

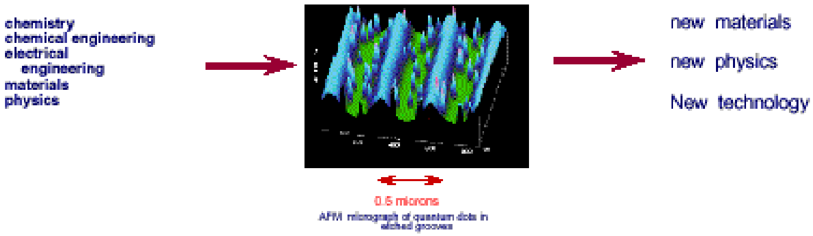


Figure 11.6. Science and technology at the atomic level.

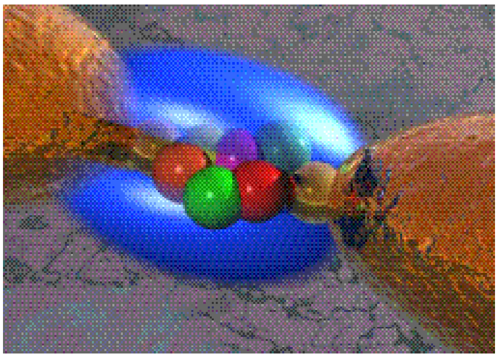


Figure 4.10. A single molecule bridging the gap between two metallic contacts, forming the smallest and ultimate limit of an electronic device (©1999 Mark Reed; all rights reserved).

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CHAPTER 8

Challenging Limits – Excerpts from an Emerging Ethnography of Nano Physicists[1]

Hans Glimell

> Behind the felt coherence, continuity, and strength of physics lies immense heterogeneity... .against our first intuitions it is precisely the disunification of science that brings strength and stability.[2]

The General Setting: A Culture of Multiple Epistemologies

The cited claim comes from a widely recognized study by the historian of science Peter Galison. My own subject matter, ambition and level of observation are quite different from his. Whereas he covered steps taken and subareas developed during the entire evolution of modern physics[3], most of my claims are rooted in an initial set of observations of the everyday practice ('culture'[4]) of only 15-20 physicists. But, of course, Galison would not be in my story at all unless there were certain analogies between his grand entity of investigation (the global physics community), and my very limited one (a small university group). These concern his basic assertion of 'disunification' as being compatible with, and even a prerequisite for a strong professional community, as well as the role he ascribes to interlanguages or '*pidgins*' in sustaining it. Also, in my account of a disparate group struggling to survive in the predicament of *competitive dynamics*, the idea of pidgins paving the way for a

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[1] Earlier published in Glimell, Hans and Oskar Juhlin (eds.), *The Social Production of Technology – On the everyday life with things*, BAS Publisher, Göteborg 2001.

[2] Galison, Peter: *Image and Logic. A Material Culture of Microphysics.* Chicago Univ. Press, 1997:p.780-781.

[3] The focus is on the fundamental role of <u>instruments and instrument building</u> for making physics the influential discipline we know today. In an earlier book, *How Experiments End* (1987), the focus was on the importance and changing meaning of <u>experimentation</u> within physics. At present, Galison is finalizing his comprehensive work with a third volume, focusing on how '<u>theory</u>' and 'theorizing' has developed throughout the history of physics.

[4] 'Culture' is used in the sense suggested by Schneider&Geertz: "a group's shared set of meaning, its implicit and explicit messages, encoded in social action, about how to interpret experience". An ethnography is a method by which culture in this sense can be studied.

cohesive heterogeneity, emerges as an interesting line of further investigation.

The field of science which is the subject of this ethnography in the making, is condensed materia physics (solid state physics). Although it demarcates itself from other subfields (e.g. Atomic Physics, Astrophysics and Reactor Physics) by a number of unifying traits, it at the same time contains several specialties comprising different epistemic cultures[5]. Its practitioners frequently talk of each other as being primarily 'theoreticians', 'experimentalists' or 'computation physicists'. Still others are addressed as 'microscopists', some having a background in engineering or chemistry, who have gradually been recruited as physicists after 'tuning' their instruments to the study of those materials representing the hot spots of the area. What matters here are the properties of 'the surface of the surface', at the point or layer farthest out, i.e. on the atomic or molecular level which our present knowledge points out as the bottom line of our understanding of Nature. One then operates at the *nano*meter scale, now increasingly used in policy for labelling purposes.

The ethnography[6] reports on how a group of nano physicists organize and represent themselves to cope with a never-ending transition or 'flux', where the making of identity seems to violate as much as obey institutional bonds and affiliations. In addition, it is about doing science in the realms where our ability to visualize Nature reaches its limit. The pattern emerging is one where the material culture as well as the micro-politics of the nano physicists observed, evolve around objects capable of accomodating unity while 'disguising' disunity, providing for protection *and* productivity:

> Boundary objects are objects which are both plastic enough to adapt to local needs and to the constraints of the several parties employing them, yet robust enough to maintain a common identity across sites. They are

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[5] Knorr-Cetina, Karin: *Epistemic Cultures: How the Sciences Make Knowledge*. Harvard University Press, 1999.

[6] In her widely recognized study *Beamtimes and Lifetimes. The World of High Energy Physicists* (Harvard Univ. Press, 1988), Sharon Traweek suggests that a full-fledged ethnography should cover four domains of a community's (groups') life: 1. ecology: its means of subsistence; the environment that supports it; the tools and other artefacts used in getting a living from that environment; 2. social organization: how it structures itself (formally and informally) to do work, to maintain and resolve conflicts, to exchange goods and information; 3. the development cycle: how it transmits to novices the skills, values, and knowledge that constitute a sensible, competent person; identifying the stages of life and the characteristic attributes of a person in each of those stages; 4. cosmology: its system of knowledge, skills, and beliefs, what is valued and what is denigrated. (Pages 7-8)

weakly structured in common use, and become strongly structured in individual-site use. These objects may be abstract or concrete.[7]

Expressed differently: facing never-ending transitions and disunity as sources of collective strength (cf the opening quotation) is living in a state of *liminality*[8]. Although not theoretically elaborated in this chapter, the co-production of science and boundary objects in ”living liminality”, dictates the agenda for this ethnographically informed investigation.

The work is still in its infancy. The bulk of the material is interviews, supplemented with a limited amount of observation of the physicists’ work at their computers[9] and in their laboratories. Most of the group members have been interviewed, some more than once. The groups’ self presentation is thus at this stage a crucial concern of the study. [10] It will remain so, although the relative weight attached to interview statements is likely to shrink as the project proceeds. Paying much attention to them in no way means that I take them as ‘true facts’ or givens. Finally, I have included here some conceptual and contextual discussions. Reflecting the project’s explorative stage, they merely serve as hints as to the scope of the entire study envisioned.

‘Moore’ of the Same vs Breaking New Ground

Success often comes along with worriy about how to sustain that success. Let us consider here the case of the microelectronics community – a celebrated ensemble of scientists, electrical engineers, policy makers, high-tech firms and low-paid labour, whose industrial success in the last decades defies every comparison. For that community, the idea of sustaining success is intimately linked with the ‘technological trajectory of miniaturization’ once mapped out as a Law by Gordon Moore[11]. At

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[7] Star, Susan Leigh and Griesemer: ”Institutional Ecology, ’Translations’ and Boundary Objects”. In *Social Studies of Science*, Vol. 19, 1989, pp387-420.

[8] A state of ”betwixt and between” the separation from one social position to the incorporation into a new one. Liminality is characterized by ambiguity in which people are neither fully one nor the other, but yet, in a way, are both. Source: Turner, V.W.: *The Ritual Process: Structure and Anti-structure*, 1969.

[9] The physics work traditionally called experimental, is now for several reasons increasingly being carried out at the desk through simulations and visualizations by powerful computers; ”doing spectroscopy with the computer”.

[10] I have no ambitions in this specific paper to explicitly relate my work and ethnography to the ‘laboratory studies tradition’ (e.g. its discussion on ethno-methodology) as developed within the SSK and STS academic communities by Karin Knorr-Cetina, Bruno Latour, Andrew Pickering, Michael Lynch and many others. (See chapter 1.)

[11] Already in 1965, the Intel engineer Gordon Moore observed that the computer memory performance seemed to double every 18-24 months. He predicted that this growth rate would continue for a long time. So far he has been proved to be right; the impressive and amazingly steady speed of downsizing (from 1971 to 1997, the number of transistors on a chip increased

any price, its axiomatic agenda announces, we must maintain our extraordinary rate of downsizing, i.e. continue to increase the number of electronic functions we can squeeze into one unit of semi-conductor material.

Two things deeply worry those under the spell of that Law. In the words of the traditional linear model of innovation, the first points 'backward', to the basic research thought of as founding the whole endeavour, to Nature itself. Hence, with further miniturization, materials will no longer behave as bulk materials, but as discrete atoms and molecules. For example, transistors built on nano technology may act unpredictably and queerly when the jumping of single electrons ('tunneling') and other quantum mechanical effects come into play . Advanced devices like computers here run the risk of being robust enough to satisfy high professional and commercial standards. The second worry plaguing the micro regime instead points forwards in the postulated R&D sequence, towards the expected manufacturing costs of operating on the nano scale. With the present technology, these costs will skyrocket, posing a mortal threat to this 'milch-cow' of today's market place.

This is, of course, exactly why 'nano heroes' are urgently required. The Greek word 'nano' means dwarf. In engineering and scientific circles the word attributes to materials or devices a fixed degree of smallness, equivalent to a specific range in the arithmetic system[12]. Although sharing the worries, many scientists in physics and electrical engineering who dedicate themselves to the invention and demonstration of new electronic properties, consider the move into nano as a challenge. By learning more about quantum effects and 'domesticating' them for the development of a new generation of computers, they try to come up with solutions where others see problems. If their efforts succeed, a gigantic leap could be made in information storage and computational power. A nanometer scale electronic 'transistor' may e.g. end up 100,000 times smaller than the present technology. However soon to appear in the near future (some

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more than 3200 times) has become known as 'Moore´s Law'. Even small things have a price though: a less known law, 'Rock´s Law', provides the addendum that the capital equipment costs for building semiconductors double every four years. (Source: http:www.intel.com/intel/museum/25anniv/hof/moore.htm)

[12] Divide one meter by thousand and you get a millimetre [1mm]. Divide that millimetre by thousand once more, then you have a micrometer [1µm]; the precision with which one today can mass-produce metal artefacts. Then take that one micron, and divide it yet again by thousand. You now have ended up on *the nanometer* [1nm, 10^{-9}m], the dimension of molecules and atoms. At our present state of knowledge, this is the smallest scale on which one can 'build' things, i.e. 'the bottom line' for any prospect of technology. Nanotechnology, finally, is the manipulation, fabrication and measurement in the range of a nanometer, defined as between 0.1-100 nm.

are here already), are micro/nano hybrids in transistors, as a first step towards a pure nanotechnology.

Now, there are almost as many approaches as there are researchers in the area on how to approach 'the nano', i.e. how one should relate to the present state-of-the-art on the one hand, and to the notoriously unknown future on the other. Here these are reduced to just three positions, vis-à-vis which the ethnographical data could be read. Two of them basically remain anchored in the described technological trajectory, determined as they both are to prolong the validity of Moore´s Law, whereas the third starts from completely different premises. The difference concerns cognitive and epistemological matters, as well as how actors profile themselves (the appropriate choice of media, partners, codes of conduct). The former two attach themselves to 'the respectable mainstream', holding the third at a good distance. Recognizing this, I label them 'reformists' and 'visionaries'[13].

Within the reformist wing, there is one conservative and one liberal faction. 'Conservative' may seem like an odd designation for 'reformist', but it stands for those having designed their scientific programme by extending the engineering and industrial skills established today. The dominant process technology in the area, CMOS (complementary metal-oxide semiconductor), provides for them the obvious point of departure, and will remain so for the foreseeable future. Even those composing the liberal fraction, accept pushing CMOS towards the quantum limits. At the same time, however, they see it as their obligation to explore other more radical options. Some science must, they claim, be 10 years ahead, while proudly mixing applied and basic research.[14]

The scientists studied position themselves as 'liberals'. They often compete with conservatives, financially as well as in other ways, whereas the third category – the visionaries – are of no daily concern for them. In spite of their denomination, the liberals sense a lot of pressure. On the one hand they are dependent on the microelectronics industry, not the least for the credentials needed to become funded by the research councils where industry greatly influences priorities. Yet their relations to industry cannot be clear-cut or relaxed, as they on the other hand need some leeway to take on problems which do not 'pay off' in the short run. To become consistently visionary is not an option for

[13] According to my dictionary, the word 'visionary' has three denotations/synonyms: clear-sighted, unrealistic, and fanciful. In my appropriation of the term here, I want to keep all of these as 'open, coexisting possibilities'.

[14] As one of my informants pointed out, this distinction could be compared with the situation concerning cars. Thus, there are those who persistently stick to the internal combustion engine as *the* car technology (cf 'the conservatives'), whereas others (cf 'the liberals') at the same time conduct research on alternative concepts like fuel cell vehicles or hybrid technologies. A third fraction, the radical reformists, solely do the latter, without paying any attention whatsoever to the hegemony of combustion (cf CMOS when it comes to microelectronics).

them, neither is being harnessed by the conservative mainstream, which leaves them trying to serve two masters without being able to please either of them fully. When, as the excerpts below will suggest, it appears as if the *social* relations of the studied group can be read pretty much like reading a ’chip’ – i.e. as configured by a highly dense space demanding subtle moves and manipulations – this general predicament comes to mind.[15]

In an earlier paper[16], the nano visionaries were put in focus. Despite their absence in the group now under study, even a slight acquaintance with them may add an extra dimension to the reading of the ethnographical data, highlighting what the liberals, after all, do not do, and would not even consider doing.

The visionaries frankly invert the common understanding of the reformists by proclaiming that it is not in fact ‘crowded’ or chaotic at the minature levels of matter. It just looks that way, as long as one employs the top-down perspective that so far has steered the very idea of engineering. Liberating themselves from that, the spokesmen of this fraction assure us that there in fact is plenty of room ”at the bottom”; an argument authoritatively stated as early as in 1959:

> The principles of physics, as far as I can see, do not speak against the possibility of maneuvering things atom by atom...Ultimately, we can do chemical synthesis...How? Put the atoms down where the chemist says, and so you make the substance.[17]

Framed this way, engineering should start from the bottom and work itself ‘upward’. That indeed is a breath-taking idea. It implies nothing less than that ‘engineering man’ would be able to replicate nature itself, becoming as clever in monitoring molecular ’machines’ as the ordinary tree which so peacefully and cleanly processes carbon dioxide and water into oxygen and molecular building blocks. He would learn how to perform this delicate act in a fully pre-planned manner, at the pace and scale of his choice. Here, ‘nano’ becomes a password for entering a brand new era; an era when a sustainable, precise production process replaces the present ”patchwork of crude chemistry and crude

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[15] In an interview made in another project concerning the situation for nanoscale solid-state physics, the metaphor ”…we basically have to maneuvre in the cracks of the Silicon Wall”, was presented to me.

[16] Fogelberg, H.&Glimell, H.: ”Molecular Matters: In Search of The Real Stuff”. A paper presented at the workshop ”Industriell och Teknisk Utveckling”, the Royal Institute of Technology, Nov 26-28, 1997. Available as ”Working Paper, 98-1”, The Section for Science and Technology Studies, Göteborg University.

[17] Quoted from the speech ”There’s Plenty of Room at the Bottom” given by the Nobel Prize Winner physicist Richard Feynman, at CalTech in 1959, introducing the idea of atomic precise construction.

machines"[18] (so much for the pride once attached to the industrial revolution).

The road envisaged here is one of a close collaboration and mutual learning between people in the molecular sciences (such as materials physics, surface chemistry and molecular biology) and those in engineering. The traditions of examining nature in its smallest realms would be merged with those of design and manufacturing. Instead of miniaturizing, one would here do the opposite:

> From today´s viewpoint, molecular nanotechnology looks more like an extension of chemistry than like an extension of miniaturization. A mechanical engineer, looking at nanotechnology, might ask, 'How can machines be made so small?'. A chemist, though, would ask. 'How can molecules be made so large?'. The chemist has the better question. Nanotechnology isn't primarily about miniaturizing machines, but about extending precise control of molecular structure to larger and larger scales. Nanotechnology is about making (precise) things *big.*[19]

The visionaries boldly mix the manufacturable (the domain of engineering and much of applied science), the possible (the domain of basic science), and the almost unthinkable (the domain of Science Fiction). They drasticly expose the utmost potential of the field, outlining lots of absolutely amazing applications. They do not hesitate to evoke enthusiasm by exploiting extremes or excesses.

Nano reformists would typically feel uncomfortable about this. They consider it a virtue to keep their feelings calm, to stick to the 'safe middle'[20], and to avoid speculation. The reformists do not promise new worlds propelled by new technological and industrial regimes; rather they want to be creative and revolutionary within the one we know, with its given rules of the game.

Coping with Cutting-Edge Competition: An Account of a Nano Research Group in Action

The Future On Fire

One afternoon in the spring of 1998 the electrical engineer Alex rushed to a window of the Silicon Technology Laboratory, where he was technical manager. With alarm, he there noted a rapidly spreading

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[18] This characterization originates from Eric Drexler, a dedicated and controversial proponent of nanotechnology.

[19] Ibid, p.76-77.

[20] I am talking here about conducts of behaviour or social codes. What one does in the research process is presumably different as the conservative motto "stick to the safe middle' probably doesn't takes you very long there. Cf Sharon Traweek's observation in her study of physicists: "You should act British, but think Yiddish!"

column of smoke rising from a nearby construction site. That site had recently been taken over by the Chalmers Institute of Technology (CIT) in Göteborg. It had housed a well-known hospital for rehabilitation of elderly people.

Normally, this event would not have been a cause for alarm, especially with the reassuring reports soon to come that no one had been hurt and that the building, so far only consisting of reinforced concrete, was only slightly damaged. Of course Alex could not know this as he stood by the window, but from his professional background he knew something else; he knew that there was a very special dimension to this fire, and a deeply worrying one. Thus the smoke as he saw it, could pose a severe threat to the successful completion of the interior yet to take shape: the much-awaited ChaMEL (Chalmers Micro Electronics Laboratory), scheduled to start in May 2000.[21]

This laboratory is to become the core of a new Microelectronics Building. It will contain an ultraclean facility with a cleanroom of 1000 m^2., which is six or seven times larger than the combined area of all present micro- and nanoelectronic laboratories at the Chalmers campus. The cleanroom is described as:

> an advanced ballroom type of class 1000, with dedicated areas of class 100 and with distributed SMIF capabilities. The use of a minienvironment concept will make it possible to locally control he particle contamination and achieve corresponding classes below class 10.[22]

Alex's worry of course was that the smoke might leave behind such a level of contamination, that the new laboratory may not fulfil these high requirements.

Later that day I went with Ben, one of my informants, to another lab: SNL (The Swedish Nanometer Laboratory). SNL is located in the basement of the Physics Research Building, situated close to the building under construction. Ben then told me that due to the smoke that had entered the building after the fire, SNL had been shut down for one and a half months[23]. Almost every single piece of its equipment had been carefully checked and cleaned. Since the fire, minute calculations have been made as to whether to proceed at all with the multi-hundred million (SEK) ChaMEL project as planned[24]; so indeed, Alex had good reasons to worry.

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[21] Source: Conversation with AA, at STL 980903, during a guided tour around labs on the Chalmers campus. Later the name for the Laboratory under construction was changed into ”MC^2” (connecting microelectronics with Einstein).

[22] The ChaMEL Newsletter, Aug 1998.

[23] The cost of this must have been considerable as SNL is used up to 20 hours a day, during 320 days a year.

[24] There are all kinds of minute calculations when it comes to ultra-sensitive technoscience like this. For instance, the trams passing by the area sfor the last 50 years have been the object of calculations as they generate vibrations that

Ben also gave me an idea of what 'ultraclean' and 'class 1000, 100, and 10' (the number of particles per mm) really means. While in the Gowning Room, putting on protective helmets and masks to be allowed into the Metallization and Optical Lithography modules of SNL, Ben explained to me that a person working in the ChaMEL cleanroom will have to submit herself to a really hard discipline. For example, smoking will not be allowed any later than two days before entering the lab. Further, to wear make-up or a beard would not be considered appropriate. So, the new non-humans (i.e. the re-equipped lab technologies) will impose their rigorous nanophysics state-of-the-art demands onto the humans. Also users' codes of behaviour outside of the workplace and working hours will increasingly be intruded upon, evolving to a strict 'body management' that constantly keeps an eye on contamination levels.

Implicit in this major initiative, is also of course the hope that ChaMEL will spur the physics research community in Göteborg to better integrate and recombine their resources, thereby attaining national as well as international excellence. This process is already well on its way, as recognized by a recent peer review evaluation.[25] However, my material also suggests that not everything is rosy about ChaMEL. The very big money now coming into the picture will inflict on this academic community new levels of market and customer orientation. The laboratory will be open to users from everywhere, a policy that brings prospects of profits and pay-off calculations onto the agenda each time the planning committe for the new facilities assembles.

An internationally highly reputable person from the semiconductor industry and cleanroom technology has been hired as the manager of ChaMEL. Once in full operation, there will be 20 full-time staff members to run the laboratory and take care of customer contacts. It's no surprise perhaps that several of the professors who have a stake in this undertaking worry about what room there will be for research maintaining academic standards.[26] The needs of penniless students have

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might be unhealthy for nano science experimentation. So far, the estimation is that they pass the test (the new lab will be a construction hanging on pillars to minimize vibrations) but the ordinary citizen of Göteborg should not be surprised to see the tracks redirected in the years to come, as soon as science says so.

[25] "The Faculty of Science, Göteborg University (GU). Evaluation of research, teaching, and administration 1997". A peer review initiated by the Board of the GU Faculty of Science, acknowledging the very close co-operation between GU and Chalmers Institute of Technology (CIT) within Physics and Engineering Physics. There are 22 full professors involved in this, 7 of which are employed by GU, and 15 by CIT. When the new building containing ChaMEL is ready, at least 8 groups plan to move in there, half of them representing the School of Physics and Enginering Physics, and half the School of Electrical and Computer Engineering.

[26] Interview XVIII.

been taken care of, as a training cleanroom of a lower capacity will be established, but the question is still raised here whether not an A-team/B-team stratification among researchers as well may follow from rising user charges.

However, within the group to which Ben belongs, the ChaMEL initiative has aroused great expectations, perhaps more so than in any other single group. Its attractiveness lies not primarily in the better instruments it will offer him and his fellow physicists, although they naturally welcome that too. What they look forward to, as clearly indicated in the interview material, is rather that with the new laboratory a 'new game' (my expression) will start. That game is about gaining visibility, recognition, and fair access to laboratory facilities. At stake here is, in the informants' own words, 'drivers licenses'; an ever so important asset if you want to make your fortune as a physicist. Therefore, the rules should be the same for everyone, but when it comes to the 'old game', the one still being played, the people in Ben's group have a nagging feeling (they never say it straight out) that they are not.

Just before leaving the nanometer lab that day, Ben and I were in the control room. From there one can monitor processing work going on in the other rooms of the lab (with glass walls in between). Also, there are some ordinary desks for paper work. Beside those desks, on a wall, the persons in charge had put together a mini-exhibition of posters displaying for visitors interesting pieces of work (etchings on materials, small devices) which had been carried out in the lab. For quite some time, Ben stood watching those posters. Then, almost murmuring, he said:

> We really should have been in here. I tell you: we really should have been represented on these posters.

Managing a 'Mission Impossible'

> The main field of research of the Physical Electronics & Photonics Section, Department of Microelectronics and Nanoscience, is related to semiconducting multi-layered structures, and the transport and optical properties of that (I-V characteristics, resonant tunneling, photoluminescence, photoconductivity, quantum transport). ...The size and quantity of the output, and the list of papers in preparation is impressive.[27]

The group under study is referred to as PEP, i.e. Physical Electronics and Photonics. It consists of 15-20 persons, half of whom are post-doc staff. It was established at CTH/GU as late as in 1995, but had a prior

[27] Source:"The Faculty of Science, Göteborg University (GU). Evaluation of research, teaching, and admini-stration 1997", p 169. A peer review conducted 1997, initiated by the Board of the GU Faculty of Science.

existence at the Technical University of Linköping. PEP runs an unusually broad research programme, covering both basic (fundamental physics) and applied science (device physics). Whereas most other groups of a similar size are active in only one or two of these, it operates in theoretical calculation and simulation, characterization (analyzing samples of semiconducting materials, and devices made out of them), and processing (making devices in a cleanroom lab). Ideas for applications are generated from theoretical ideas and calculations, and they are then taken to the point of demonstrating that they work, but no farther. Claude, the head of the group, refers to this as 'first strike capacity'.

Reflecting its tasks, the high quantity of publications is linked to a great breadth:

> We as a group publish papers in five different categories of science journals: mathematics, theoretical physics, experimental physics, microelectronics, and photonics. I myself am one of the few in the world, perhaps even the only one, who publishes in all of these five.[28]

As a social scientist used to other traditions, the relationship between 'We as a group' and 'I myself' in this excerpt, at first caused me a certain confusion. Hence, I soon noticed that on the numerous publications which decorate the otherwise naked walls in the hallway of PEP's somewhat shabby office area, there was never one name, never *the* author. There were three or four names on the front pages, sometimes even more.[29] There are many different ways to qualify as an 'author': suppling the 'sample' (the often expensive wafers or substrates of multi-layered semiconductor materials upon which all analyzing or processing are made), coming up with an interesting theory or performing the calculation triggering the project, providing access to essential equipment involved, etc. In addition the head of a group, at least one of this size, is always included.

Is Claude then a person bold enough to take the credit for what actually should be attributed to others? Of course not. What I am describing is the common practice and logic of the field. Physics is by and large a collective endeavour, a teamwork, and as in sports, there are leaders who also receive their medal when the team wins. But this is not the whole picture. For more complex reasons, it *is* very important for Claude to emphasize that he too is a highly recognized (and he is[30]),

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[28] Excerpt, Interview IX.

[29] Indeed, within physics there are examples of scientific papers for which everybody working in an institute, or in two collaborating ones (sometimes up to 40 or 50 people), are registered as authors.

[30] "XY is an extremely proliferate scientist with more than 140 publications in refereed international journals in the period 1992-1996." Excerpt from a peer review of all joint natural science/technology research programmes at Göteborg

competent scientist. Not for personal (after all he already is a professor) or personality reasons (neither does he strike you as the boasting type), but for 'ecological' reasons: it is crucial for the group's sustainability that declarations like the one cited are made.

In my understanding, the PEP group is essentially on a 'mission impossible'. As we have seen, its research programme, the core of its collective life, is very broad. Organizing oneself to be two or three times as broad as many of your fellow researchers (=competitors) in a field already characterized by 'a cutting edge competition', is asking for trouble – almost suicidal, I would say. Fears of failing to come up to the mark, should be widespread. But that is just not very productive, and here productivity is the only thing that counts. What management could there then be for a 'mission impossible'?

There are, it seems to me, two options here. The first would be to develop a highly integrated group by encouraging daily collaborations and discussions, so that everyone eventually comes to grasp the entire programme by learning a lot from the others, thereby relieving some of the stress. But in practice this is a very risky strategy, due to the hard competition. You could easily end up with a group with a solid, evenly distributed knowledge, but at a second-rate level. The second option is to specialize, discouraging redundancy of skills and overlaps. However, with a specialized work organization along those lines, one runs the risk of creating a dysfunctional atomisation of the group members. To compensate for that, one can try to centralize integration as much as possible, establishing a social and professional order within which one person at the top accounts for *all* the synthesizing and boundary-making work.

This person had better be a very strong guy (men are what we normally find here); at least he must be unanimously *considered to be* strong and competent. As he, in a sense, really *is* the group. It would dissolve in no time without this credibility of his. What then at first may appear as 'boasting', is on a closer look an important cultural practice in the group. It reassures that the specific 'contract' of the group works, and thus that the mission might not be that impossible after all. Group confidence is built with recurrent convictions and rhetoric about strong leadership, control, and trust:

> In device physics, I think we are the best group in Europe. Claude has a very broad knowledge, very, very broad. The group is all grounded on this. He is a very diligent and motivated person, and I myself have been thoroughly educated by working for him.[31]

University and Chalmers Institute of Technology, carried out by an international group in 1997.

[31] Excerpt, Interview VIII.

If the professor is a good, strong person, there will be no problem. There will be trust and collaboration. It is more in groups which are not well organized and managed, where you could have problems with people fiddling in some way.[32]

As much as they ‘construct’ their leader and his virtues in a way that serves the common need, thereby corroborating and making sense of the invisible contract tacitly agreed upon, the PEP members similarly ‘construct’ their own positions. Often without being asked about it, people being interviewed made clear to me which clear-cut category they were in; ”I am a theoretician”, ”I am an experimentalist”, ”I am in device physics”, etc. Such remarks were in fact reiterated almost as if they were a mantra. Mapping and reproducing boundaries that attribute to everyone his unique position, stands out as a core activity in the representational practice of the group.

It appears to be part of the game to ”pretend” that one has less in common with the others in the group than what is actually the case. Here, the earlier discussed ”chip analogy” seems to apply, as one senses a fear of unpredictability or tension as shaping the intragroup relations. The individuals are careful not to knock into each other (as atoms may do when tunneling effects or ’quantum chaos’ take over); there is hardly any room for actions and initiatives violating the very vulnerable order of things.

At the same time, this pattern is inscribed into the artefacts engaged in PEP’s work. Hence, fully in line with the social contract I have postulated, it has been decided to give each member his own work station or own instrument, leaving him as independent as possible[33]. There is e.g. one costly X-ray lab facility that only two persons use, and an even more expensive Photo Luminescence Lab, used exclusively by one person.

In my interpretation, the need to confirm this contract, could also be traced in the interviewees’ answers regarding ‘the outside’ – e.g. making contacts outside academia, discussing long term implications of the research, giving visibility to what one has achieved. This is exclusively the territory of the leader, as several made clear when I asked whether they had, or wanted to have, an involvement in the wider political or social contexts of their research area:

No, I have no contacts with current local initiatives in the microelectronics field, I wouldn`t know what they are really, it is just what I read in the newspaper. I am not at all on that level – our professor is.[34]

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[32] Ibid. The question that this statement answered was whether the high pressure to publish extensively, did not sometimes result in people profiting on others’ work without making them co-authors or even mentioning them.
[33] Interview XIII.
[34] Excerpt, Interview II.

> I don`t feel like having any *personal* responsibility for taking part in discussions about applications, or about the possible social benefits of our research. If we get involved in that, it is the professor and perhaps some other persons who must have that responsibility.[35]

Thus, while the team members almost systematically praise their team leader to the skies[36], they also see themselves as useful and competent, though within a narrow sphere, a clear-cut niche. If one wants to know what goes on 'outside', one had better ask Claude. He is the only one expected to maintain an informed on-line-relation to the wider 'real world'. Here there seems to be no hesitation or ambiguity concerning this centralised way of orchestrating 'the show', neither any hypocrisy or false modesty. It simply reflects the rules given by the competitive dynamics of their trade. Claude himself candidly confirms and salutes this imperative nature of the social order:

> It just has to be that way, that I am the only one who has access to the synthesis, who can form a whole of things. The others understand by listening to me.[37]

Hence, to conclude this section by taking the chips analogy yet one step further: Just as micro- and nanotechnology is based on superconductor materials that consist of layers that perfectly isolate, and other layers that on the contrary are super-conductive, it seems as if certain layers of the group in parallelling this itself must be open(ed) for a lot of contacts (connections, conductivity), whereas other layers of it must be strictly isolated from 'the outer world'. The crucial and delicate task of the team leader then, seems to be to monitor this process of connecting and disconnecting different 'layers' of the group.

The Infra-Red Photon Detector

> It is not unusual that some external person opens our eyes to the common potential we have", Derek tells me. "They come here and take advantage of the knowledge of several persons in the group. We recently had three Russians from the instute in St Petersburg here, and then there is this professor from Shanghai that Elias knows, he has been here for a month, is leaving tomorrow. This time, he was here last summer as well, he came

[35] Excerpt, Interview III.

[36] A factor I don't have room to go into here, but that is probably quite important for the sometimes servile way in which this praising comes out, is PEP's ethnic composition. The majority of the staff comes, which is uncommon also in this international field, from nations whose cultures often are labeled elitist or authoritarian.

[37] Excerpt, Interview IX.

to work quite a bit with Fabian, and last week also with me, and with Ben a little bit.[38]

”That may be it”, I thought when hearing Derek say this. ”Maybe here is an illustrative example of an integration mechanism that links the PEP members together, that transgresses the internal barriers”. Derek went on briefing me about the project. The idea is to develop a thermo-camera which using photonics can recognize signals, a sensor that could form the basis for an advanced infra-red detector technology. Elias had an idea how to construct such a sensor, and when earlier this year his computer was up-graded, an opportunity to make elaborate calculations of its potential arose. ”We invested quite some money here to speed up Elias’ calculations”, as Derek put it.

Today’s commercially available detectors are efficient in seizing the photons (at a rate of 90%) but when they are made at small sizes their resolution is very poor. The sensor that Elias has in mind, founded on a new composite of several layers of gallium arsenide, offers, according to his new calculations, a much improved resolution and can seize roughly 50% of the photons. So far, alternatives to the present technology have seized only 1%. This would be a major improvement apparently, if it succeeds. ”For what purposes?”, I asked. Derek reckoned mainly for military applications, radar technology, perhaps also medicine, tracing the sources of cancer.

On the following day, I interviewed Gao[39], the researcher from Shanghai. He told me he has known Elias for many years, and that they were once colleagues at another institute. Where he now works, the focus is on basic research, but a policy that favours more applied work has been launched. Gao had been in Göteborg before. He knew that the group was small but broad. From his point of view there are many advantages in collaborating with such a group. It could catalyze the transformation of his institute into a more applied direction. And things could be carried out more quickly and informally here. ”In China”, he says, ”one really needs good contacts to keep the common service support high.”

As far as the infra-red detector was concerned, Gao knew that within the PEP group there was a good combination of theoretical calculation, simulations and the actual processing of the device. For instance, it was obvious to him that Fabian could feed Elias valuable new ideas about the physical properties of the materials, and that Derek could contribute with his simulations of the electronic devices required to receive the signals from the sensor. The reason why the detector project was interesting for the Shanghai Institute in the first place concerned its potential for weather observations. A more precise satellite technology could improve food production, always a top priority in China.

[38] Excerpt, Interview XIII.
[39] Interview XIV.

Next in my sequence of interviews on the infra-red detector project, was Elias. He told me that the start of the project goes back 4-5 years, when a female researcher from the Shanghai Institute stayed for six months with the group, then still situated in Linköping. A theoretical simulation paper was written, and since then three or four subsequent papers have been published. It all developed gradually; last year when Gao was visiting they worked a lot on the material, and now they focus on the design and optimization of the device. ”But what is it”, I then asked, ”more specifically that is so attractive here?”:

> The Chinese gain a lot from working with us on this. They are now pushed to be more device oriented, more of information processing applications, and we are the best group in the world as far as theory on the infra red photon detector is concerned. Also, we have here some simulation program on the read-out circuit which is not possible to get from the US.[40]

At this point, I was a bit puzzled about how to understand Fabian's role in this. Derek had stated that Gao, on this visit, worked a lot with Fabian, but I could not hear much about that in Elias' account. So I asked about it, and on the following day when interviewing Fabian, I asked him a similar question; this is how they answered:

> I haven´t worked much with him”, Elias stated somewhat curtly, ”I do devices, he does materials. ...But Gao asked me to contact Fabian some months ago, to tell him that he was coming here. Fabian liked it, he need samples, and he needs to come closer to the device. We are a device physics group.[41] (Elias)

> We, Gao and I, discussed a little already last summer, our equipments are complementary you see, and then there is a point to collaborating. We have low temperature photon luminescence, which he doesn't have in Shanghai. And Elias' simulation work is not enough, one always have to go back to theory to calculate the exact electronic structure of the material. That´s why Gao worked so much with me this time.[42] (Fabian)

Investigating what possible reciprocity there was in the Gao-Fabian part of the detector project, I asked the latter what he gained from working with Gao. He explained that he himself needed a good sample, and that in Shanghai they have a growth facility.[43] In addition, the work was,

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[40] Excerpt, Interview XV.
[41] Ibid.
[42] Excerpt, Interview XVI.
[43] A 'sample' is a wafer or substrate of semiconductor material that you design in a way that then allows you to carry out your experiments; it captures or contains one may say your theoretical potential. One 'grows' a sample, and the equipment required for that is expensive. At Chalmers there are only two groups

Fabian acknowledged, a perfect test of the photon luminescence lab that he had been building up for more than a year. Everything had worked out fine; the lab had met expectations. And he told me that he and Gao will publish one major and one short paper.[44]

Ben is the fourth person with whom Gao has had a working relationship during his summer stay in Göteborg:

> I know exactly what is expected from me in this project; my specific task here is to produce some very thin nano wires. The theoretical part, Elias' work, I don't know much about, and it would´t help me really if I knew either.[45]

To my next question he informed me that this task has high priority for him, but not top priority; he frequently checks with Claude on all judgements like that. It is not a big job really; it should be quite easy. If it wasn't, he added, then to do it he must use that particular part of the nano lab, the E-beam litho-graphy, to which he still does not have a "drivers license". "But it is close now, we are at least half-way to getting full access", Ben tried to convince me.

In my interpretation, the detector project establishes what Galison refers to as 'a trading zone' within the PEP group; work and skills that normally are kept separated, now for some time naturally hook onto each other. On his intermittent stays, Gao arrives with a problem the formulation of which is not split up along the usual lines of division. This provides the basis not only for his exchange of values with the group, it also makes that happen *within* the group, thereby fulfiling the similar role as a lingua franca or a 'pidgin'. Other collaborations with external partners described to me seem to trigger the same pattern of unfreezing integration and intragroup interactions.

Persons not originally thought of may be 'pulled into' such a trade. In this case Fabian frequently utilizes a laboratory run by Harry, whereas Harry never asks Fabian for any favours. Recently, during the period when Fabian was working with Gao, he mentioned this to Harry. After chatting a while, it occured to them that Fabian suddenly had something to offer (trade). Harry had for many years wanted to do a certain kind of analysis, but lacked a 'sample' on which to do it. But with Fabian's new relation to Gao, he could now help Harry by asking Gao to grow such a sample at his home facility in Shanghai (by working in his own lab for Gao); Fabian generated a value he then could exchange to pay Harry back.

Another mechanism coming through in my material exercising a similar function, concerns the interface between these physicists'

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which 'grow materials'. From Gordon, Fabian can get a sample 'free'; at an estimated worth of at least a few hundred thousand SEK.

[44] On their frontpages, as authors, will be Gordon, Fabian, Elias, Claude, and perhaps some more persons in Shanghai who have grown the material.

[45] Excerpt, Interview XVII.

instruments. There is often a certain overlap between them, sometimes instead a no man's land. One could conceive of this as though the artefacts channel or mediate an 'added' communication between their human operators, taking the shape of a kind of 'wordless pidgins'. The elaboration and further illustration of this, however, is beyond the scope of this chapter.

Waiting For A License

> The thing is...[he continues]...that in this field nobody is doing exactly the same thing, there is always a slight difference, but still we do very similar things. The good thing about this is that it makes people produce, the bad thing is that people may 'block you' when you want to use the facilities, and they do become aggressive sometimes. I do not take it personally, you cannot do that, there is always stress here; I always try to come back as a nice person. And I have learned to work on three or four things at the same time, if I'm blocked on one I can always work on another, to keep myself constantly busy.[46]

> At first, after having moved here, I was shocked, I really was shocked. I simply cannot understand how people can be like that.[47]

The above statements were made by the same person – Ben. But obviously there are two faces of Ben here. First, there is the patient and tolerent Ben. That is much the way I have come to know him: a friendly, open-minded and forward-looking person, who only reluctantly would dwell upon difficulties. The other face of Ben, however, is not quite like that. Thus, there is that second statement above giving voice to the frustrated Ben. The statements were made on different occasions; the second six months after the first one. Moreover, they were made in different contexts; the first in an interview with him at his office, the second when the two of us were crossing the campus area after visiting the nanometer lab, only a few minutes after Ben had made that comment about the absence of PEP on the exhibited posters.

In a small group like PEP, claiming expertise and excellence in a broad range of Physics and Electronics, everyone's work is crucial; no single 'cog' could lag without disrupting the entire wheel. But it could be argued perhaps, that Ben many times carries a particularly heavy burden in taking PEP's common projects 'all the way'. At least that was what Claude once explained to me:

> The strategic and difficult task...[he explains to me]...always is to balance our efforts between theoretical and calculation work (the simulation part),

[46] Excerpts, Interview VIII.

[47] Source: Conversation with BB, 980903, during a guided tour around labs on the Chalmers campus.

> the process part, and the characterization work that makes up the third part. In most cases, it is in the process part that you fail, you don´t have the resources required or you are not clever enough there. There is an enormous pressure to be efficient there, in the lab. It is like sending off a runner into a rough terrain, where it is absolutely essential that he is equipped with the correct map. But that is not enough, he also must be capable of running really, really fast once he gets there.[48]

Well, in Ben´s own judgement, he has a good map, no problem, and he is also quite confident that he is a good runner:

> I'm always on the run...[he tells me in his very relaxed and pleasant way]. I am a very active person, fast at getting things done. I work 3/4 of my time in the cleanroom, it costs 400 SEK/hour there so you must be well prepared, theoretical preparations, and others, so that you don´t waste time. I always know what I should do.[49]

So what is the matter then? Do there have to be two Bens? What is at stake? Some of the most valuable patches of the terrain, where desirable things can be found, are shut off to you, surrounded by an invisible enclosure. You can get in there only if allowed a 'drivers license', and you do not get that by just being a hell of a runner or by bringing the best of maps; you also need a sufficient amount of social credentials. These are not easy to come by. They can be gained only by making the impression of being dedicated and persistent. Withstanding high stress seems to be part of building credibility in these settings. Consider what three interviewees (one of them a woman) stated:

> You seem to be of a rare sort [I say], being a woman in this area, how come you think there are so few? The physical burden in this work is really high...[she assures me]...we have to work at least 10 hours per day, and the lab part can be quite exhausting. That is why there are so few women, women have their children to take care of. The men quite often consult me about human relations matters. I think it would be good to have a few women in every group; not too many though, as many women think much about their family, it is not so good for results.[50]

> You don't find many women in the device physics, they think it is too tough. And it is, physically when working in the lab, and psychologically, the pressure that´s on you.[51]

> It really takes a strong person to stand a situation when you get stuck in the lab after perhaps having worked hard on a project for two years. That

[48] Excerpt, Interview X.
[49] Excerpts, Interview VIII.
[50] Excerpt, Interview XI.
[51] Excerpt, Interview VIII.

really is tough, you are always so dependent on equipment, and access, and everything else.[52]

Being tough, determined and dedicated is still not enough to obtain that drivers license. You also have to be highly responsible, friendly, gentle and sensitive at the micro-social level. That is, when working in the most restricted areas, as in the cleanroom (the 'Holy Laboratory'), your job is as much to make bonds of trust and friendship as it is to make oxidations or etchings on samples of silicon. In this case, this not the least means complying with *the cleanroom etiquette*, which is extensive. Some of the rules of this etiquette were (by Ben) formulated thus:

- Always stick to the booking rules.
- Rigorously follow the instructions of the machine.
- Always report faults in the equipment; never escape from anything not perfectly in shape.
- Leave the place cleaner than you found it.
- Be friendly, but be careful not to disturb others.

Ben suggested that an etiquette like this needs to be strictly observed whether after a long night's work[53] or when you are rested and alert. Otherwise, all the accumulated trust capital may vanish in a second. Sometimes only 15 seconds of work at a cleanroom instrument determines the outcome of several months' work for a person. Then you'd better not be the one who with a sudden gesture or a loud 'hi there', disrupts that person´s crucial attention. Again, we may recall 'the chip analogy'; just as the physics involved here, the social material out of which collaboration and respect are to be made, is highly sensitive, allowing no careless or undisciplined moves.

So, a lot of demands and a lot of pressure are placed on those sent off to do "the running" in the most competitive processing labs. We should really not raise any eyebrows if the frustrated Ben pops up now and then. And he is still waiting for his 'license' concerning that important part of the equipment. It is not that he is not entitled to it; in principle, the laboratories I talk about here are open to all researchers. 'License' is not a formal piece of paper, but consists of a certain amount of tutoring by a particular certified lab technician, who in fact acts as a gate-keeper. This tutoring has been promised to Ben several times, but each time, as Ben stated it, "..it was a yes, but not a real yes, and then I don´t push it further".

I very much doubt that this delay is because he has neglected or violated any of the requirements or codes of conduct mentioned. Rather, it could be 'just' a matter of time: the incredible speed of some of the

[52] Excerpt, Interview X.

[53] Nightwork flourishes here: The cleanroom in the Swedish Nanometer Laboratory I visited with Burt is often frequented 20 hours a day, during something like 320 days a year.

physics being carried out may be in stark contrast to the equally stark inertia on the social side. If so, gaining new social credentials stands out as a sheer Sisyphean endeavour. In my understanding, that was the painful insight with which Ben struggled the day he remained standing in front of the posters.

Making the Most of Matters: A Few Concluding Remarks

Among the nano scientists under study, I in this initial account chose to focus primarily on two members 'trapped' in the competitive dynamics that they themselves regard as their predicament. Doing so, I then tried to illustrate the logic and implications of the work organization applied, reflecting the wider concerns and constructs of the group. Whereas the psychology of working as a PEP physicist was underlined in some passages, others focussed more on structural properties of this scientific community. Obviously, an extended body of material and analysis are planned for the subsequent phases of the project, encompassing in-depth studies of work making up crucial epistemological politics and practices which so far have not been explicitly addressed.

However, even the rather limited material gathered so far, may contain some useful suggestions as to how epistemological concerns in this community might be studied. For instance, it makes the observation that external partnerships as well as the interfaces of the scientists' instrumentation may act as a 'pidgin'. That provides certain clues about where and how meaningful and minute studies of the group´s epistemological practices could be staged; perhaps the pidgins not only point to 'organizational' integration of resources, but also to where epistemological 'density' and contestation are to be found.

The part of the narrative focussing on the 'drivers license' might have left the impression that the PEP group generally is hampered or held back by waiting for that license. An important aspect of this community however is that it too is 'global', both in terms of composition and reach. Its access to instruments or support from colleagues is not restricted to 'the local'. If you get stuck there, you often have the option of collaborating with other groups. There are Shanghai, St Petersburg, Grenoble, and several others spots on the maps illustrating the action sphere of the group. Also, its members may now and then choose to return 'back home', i.e to the Linköping facilities where many still have valid licenses. Thus, the group's liminality between its former affiliation and the new one in Göteborg works both ways; sometimes shutting them out from both campuses, while at other times allowing access to both.

Yet, being mobile and global on the 'outside', does not provide for a spacious 'inside'. On the contrary, my account suggests that things are quite tight and tense when it comes to manoeuvring in the everyday social realms of this group. Tight to such an extent, even, that ”nano conditions” seem to prevail also for the humans. Struggling from their position as nano ’liberals’, lacking the relative institutional security (industrial back-up) of the ’conservatives’ and the intellectual freedom of the ’visionaries’ (cf the second section above), the members feel squeezed in (psychologically as well as financially). To cope, they reckon, they have to organize themselves as a highly specialised squad, where every part is ultra-productive. Following from this, intra-group communication or interaction must be kept at a minimum, leaving the large share of coordination and integration to merely one person or function.

That may be a too high price to pay. After all, at the end of the road the group members are dependent on each other, as it is the combination of their individual contributions or profiles – e.g. theoretician, experimentalist, calculation physicist, etc – that supplies the ecological niche from which it gets its living (cf note 5). Being ’accountable’ has been considered crucial for the articulation work at the heart of any coordination of human work. So indeed, there may be a good reason for the tension and nervousness one sometimes senses here. At this level of ”social compression”, the involved elements (i.e. humans) could, just like molecules, start jumping around in hitherto unknown or unpredictable, and perhaps also threatening, manners.

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