Invisible Origins of Nanotechnology: Herbert Gleiter, Materials Science, and Questions of Prestige[1]

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Herbert Gleiter promoted the development of nanostructured materials on a variety of levels. In 1981 already, he formulated research visions and produced experimental as well as theoretical results. Still he is known only to a small community of materials scientists. That this is so is itself a telling feature of the imagined community of nanoscale research. After establishing the plausibility of the claim that Herbert Gleiter provided a major impetus, a second step will show just how deeply Gleiter shaped (and ceased to influence) the vision of the National Nanotechnology Initiative in the US. Finally, then, the apparent invisibility of Gleiter's importance needs to be understood. This leads to the main question of this investigation. Though materials research meets even the more stringent definitions of nanotechnology, there remains a systematic tension between materials science and the device-centered visions of nanotechnology. Though it turned the tables on the scientific prestige of physics, materials science runs up against the engineering prestige of the machine.

The website of a 2002 symposium on nanostructured materials offers a rather typical "potted history" of nanotechnology. It begins with the standard reference to Richard Feynman's prophetic vision of 1959 (a historically questionable reference, to be sure, see Feynman 1960, Toumey

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[1] A first draft of this study was presented at the CHF Cain Conference on "Nano before there was nano," March 19, 2005. It draws on many conversations, especially with Horst Hahn (Darmstadt Technical University, Research Center Karlsruhe), Hanno zur Loyen (USC, Columbia), James Murday (Naval Research Laboratory), Gary Peterson (CHF Fellow, also at University of Pittsburgh), Eckart Exner (formerly at Darmstadt Technical University), and Herbert Gleiter (formerly at Saarbrücken and Research Center Karlsruhe). I thank Cyrus Mody, Aant Elzinga, and various referees for stimulating and detailed critical commentary. I couldn't do justice here to all the points they raised.

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2008). It then cites a breakthrough moment when this prophecy came to be realized, and finally describes the productive present state and promising prospect of further nanoscale research. Somewhat unusual about this history is only how it identified the breakthrough moment:

> In 1959 Richard Feynman at Cal Tech spoke of "Plenty of Room at the bottom" to highlight the tremendous scientific and technological potential of materials and devices at atomic/molecular dimensions. Nearly twenty years later, Herbert Gleiter focussed on the benefits of ultrafine grains in solids and coined the term nanostructured solids. Today, Nanoscience and nanotechnology is the fastest growing research area. It will require a very strong interdisciplinary approach to translate the extraordinary possibilities offered by nanomaterials into practical devices.[2]

It is safe to say that Herbert Gleiter's accomplishment is known only to a certain community of materials scientists and that his contribution is not readily recognizable to most who are involved with nanotechnology. That this is so can be viewed as a telling feature of the imagined community of nanoscale research. It speaks to the difference between what nanotechnology is taken to be and where it has been most successful so far. Accordingly, this paper begins by establishing the plausibility of the claim that Herbert Gleiter provided a major impetus or starting point of the nanotechnological enterprise. Moreover, it is possible to trace in a second step just how deeply Gleiter shaped and ceased to influence the vision of the US Nanotechnology Initiative. Finally, then, the apparent invisibility of Gleiter's importance needs to be understood. This leads to the main question of this investigation. Materials science research meets even the more stringent definitions of nanotechnology, but there remains a curious mismatch between materials science and the device-centered visions of

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2. Indian Institute of Technology, Dehli: National Symposium on Nanostructured Materials, December 5–6, 2002, http://www.iitd.ernet.in/utilities/archives/symp_nano.html—accessed on March 15, 2005 (no longer available January 2006). Historiographically more significant, Robert Cahn tells the same story in his history of materials science: "At a meeting of the American Physical Society in 1959, the Nobel prize-winning physicist, Richard Feynman, speculated in public about the likely effects of manipulating tiny pieces of condensed matter. [. . .] Attention had been focused on nanostructured materials by a lecture delivered in Denmark by Herbert Gleiter (1981); in a recent outline survey of the field, Siegel (1996) describes this lecture as a 'watershed event'" (2001, p. 398). Cahn adds that it was Gleiter who founded the research field of nanostructured materials (2001, p. 400).—Customarily, the breakthrough from Feynman to nanotechnology is attributed to Binnig and Rohrer's development of the STM, but also to Eigler and Schweizer's achievement of moving atoms at will, to Drexler's visions, or to the announcement of the US's Nanotechnology Initiative.

nanotechnology. Though it exercises control at the molecular level to exploit novel nanoscale-dependent properties, it seems that "there must be more" to nanotechnology—but what more is there to be had, and what gets lost in its pursuit?

In the end, then, this paper seeks to shed light on one of the major metaphysical ambitions of nanotechnology, namely to invest matter with machine-like qualities (Jones 2004). It does so in a round-about and suggestive manner, namely by telling a "telling story" of the development of nanotechnology. It is important, therefore, to keep in mind the methodological status of such an endeavor: What looks at first like a historical investigation is a one-sided reconstruction that aims to show why it is plausible to advance the quasi-historical claim about Gleiter as a founding father of nanotechnology. All this investigation needs is a simple picture of the relation between solid state physics and materials science. This picture is familiar to researchers who work at the interface of these two fields but it is not the only one and does not reflect the internal struggles within both communities (Bensaude-Vincent 2001, Bensaude-Vincent & Hessenbruch 2004, Weart 1992). Similarly, when it comes to explaining Gleiter's invisibility in most stories of nanotechnological development, the explanation draws on accounts of nanotechnology as a "technoscience" that proceeds in an engineering mode. Such an account is supported, for example, by the kinds of questions Gleiter and his nanotechnological peers ask about new materials, but this alone cannot establish the profound difference between Gleiter's scientific interests and the technoscientific attitude that typically informs nanotechnological research (Nordmann 2008). The "explanation" of the peculiar fate of Herbert Gleiter's accomplishments thus draws on general features that cannot simply be presupposed but require further study. Instead of settling an issue, this explanation serves heuristically to recommend the assumptions that it employs.

1. Basic Ideas.

In order to fully appreciate Herbert Gleiter's "basic idea," it helps to be reminded of orthodoxy. In 1964, John Ziman expressed in the opening page of his *Principles of the Theory of Solids* what defined not long ago a hierarchical relation between physics and materials science: All of solid state physics can be explained in terms of perfect crystals. Materials science steps in only where real material properties must be explained in terms of defects.

> A theory of the physical properties of solids would be practically impossible if the most stable structure for most solids were not a regular crystal lattice. The N-body problem is reduced to manageable proportions by the existence of *translational symmetry.* That

> means that *there exist basic vectors,* $\mathbf{a}_1$, $\mathbf{a}_2$, $\mathbf{a}_3$ *such that the atomic structure remains invariant under translation through any vector which is the sum of integral multiples of these vectors.*
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> In practice, this is only an ideal. Every solid is a bounded specimen, so that we must not carry our structure through the boundary. But the only regions where this matters are the layers of atoms near the boundaries, and in a block of N atoms these constitute only about $N^{2/3}$—say 1 atom in 10^8 in a macroscopic specimen. Most crystalline solids are also structurally imperfect, with defects, impurities and dislocations to disturb the regularity of arrangement of the atoms. Such imperfections give rise to many interesting physical phenomena, but we shall ignore them, except incidentally, in the present discussion. We are concerned here with the perfect ideal solid [. . .] (Ziman 1964)[3]

Ziman states two limits to the view that there can be a physical theory of perfect ideal solids, and in effect, relegates the phenomena at these limits to another kind of enterprise, namely that of materials research. Openly acknowledging that his simplification omits for practical and didactic purposes many interesting phenomena, Ziman states that boundaries and surfaces can be neglected, and for the most part also the irregularities and imperfections of the bulk. In the context of nanotechnological research, however, the relation is inversed. The limits of solid state physics are constitutive for nanoscale phenomena: In a nanoparticle, a great proportion of atoms lie near the boundaries, and the interesting properties of nanostructured materials depend crucially on the departures from regular crystalline states and thus on imperfections, defects, impurities, and dislocations. Indeed, this was first suggested by Herbert Gleiter when he proposed in 1981 that material properties will change dramatically when the proportion of atoms near a boundary increases from 1 in 10^8 to 1 in 2.[4]

Gleiter earned a doctorate in physics with a dissertation on the interactions of displacements with coherent, tensed, disordered, and ordered particles. This theoretical investigation had immediate practical relevance for

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[3] In the context of nanoscience and technology studies, it is a matter of interest and some irony that in recent decades the same John Ziman produced analyses of science and technoscience, coining the term "post-academic science" that serves also to mourn the lost status of an ideal (and idealizing) academic science and to provide a critical perspective on the rise of nanotechnological research, see Ziman 1968, 2000.

[4] Another way of putting this: When Feynman famously proposed in 1959 that one might write the *Enyclopedia Britannica* on the head of a pin, he did not realize that he would thereby change the physical properties of the pin. (I owe this apt observation to Axel Blau.)

particle-hardening of metals in specific applications such as turbines, jet engines, and the like (Gleiter 1964).[5] In 1972, he published a book with B. Chalmers on *High-Angle Grain Boundaries.* Its opening pages raise a somewhat speculative "what if" question that prefigures Gleiter's later researches. The authors consider a type of departure from the perfect crystal where the immediate environments of atoms, their nearest-neighbor configurations are changed in such a way that the crystal moves so far from equilibrium atomic spacing that, at some point, it ceases to be a crystal:

> We must, therefore, consider how the atoms in the boundary region can adjust their positions so as to increase the strength and decrease the energy of the boundary from the values we would expect from the 'rigid' contact concept [. . .] we must distinguish between two ways in which departure from the perfect crystal can be envisaged. One is by approximately linear elastic distortion, in which the distances between atoms change by an amount not exceeding a few per cent. The force-displacement relationships are Hookean in this regime and the environment of each atom remains essentially unchanged in the sense that the numbers of neighbors (nearest, second, etc.) do not change. The second is more drastic, in the sense that an atom moves to a position in which its nearest-neighbor configuration is changed and its departure from equilibrium interatomic spacing is outside the linear Hookean range. There is, of course, no absolute line of demarcation between these two regimes, but the distinction appears nevertheless to be useful. (Gleiter and Chalmers 1972, p. 2)[6]

While there is no absolute line of demarcation between the two regimes, Gleiter's question takes the form of asking whether a gradual shift from one regime to the other will at some point involve a qualitative change. If a material consists of grains and if, in a sense, it is compacted from particles, Gleiter's question corresponds to the following conjecture: If the

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[5] This line of work caught the attention of Bernie Kear (then at Pratt & Whitney, later at Rutgers). In 1990, Kear organized in Atlantic City a nanomaterials conference that was the precursor of bi-annual of events (from Nano 1992 in Cancun to Nano 2008 in Rio de Janeiro). Bernie Kear's name will reappear at various points in this paper, but the Gleiter-Kear connection and its significance for the formation of the nanoresearch enterprise clearly requires further exploration.

[6] This 1972 collaboration places Gleiter's research in a wider context of ongoing work within solid state physics and materials science and engineering. Characteristic for Gleiter's approach is his interest in qualitative changes that might result from extrapolation.

grain decreases and if the material is compacted from nanosize particles, the material is internally structured by grain boundaries with most atoms so close to those boundaries that their nearest-neighbor configurations are far from equilibrium interatomic spacing as in a crystal lattice.[7] This conjecture is, in effect, Gleiter's basic idea which he formulated explicitly and began exploring experimentally in a 1981 paper on "Materials with Ultra-Fine Grain Sizes."[8] The paper announces "a new class of materials" which at this point Gleiter calls "interfacial" or "microcrystalline." Among the attractive novel features of these materials is the fact that "they may be 'alloyed' on a nanometer scale" (Gleiter 1981, p. 15).

Even though, in 1981, Gleiter does not yet use the term "nanocrystalline material,"[9] his characterization of these new materials meets the definition of nanotechnology by drawing on novel nanoscale-dependent properties. On a practical level, this consists in the fact that these materials "may be 'alloyed' on a nanometer scale irrespective of miscibility, type of bonding, structure, molecular weight, etc." In other words, it is easy to compound nanoparticles into a material because the atoms in the boundary region of a nanoparticle (that consists of nothing but a boundary region) can adjust their positions so as to increase the strength and decrease the energy of the boundary, irrespective of the usual constraints from the volume or bulk of a material.

More consequential even than this is Gleiter's theoretical characterization of the new class of materials. Their second attractive feature consists in the fact that "their atomic and electronic structure may be different from the atomic and electronic structure of the glassy or cystalline state of the same material." This statement carefully prepares the somewhat bolder and far-reaching claim that these "new materials" are new in that they represent an entirely new state of matter. Gleiter goes on to state this more openly:

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[7] In the terms of Science Studies, this reconstruction of Gleiter's approach is strongly internalist. Gleiter's basic idea appears as a theoretical extrapolation with practical significance (as such like Moore's Law in semiconductor research and its pursuit of a trajectory of miniaturization). This mode of thought was extended one more time in Gleiter's later researches: After exploring what happens to crystalline structures in the course of the miniaturization of grain sizes, he is now looking at the effects of the miniaturization of amorphous or glassy structures.

[8] An even earlier formulation (without a visionary or programmatic dimension) can be found in a brief abstract by Marquardt and Gleiter 1980.

[9] For the first use of "nanocrystalline materials" see Gleiter and Marquardt 1984; Birringer, Gleiter et al. 1984. Gleiter himself refers to his 1981 paper as the first statement of the "basic idea" in 1989, p. 226, and 1993, p. 10.

> Grain boundaries and interphase boundaries represent a special state of solid matter due to the fact that the atoms forming an interface are subjected to the (periodic) potential field of the crystals on both sides of the interface.[10] As a consequence, the arrangements of atoms in interfaces basically differ from the amorphous and crystalline states. [. . .] Hence, the structure and the properties of a solid in which the volume of the interfaces becomes comparable to or larger than the volume of the crystals (microcrystalline or interfacial materials) may be different from the structure and properties of the same materials in the crystalline or the amorphous state. [. . .] For example, in the case of gold, the material contains 50 vol. % grain boundaries if the diameter of the crystals is about 3 . . . 6 nm. As the material may consist of crystals of the same or of different types, the attractive features of such microcrystalline materials are as follows: (i) They may provide an opportunity to generate a state of matter which is different from the glassy and crystalline state. (Gleiter 1981, p. 15–16)

In terms of practical developments, Gleiter's suggestions led to various techniques for creating nanocrystalline materials. This is reflected in the following four statements, somewhat arbitarily selected from various contexts: (i) "The term 'nanoparticle' appeared in the literature around 1982 in connection with powder particles having physical dimensions of one to ten nanometers in diameter. These particles were prepared by H. Gleiter and co-workers by the gas condensation of metal vapors in a low-pressure inert atmosphere. These particles were then condensed and consolidated into small solids, and the products were called 'nanostructured' materials" (Schwarz 1998, p. 93); (ii) "Pioneer explorations to synthesize NC samples were performed by Gleiter et al. in early 1980s" (Lu 1999, p. 1127); (iii) "Initial development of new crystalline materials was based on nanoparticles generated by evaporation and condensation (nucleation and growth) in a subatmospheric inert-gas environment (Gleiter 1989)" (Hu and Shaw 1999, p. 20), and (iv) "The field of nanocrystalline (or nanostructured, or nanophase) materials as a major identifiable activity in modern materials science results to a large degree from the work in the 1980s

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[10] Note a theoretically suggestive play on words here: Where Gleiter speaks of "interfaces" as well as "interphase boundaries" a particular *phase of matter* emerges at the *interface* of two nanoscale crystals with different *phases,* thus an *interphase* for example of the phases of lead- and aluminium-crystals. The following discussion will show more clearly how Gleiter shifts attention from scale-independent crystal phases to crystal-size-dependent 'nanophase' material.

of Gleiter and coworkers, who synthesized ultrafine-grained materials by the in situ consolidation of nanoscale atomic clusters" (Koch 1999, p. 94).[11]

Along with these practical developments came more pointed theoretical characterizations of the new materials as they represent an entirely new state of matter:

> Two fundamental types of solids are distinguished according to their characteristic ranges of structural order: crystals with long range order and non-equilibrium systems (glassy or other "amorphous" solids) with short range order only.
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> This note reports evidence for the existence of a third solid state structure characterized by the absence of long or short range order, similar to a gas-like structure, and, hence, conventionally classified as "gas-like" solids. Generally, conventional macroscopic solids are formed from liquid or gaseous constituents which relax during solidification into structures of short (glassy) or long range (crystalline) order. It is proposed to synthesize gas-like solids by compacting pre-generated randomly oriented crystals with sizes *d* below 10nm ("nanocrystals"). Under the conditions applied in the experiments, this method of "nanocrystalline solids" which are produced by a suitable compacting technique, seems to lead to a new class of solids. (Birringer, Gleiter, Klein, and Marquardt 1984, p. 365)

Gleiter and his collaborators here express most fully the inversion of the traditional relation between solid states physics and materials science. John Ziman spoke of defects as interesting special cases at the limits of physics. For Gleiter, all materials are characterized by a greater or smaller number of defects, the limiting case being the idealized defect-free crystals of solid state physics.[12] By considering the entire range of materials,

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[11] While the commercial significance of Gleiter's nanocrystalline materials was quickly recognized and found its expression in the Saarbrücken Institute for New Materials, Gleiter's ties to industry still need to be investigated. It appears that Gleiter was more influential in developing production methods than in optimizing specific application-oriented material properties. Altogether neglected in this paper is Gleiter's contribution to modelling and simulation techniques, see already Weins, Gleiter, and Chalmers 1971, and more recently Keblinski, Phillpot, Wolf, and Gleiter 1999 or Yamakov, Wolf, Phillpot, Mukherjee, and Gleiter 2002.

[12] The ubiquity of interfacial boundaries is tantamount to a dominance of defects; compare the following expression of the basic idea: "It is the basic idea of nanocrystalline materials to generate a new class of disordered solids by introducing such a high density of defect cores that 50% or more of the atoms (molecules) are situated in the cores of these defects" (Gleiter 1989, p. 226).

materials science is the science of material states and phase-transitions between them, and thus for Gleiter a primarily theoretical enterprise with practical implications. In the transition to nanostructuring and the resulting dominance of defects, this theoretical materials science has come into its own.

2. The Production of Neglect.

The presentation of Gleiter's basic ideas and experimental findings may suffice to plausibly consider him a "founding father" of nanotechnology. This appears warranted especially by his early use of the term "nanocrystalline materials," the recognition of discontinuous, size-dependent nanoscale properties, and the explicit, some would say: visionary formulation of a research program dedicated to the production, investigation, and exploitation of these novel properties. Nineteen years before the National Nanotechnology Initiative, nine years before Eigler and Schweizer manipulated single atoms, five years before Eric Drexler's *Engines of Creation,* four years before the identification of the buckyball, and in the same year as Binnig and Rohrer's invention of the scanning tunneling microscope, Herbert Gleiter can be seen as the first productive nanotechnology researcher who thought of himself in these terms.

It is impossible, however, to conceive the emergence of nanotechnology as a development internal to science, let alone a single scientific discipline. Nanotechnology is at least as much a social as a scientific phenomenon. While certain origins can be traced to various scientific and technical developments, early uses of "nanotechnology" and related terms, nanotechnology emerged as a prominent research and funding scheme only in 1999 and 2000 with the announcement of the National Nanotechnology Initiative in the United States. To be sure, this announcement was publicly justified as a specific proactive response to international developments:

> The U.S. Government, for one, invested approximately $116 million in fiscal year 1997 in nanotechnology research and development. For FY 1999, that figure has risen to an estimated $260 million. Japan and Europe are making similar investments. Whoever becomes most knowledgeable and skilled on these nanoscopic scales probably will find themselves well positioned in the ever more technologically-based and globalized economy of the 21st century. That helps explain why the White House National Science and Technology Council (NSTC) created the Interagency Working Group on Nanoscience, Engineering and Technology (IWGN) in 1998. (Amato 1999, p. 2)

Only after the White House "reacted" as it did with the NNI to a perceived competitive threat from Europe and Japan, Europe and Germany reacted, in turn, by also establishing "nanotechnology" as a broad research agenda in its own right.[13]

If Herbert Gleiter is to be considered a founding father of nanotechnology, broadly conceived, his role in the emergence of a public research agenda needs to be clarified also. Was he, like Richard Feynman, Norio Taniguchi (who coined the "nanotechnology" in 1974), or Eric Drexler one who did work that appears prophetic only in retrospect, or did his research shape the definition and contribute to the scientific legitimacy of the NNI? The answer to this question can provide further evidence of Gleiter's significance. At the same time, however, it suggests where a parting of the ways took place that accounts for his disappearance for the most part from the grand nanotechnology narratives. As it turns out, his disappearance coincides with a demotion of materials research on the one hand, of theory-driven nanoscale research on the other.

A reader in the year 1999 of the journal *Nanostructured Materials* (founded in 1992) could have discovered among the list of editors a constellation of persons that was consequential for the NNI. Next to prominent researchers like Richard Smalley, Bernie Kear, C. C. Koch, L. E. Brus, T. Tsakalos, and others, that constellation would have consisted of Richard Siegel as one of three principal editors, Herbert Gleiter as member of the editorial board, and Horst Hahn as associate editor. In a contribution to *Scientific American,* Richard Siegel described their relation in the following terms:

> In 1981, though, a watershed event occurred. At a conference at Risø National Laboratory in Denmark, German physicist Herbert Gleiter then at the University of the Saarland suggested to his audience that materials made by consolidating ultrafine particles would themselves have radically different characteristics. Following this talk, Gleiter's laboratory published several provocative studies of nanocrystalline metals, which stirred much excitement in the materials research communities both in Europe and in the U.S.
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> My own involvement with nanostructuring began quite serendipitously at a conference in India four years later. There I met Gleiter's former student Horst Hahn. Hahn, who is now at the University of Darmstadt, was then about to begin a postdoctoral appointment at Argonne, and I helped to set him up, giving him

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[13] Part of this reaction was, for example, the establishment in 1998 of a first research institute for nanotechnology at the Forschungszentrum Karlsruhe, with Herbert Gleiter as its head. The story of Japan is more complicated and cannot be told here.

> the vacuum equipment he needed to build a chamber for synthesizing atom clusters. He and I soon began to discuss whether ultrafine powders might be used in making materials other than metals—the task he had initially planned to pursue. Within a few months, we had succeeded in producing a ceramic, nanophase titania, made from 10-nanometer clusters of titanium that were reacted with oxygen. (Siegel 1996, p. 75)[14]

Soon after the beginning of their collaboration, Siegel and Hahn copublished a review article on “Nanophase Materials” (Siegel and Hahn 1987). Also, along with Bernie Kear and six others, Siegel became a member of the Committee on Materials with Submicron-Sized Microstructures that issued a 1989 report to the National Research Council on “Research Opportunities for Materials with Ultrafine Microstructures.”[15] Gleiter and his collaborators are frequently cited in this report. In the attached biosketch for Richard Siegel, he is presented as group leader at Argonne National Laboratories in the area of metal physics and defects of metals whose research has concentrated “mostly recently on the synthesis, characterization, and properties of ultrafine-grained nanophase materials, particularly ceramics” (Kear, Cross et al. 1989, p. 110).

Due to his stature and involvement with the issues, perhaps also as founder and director of Nanophase Technologies Corporation (for which he received in 1991 a U.S. Federal Laboratory Consortium Award for Excellence in Technology Transfer), Siegel was invited to play a major in role in the preparation of the NNI. Míhail Roco recalls the various steps of this preparation-process:

> We began with preparing supporting publications, including a report on research directions in 10 areas of relevance, despite the low expectation of additional funding at that moment. NNI was prepared with the same rigor as a science project between 1997 and 2000: we developed a long-term vision for research and development, we completed an international benchmarking of nanotechnology in academe, government, and industry [. . .] (Roco 2004, p. 894)

In the first phase of this process, Siegel chaired a 1997 workshop and (together with Evelyn Hu and Mjhail Roco) edited its proceedings on “R&D

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[14] Especially for its use in cosmetics, nanoparticulate titanium dioxide serves to this day as an exemplary nanotechnological product.

[15] The expression “submicron-sized microstructures” nicely captures how one talked about nano before there was nano.

Status and Trends in Nanoparticles, Nanostructured Materials, and Nanodevices in the U.S." This report emphasized Gleiter's importance in the section on synthesis and assembly (mostly in Schwarz 1998). Siegel also served as the main editor of the benchmarking survey *Nanostructure Science and Technology: A Worldwide Study.* Again, it includes numerous references to Gleiter (see, especially, Hu and Shaw 1999, Cox 1999, Koch 1999).

This 1999 study, however, marks a turning point. It provided the last crucial element in the argument for the NNI, namely the need for the US to defend or assume the lead in international nanotechnological developments. From here on, NNI-reports have focused on the US research-agenda, nanotechnological accomplishments and challenges at home. The 1999 study is also the last to give prominence to materials research: Richard Siegel has not been involved with later NNI overviews of nanotechnology research, and one will look in vain for any mention of Herbert Gleiter or even for research priorities regarding new materials, particles and coatings.[16] One reason for all this may have been produced by the 1999-study itself: The result of the international comparison was that the US was leading in most areas of nanotechnological research, including "Synthesis and Assembly," "Dispersions and Coatings," and "High Surface Area Materials." Notably, however, the report states three times (and a fourth time in a table) that "in the nanodevices area, Japan seems to be leading quite strongly, with Europe and the United States following" (Siegel et al. 1999, abstract, pp. xix, xxi,10).[17] If the NNI was to assure US dominance where it was most clearly challenged, the area of nanodevices had to move center stage. Inversely one might argue that on certain notions of nanotechnology, nanodevices are the most prominent and

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[16] Compare the National Science and Technology Council's Supplement to the President's FY 2004 Budget *National Nanotechnology Initiative: Research and Development Supporting the Next Industrial Revolution.* This report relates the success-story of wear-resistant coatings in the box "Nanotechnology on a Fast Track" (NSTC 2003, p. 6). When it comes to identifying challenge areas, however, the section "Nanostructured Materials by Design" focuses on functionalized materials and tellingly offers "The Fullerene Ideal" and its "Molecular Perfection" as a research example (NSTC 2003, pp. 15–16). Accordingly, there is in the prospective part of the report only brief mention of selective coatings that can function in cantilever devices (NSTC 2003, pp. 15 and 21). This contrasts sharply to European reports that are far more likely to highlight repellant surfaces, improved textiles, scratch-free paints, etc. (Europe and Japan are no longer mentioned in the 2003 NNI report.)

[17] By "nanodevices" the report means nanotubes for high brightness displays, biomedical sensors, disk drive read heads that exploit the giant magnetoresistance effect, and the like (Siegel et al. 1999, p. xx). Of course, the imaginative reach of the term "nanodevice" reaches all the way to robots, assemblers, or visions of molecular manufacturing.

prestigeous area of application and that it is here where one would most want to excel in the first place. Either way, by finding that the US was doing well in regard to nanoparticles and nanostructured materials, the materials researcher Richard Siegel may have inadvertently prepared the ground for the neglect of materials research in the NNI's vision of nanotechnology.[18]

3. Material and Device, Theory and Capability.

Though it remains difficult to single out particular ideas or achievements at the origin of nanotechnology, it should now be easy enough to appreciate why Gleiter's have been singled out by some: He may have been the first self-described productive nanoscale researcher, his research was exemplary in that it still meets stringent definitions of nanotechnology as exploiting discontinuous scale-dependent properties, and there was at least one prominent trajectory of Gleiter's influence on the NNI which, in turn, set an international standard for nanotechnology institutionalized as a research priority.[19] In light of all this, the question shifts to the relative obscurity or invisibility not only of Herbert Gleiter but of the materials research tradition represented by him in the grand narratives and programmatic visions of nanotechnology.

The answer to this question will elucidate a familiar, but only vaguely expressed general sentiment: New ceramics, paints, coatings, textiles, aerosols may be good examples of nanotechnology's present economic significance, but they fall short of the ultimate ambitions of nanotechnology. These concern nanoengineered systems and devices.[20] In light of this sentiment, Gleiter's brand of materials research assumes a somewhat paradoxical character. After defeating at the nanoscale the supposed theoretical dominance of solid state physics, materials science is now running up against a particular ideal of engineering, against the prestige of

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[18] To be sure, this neglect in the vision is not matched by neglect in funding or commercial significance where materials research continues to be a driving force. Indeed, one might argue that materials research has become a victim of its own success and that it can afford to be indifferent to this.

[19] Other trajectories of influence remain to be explored, for one of them see note 5 above.—Even the 2003 NNI-report (see note 6 above) still includes as a faint echo an oversimplified gesture to Gleiter's basic idea: "nanostructured materials manifest the unique properties of their component parts" (NSTC 2003, 16). Compare Siegel's "intermediary" formulation that was quoted above: "materials made by consolidating ultrafine particles would themselves have radically different characteristics" (Siegel 1996, p. 75).

[20] Anecdotal evidence for this can be found in the area of medical nanotechnology, for example. Researchers typically present important work on improved material for bone implants, coatings for artificial joints etc. but they will not end their presentation without stating the long-term goal of using selective coatings for targeted drug delivery.

the device over the mere material. Put another way, when materials research discovered a new class of materials and invited theoretical characterizations of material states and phase transitions, it ran up against the nanotechnological disinterest in the development of theory and its single-minded acquisition of capabilities of mastery and control.[21] This dual predicament—the prestige of the device over the material, of achieved capability over significance for theory-development—can be illustrated and elucidated by considering the fate of the term "nanophase materials."

As opposed to the more neutral, and merely descriptive designation "nanostructured materials," Siegel's suggestion to speak of "nanophase materials" offers a theory-based characterization.[22] Indeed, it picks up on Gleiter's suggestion that nanocrystalline materials represent a new class of gas-like solids, a new material state next to the familiar crystalline and amorphous or glassy states. If Gleiter's term "gas-like" may be misunderstood as asserting that these materials are homogeneously disordered throughout, Siegel and Hahn avoid this misunderstanding in their definition of "nanophase material." While "local atomic structures of individual nanocrystalline interfaces [. . .] are likely to manifest ordered structural order," the nanophase is characterized by the fact that "the sum of all boundaries of a nanophase material [. . .] represents an aggregate solid-state structure without long- or short-range order." Given that all possible "interatomic distances occur with similar probabilities" it is characteristic of nanophase material that its properties depend strongly upon atomic arrangements and thus also on morphological structure at atomic and molecular scales (Siegel and Hahn 1987, pp. 409–410, 405). Indebted to Gleiter's characterizations, the label "nanophase materials" recommends them as specifically nanotechnological products, emphasizing their discontinuously novel character.[23] It is all the more telling, then, that the

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[21] For discussions and further evidence of nanotechnology's systematic neglect of theory see Nordmann 2004a and 2004b. Compare Cahn: "In materials science, we strive to achieve by reproducible means what no one could do before" (2001, p. 182).

[22] In his biographical account, Siegel writes simply: "My colleagues and I had been studying these substances since 1985, when, in need of a title for a research proposal late one evening, I dubbed them 'nanophase materials'" (Siegel 1996, p. 74).

[23] In contrast, the term "nanostructured materials" does not inherently suggest such a discontinuity. It allows for a merely extrinsic patterning of otherwise unaltered materials, for example, by lithographic techniques. In light of this term, it appears as a surprise *that* such nanostructuring does alter the properties of the material (and not just how these properties are changed). Nanotechnology, of course, esteems surprises highly. The unpredictability of nanoscale phenomena from known classical and quantum theories is considered to be one of the attractive and intellectually appealing features of the nanocosm. To be sure, this estimation of wonder, surprise, novelty reinforces the skepticism about theories of structure-property relations at the nanoscale.

term has not taken hold.[24] In a 1993 paper on "Nanostructured Materials" Gleiter briefly comments on the terminological shift:

> Other names that were used in the past were "nanocrystalline" or "nanophase materials" as well as "cluster-assembled materials." Since these names no longer do justice to the expansion of the field in recent years, the term "nanostructured materials" has been proposed recently. (Gleiter 1993, p. 10)[25]

The expansion of the field consisted most notably in the inclusion of highly ordered structures with fixed interatomic distances like the Buckminster Fullerene and carbon nanotubes. "Nanostructured materials" is more than a general label, however, that covers Gleiter's new materials alongside Smalley's buckyballs, that includes the tradition of hardening metals through the introduction of defects by hammering alongside the artistic tradition of supra-molecular chemistry and its associated ideal of control of atomic structure.[26] To the extent that "structuring" connotes the imposition of order, the term "nanostructured materials" favors the ideal of control and downplays the defining features of "nanophase materials," namely the various expressions of its "disordered" character: the constitutive role of defects and departure from perfect crystals, heterogeneous construction, incoherent boundary layers, gas-like disorder with its improbable, unstable states, along with the persistent practical problem of preventing the aggregation of these materials into coarser, more ordered states (see Gleiter, Birringer et al. 1984 and still along the same lines Gleiter 1993). From these descriptions and as opposed to "rational bodies" like nanoshells, buckyballs, or carbon nanotubes, it does not sound as if nanophase materials are suitably stable functional elements in the construction of nanotechnological systems or devices. While the label "nanostructured materials" suggests that they have been engineered according to human designs, "nanophase material" represents a material state as if it were an inchoate state of nature.

This analysis suggests that the term "nanophase material" does not fit a certain nanotechnological rhetoric, that it does not support an apparently

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[24] This is not to say that the terms "nanophase" or "nanocrystalline" have vanished in their entirety (see, for example, Heegn, Birkeneder, Kamptner 2003).

[25] Robert Cahn notes that the international scientific community settled on 'nanostructured' materials as the preferred term, followed by 'nanophase' and 'nanocrystalline' materials (2001, p. 398). He warns that the term 'nanostructures' is, at any rate, too broad.

[26] Joachim Schummer has argued that the latter tradition provides an aesthetic origin for nanotechnological visions of functionalizable, device-like molecules. I agree that this (aesthetic) ideal of supra-molecular chemistry dominates at least the grand narratives and programs of nanotechnology. In a sense, I am here providing a complementary story (see Schummer 2006).

preferred conception of engineering according to which nanotechnology exercises precise control of atomic and molecular structure.[27] The same can be said of the associated experimental and visual rhetoric. Scanning probe microscopes as paradigm tools for nanotechnological research are of little use to nanophase materials. With the entire inferential structure built into an STM, for example, it appears to give immediate visual access and even a level of control over the atomic structure of a surface. In contrast, the need to look inside a material and discern the distributions of atoms along its internal boundaries limits research on nanophase materials to electron microscopy and the traditional methods of inference from spectroscopic and crystallographic data. To the extent that scanning probe microscopes are themselves nanotechnical tools and exemplars of nanoscale precision and control, nanophase materials research does not appear to have quite arrived in the new world of nanotechnology.

The prestige of the nanotechnological device, its precise determination and control of atomic structure is manifested also in the images produced by the STM and the electron microscope, respectively. The STM typically affords a God's (or engineer's) eye view of an atomic landscape that is open to exploration and intervention. The STM image looks clean, suggesting a brightly colored world of clearly discernible, solid objects. Its implicit visual message is always: we can go here and do things, this is a world similar enough to the macroscopic world of our experience to permit mechanical engineering, the creation of circuits and switches, and the like (compare Nordmann 2004b). In contrast, an electron microscopic interior view of a material looks dirty, showing a somewhat fuzzy distribution of black dots, neither ordered nor entirely disordered but swarm-like, without sharp boundaries and difficult to get hold of. It communicates the remoteness of this interior world at the nanoscale, our difficulty of access and control, indeed, the utter futility of wanting to engineer and significantly change anything by tampering with individual atoms.[28]

[27] Indeed, Gleiter and his collaborators frequently express that they have no such control. "Many of the studies performed so far are hampered by difficulties typical to newly developing areas; for example, by difficulties in specimen preparation, by a lack of reliable methods for specimen characterization and by the present limitations in modeling such systems theoretically" (Gleiter 1989, p. 227). Compare Siegel and Hahn (1987, p. 410): "The actual local atomic nature of these boundaries is as of yet undetermined, but atomic resolution electron microscopy on nanophase materials in progress is expected to elucidate these structures." The limitations mentioned here are crucial for theoretical understanding, of course, not necessarily for the production and characterization of nanophase materials. Suryanarayana 2005 shows that these limits have been pushed outwards but by no means surmounted in principle.

[28] As was shown by Baird and Shew 2004, the experimental and visual rhetoric of the STM needs to be distinguished from its actual usefulness in laboratory research. In many

All this has shown how a certain engineering ideal of atomic precision, of designed systems and devices serves to downplay the development of "mere" materials. Finally, a similar case should be made for the commitment to theoretical questions that is inherent in the characterization of nanostructured material as "nanophase." It should be shown that the methods for producing the novel materials proved far more influential than the suggestion that these materials represent a different state of matter, and also, that for Richard Siegel and most others, attempts to model and understand local processes at the boundary layers lead a parallel, considerably detached life from innovation processes and the acquisition of new skills in the production of materials and manipulation of their properties.[29]

Since the absence of activity or its lack of relevance is methodologically difficult to establish, only an indirect line of evidence can be offered here. It concerns the current uses of the term "nanophase." While the origin of the term can be traced to the theoretical characterization of a special material state, its later incarnations carry no trace of this. The website of *Nanophase Technologies*—the company founded by Richard Siegel—describes a broad range of products and services but nowhere suggests what all these products have in common. The *Nanophase Research Training Network* does not refer to a class of materials at all but uses the term as an acronym for "*nano*scale *ph*oton *a*bsorption and *s*pectroscopy with *e*lectrons." Most tellingly, perhaps, the *Center for Nanophase Materials Sciences* at Oak Ridge National Laboratory includes a *Nanomaterials Theory Institute.* Its purpose is to meet computational challenges such as "the design of functional nanomaterials and virtual synthesis." Devoted to computational nanoscience it produces simulation tools that support the vision of perfect control, its website featuring a computer simulation of a fullerene molecule that appears to drag a helium-atom fluid through a carbon nanotube.[30] "Nanophase" is thus what philosophers of science have considered a

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cases, electron microscopy proves superior (indeed, it may be superior already because of the STM's black-boxed inferences which are harder to control than those of electron microscopy). And yet, in the competitive world of nanotechnological demonstrations of imaging-skills, any discipline is hampered that, for systematic reasons, is limited to "boring" or "dirty" images. (Inversely, one might argue that the practical accomplishments of materials research make it less necessary to proffer images as substitutes for real technical breakthroughs: the new materials speak for themselves, while nanoscale devices need visually compelling proofs of possibility or concept to speak for them.)

[29] Nordmann 2004a argues along similar lines in a case study from the nanotechnological field of molecular electronics.

[30] The three examples cited here correspond to a Google-search on February 13, 2009 that yielded 15,400 hits for "nanostructured material" and only 2,850 for "nanophase material" (the plural "materials" yields more, namely 479,000 as against 41,200). For Nano-

theoretical term that has become uprooted from its theoretical setting and now serves many masters.

According to a simplistic view of nanotechnology, it is divided into two camps. One camp is reserved for a small band of Drexlerian outsiders who naively posit principles of macroscopic mechanical engineering and simply scale them down to atoms and molecules. Everyone else and all serious nanoscale researchers are said to be in the other camp. This paper has only been able to suggest that the fault lines run quite differently through the various nanoscale research communities. Within materials research, there are those who rationally design near-perfect bodies as building blocks or substrates for nanotechnological systems and devices[31], and there are those who produce in a controlled manner structures of deliberate disorder that are useful in their own right. The term "nanophase" is taken out of context and used in radically different ways—as are terms like "self-assembly," "bottom-up engineering," or "control." Most importantly, there remains a fundamental tension between emphasis on the novel, surprising, unpredictable character of nanoscale phenomena and the ambition to construct machine-like systems and devices.[32]

Whether Herbert Gleiter should figure as a founding father in histories of nanotechnology (because he may have been the first researcher to explicitly pursue a productive nanotechnological research program) or whether he is rightly overlooked in such histories (because he recommended for their theoretical interest as well as practical significance a new class of materials with "gas-like disorder") is a matter of how these fault-lines get drawn and redrawn. It is therefore not a matter of what nanotechnology is or is not, but where the nanotechnological research agenda will go, whether it will come to terms with the dual notions of instability

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phase Technologies, see http://www.nanophase.com, for the Nanophase Research Training Network, which ended in 2004; see http://www-users.york.ac.uk/~rwg3/nanophase.html, regarding the Center for Nanophase Materials Sciences at Oak Ridge National Laboratories, see http://www.cnms.ornl.gov/workshops/inaugural/CNMS_Fact_Sheet_2005-Feb.pdf (all three sites accessed on February 13, 2009).

[31] Robert Cahn discusses this heterogeneity of materials science research. Instead of referring to sub-disciplines or specializations, he uses the term "parepistemes." The research field of nanostructured materials serves him as a prime example of a 'parepisteme' (Cahn 2001, pp. 159–185 and 401)—but compare Bernadette Bensaude-Vincent's account (2001).

[32] In his book on *Soft Machines,* Richard Jones suggests how this tension can be overcome. It remains to be seen whether his account can serve to reorient deep-rooted engineering paradigms or whether it proves to be a semantic exercise to have it both ways (that is, to speak of machines where the notion of a 'machine' no longer makes sense), see Jones 2004.

and control, and whether, for example, it will seek a kind of disciplinary unification in theories of complex structure-property relations at the nanoscale.[33]

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[33] The debates that might still lie ahead could benefit from a reconstruction also of the controversies or disagreements that were sparked by Gleiter. This, however, has to be subject of another paper.

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