Philosophy of NanoTechnoScience

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ABSTRACT

Nanoscientific research has been characterized as an "engineering way of being in science." This mode of research calls for a philosophy of technoscience that investigates the four questions: i) What is the role of theory and theory-development in nanoscale research, and what kinds of theories are needed for nanotechnological development? ii) What are the preferred methods and tools and the associated modes of reasoning in nanoscientific research? iii) What is nanotechnoscience and how are its objects constituted? iv) What kind of knowledge do technoscientific researchers typically produce and communicate? The consideration of these questions yields a survey of nanotechnoscience in terms of disciplinary questions (a complex field partially disclosed by stretching closed theories), of methodology (constructions and qualitative judgments of likeness), of ontology (a thin conception of nature as unlimited potential), and of epistemology (acquisition and demonstration of capabilities). In all four cases, the strictly philosophical discussion leads to societal dimensions and questions of value.

I. INTRODUCTION: PHILOSOPHY OF SCIENCE AND OF TECHNOSCIENCE

One way or another, the philosophy of science and nature always informs and reflects the development of science and technology. It appears in the midst of disputes over theories and methods, in the reflective thought of scientists, and since the late 19th century also in the analyses of so-called philosophers of science. Four philosophical questions, in particular, are answered implicitly or contested explicitly by any scientific endeavor:

1. How is a particular science to be defined and what are the objects and problems in its domain of interest?
2. What is the methodologically proper or specifically scientific way of approaching these objects and problems? What kind of knowledge is produced and communicated, how does it attain objectivity, if not certainty, and how does it balance the competing demands of universal generality and local specificity?
3. What is its place in relation to other sciences, where do its instruments and methods, its concepts and theories come from, and should its findings be explained on a deeper level by more fundamental investigations?

When researchers publish their results, review and critique their peers, argue for research funds, or train graduate students, they offer examples of what they consider good scientific practice and thereby adopt a stance on all four questions. When, for example, there is a call for more basic research on some scientific question, one can look at the argument that is advanced and discover how it is informed by a particular conception of science and the relation of science and technology. Frequently it involves the idea that basic science identifies rather general laws of causal relations. These laws can then be applied in a variety of contexts and the deliberate control of causes and effects can give rise to new technical devices. If one encounters such an argument for basic science, one might ask, of course, whether this picture of basic versus applied science is accurate. While it may hold here and there especially in theoretical physics, it is perhaps altogether inadequate for chemistry. And thus one may find that the implicit assumptions agree less with the practice and history of science, and more with a particular self-understanding of science. According to this self-understanding, basic science disinterestedly studies the world as it is, whereas the engineering sciences apply this knowledge to change the world in accordance to human purposes.

Science and scientific practice are always changing as new instruments are invented, new problems arise, new disciplines emerge. Also, the somewhat idealized self-understandings of scientists can change. The relation of science and technology provides a case point. Is molecular electronics a basic science? Is nanotechnology applied nanoscience? Are the optical properties of carbon nanotubes part of the world as it is, or do they appear only in the midst of a large-scale engineering pursuit that is changing the world according to human purposes? There are no easy or straightforward answers to these questions, and this is perhaps due to the fact that the traditional ways of distinguishing science and technology, basic and applied research do not work any longer.

As many authors are suggesting, we should speak of “technoscience” [1,2] which is defined primarily by the interdependence of theoretical observation and technical intervention [3].[1] Accordingly, the designation “nanotechno-science” is more than shorthand for “nanoscience and nanotechnologies” but signifies a mode of research other than traditional science and engineering. Peter Galison, for example, notes that “[n]anoscientists aim to build – not to demonstrate existence. They are after an engineering way of being in science.”[5] Others appeal to the idea of a “general purpose technology” and thus suggest that nanotechnoscience is fundamental research to enable a new technological development at large. Richard Jones sharpens this when he succinctly labels at least some nanotechnoscientific research as “basic gizmology.”[2]

Often, nanoscience is defined as an investigation of scale-dependently discontinuous properties or phenomena.[6] This definition of nanoscience produces in its wake an ill-defined conception of nanotechnologies – these encompass all possible technical uses of these properties and phenomena. In its 2004 report on nanoscience and nanotechnologies, the Royal Society and Royal Academy of Engineering defines these terms as follows:

> Nanoscience is the study of phenomena and manipulation of materials at atomic, molecular and macromolecular scales, where properties differ significantly from those at a larger scale. Nanotechnologies are the design, characterisation, production and application of structures, devices and systems by controlling shape and size at the nanometre scale.[7]

The notion of “nanotechnoscience” does not contradict such definitions but assumes a different perspective – it looks from within the organization of research where fundamental capabilities are typically acquired in the context of funded projects with a more or less concretely imagined technical goal. This is what Galison means by an engineering way of being in science. Even though a great deal of scientific knowledge and experience goes into the acquisition of such capabilities and the investigation of novel phenomena, it is not quite “science” because the point of this investigation is not normally to question received conceptions and to establish new truths, nor is it

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[1] This is in reference to Ian Hacking's distinction of "representing" and "intervening" [4]: *In technoscientific research, the business of theoretical representation cannot be dissociated, even in principle, from the material conditions of knowledge production* and thus from the interventions that are required to make and stabilize the phenomena. In other words, technoscience knows only one way of gaining new knowledge and that is by first making a new world. If the business of science is the theoretical representation of an eternal and immutably given nature, and if the business of technology is to control the world, to intervene and change the "natural" course of events, "technoscience" is a hybrid where theoretical representation becomes entangled with technical intervention.

[2] Jones used this term in conversation (and on his website www.softmachines.org) and referred for example to Nadrian Seeman’s systematic exploration of DNA as a building block or component of future technical systems.

to produce conjectures and then try to falsify them, or to develop theories that close important gaps in our understanding of the world. And even though nanoscale research practice involves a good bit of tinkering and pursues technological challenges and promises, it is also not "engineering" because most researchers are not in the business of building devices for more or less immediate use. At best, they lay the groundwork for concrete engineering projects in the future.

For this "engineering way of being in science" a philosophy of technoscience is needed that asks for nanotechnological, biomedical, or semi-conductor research the four questions that were identified above: What is the role of theory and theory-development in nanoscale research, and what kinds of theories are needed for nanotechnological development? What are the preferred methods and tools and the associated modes of reasoning in nanoscientific research? What is nanotechnoscience and how are its objects constituted? What kind of knowledge do technoscientific researchers typically produce and communicate? The four main sections of this chapter will tend to these questions – and in all four cases, strictly philosophical considerations will shade into societal dimensions and questions of value. That this is so is due to the fact that there may have been "pure science" but that there is no such thing as "pure technoscience." Indeed, one way of characterizing technoscience is by noting that academic laboratory research is answerable no longer just to standards of peer researchers but that it has entered the "ethical space" of engineering with its accountability also to patrons and clients, to developers and users [8,9].

II. FROM "CLOSED THEORIES" TO LIMITS OF UNDERSTANDING AND CONTROL

(1) Closed Relative to the Nanoscale

In the late 1940s, physicist Werner Heisenberg introduced the notion of "closed theories." In particular, he referred to four closed theories: "Newtonian mechanics, Maxwell's theory with the special theory of relativity, thermodynamics and statistical mechanics, non-relativistic quantum-mechanics with atomic physics and chemistry." These theories he considered to be closed in four complementary respects:

1. Their historical development has come to an end, they are finished or reached their final form.
2. They constitute a hermetically closed domain in that the theory defines conditions of applicability such that the theory will be true wherever its concepts can be applied.
3. They are immune to criticism; problems that arise in contexts of application are deflected to auxiliary theories and hypotheses or to the specifics of the set-up, the

instrumentation, etc.

4. They are forever valid: wherever and whenever experience can be described with the concepts of such a theory, the laws postulated by this theory will be proven correct.[10][3]

All this holds for nanotechnoscience: It draws on an available repertoire of theories that are closed or considered closed in respect to the nanoscale but it is concerned neither with the critique or further elaboration of these theories, nor with the construction of theories of its own.[4] This is not to say, however, that closed theories are simply "applied" in nanotechnoscience.

When Heisenberg refers to the hermetically closed character of closed theories (in condition 2 above), he states merely that the theory will be true where its concepts *can* be applied and leaves quite open how big or small the domain of its actual applicability is. Indeed, he suggests that this domain is so small that a "closed theory does not contain any absolutely certain statement about the world of experience" [10]. Even for a closed theory, then, it remains to be determined how and to what extent its concepts can be applied to the world of experience.[5] Thus, there is no preexisting domain of phenomena to which a closed theory is applied. Instead, it is "a question of success,", that is, of calibration, tuning, or mutual adjustment to what extent phenomena of experience can be assimilated to the theory such that its concepts can be applied to them.

(2) Applying Theory to the Nanoscale: Fitting vs. Stretching

This notion of "application" has been the topic of many recent discussions on modelling[6] – but it does not capture the case of nanotechnoscience. For in this case, researchers are not trying to bring nanoscale phenomena into the domain of quantum chemistry or fluid dynamics or the like. They are

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[3] Heisenberg's notion of closed theories influenced Thomas Kuhn's conception of a paradigm [11]. It also informed the so-called finalization thesis, one of the first systematic accounts of technoscience [12]. Heisenberg also emphasized a fifth and especially contentious aspect of closed theories: An expansion of their domain of application will not introduce a change to the theory. This aspect and Heisenberg's particular list of closed theories plays no part in the following discussion.

[4] In the case of nanotechnoscience, this repertoire includes far more than the four theories singled out by Heisenberg. It is a bold claim, to be sure, that nanotechnoscience is not concerned with the construction of theories of its own. One counterexample might be the discovery and subsequent theoretical work on the giant magnetoresistance effect [13]. Also, there are certain isolated voices who call for the development of theory specifically suited to the complexities of the nanocosm [14,15]. These voices are isolated, indeed, and the consensus appears to be that the development of nanotechnologies can do without such theories – which might be hard to come by anyway [16].

[5] Here, Heisenberg might have been inspired by Heinrich Hertz who formulated the *Principles of Mechanics* as a closed theory [17]. He defined as mechanical problems all those phenomena of motion that can be accounted for by his fundamental law, albeit with the help of additional assumptions. Phenomena that cannot be accounted for in such a way, are not mechanical problems and simply outside the domain of mechanics (for example, the problems of life).

[6] See the work, in particular, of Nancy Cartwright, Margaret Morrison, and Mary Morgan [18,19].

not using models to extend the domain of application of a closed theory or general law. They are not engaged in fitting the theory to reality and vice versa. Instead, they take nanoscale phenomena as parts of a highly complex mesocosm between classical and quantum regimes. They have no theories that are especially suited to account for this complexity, no theories, for example, of structure-property relations at the nanoscale.[7] Nanoscale researchers understand, in particular, that the various closed theories have been formulated for far better-behaved phenomena in far more easily controlled laboratory settings. Rather than claim that the complex phenomena of the nanoscale can be described such that the concepts of the closed theory now apply to them, they draw on closed theories eclectically, stretching them beyond their intended scope of application to do some partial explanatory work at the nanoscale.[8] A certain measurement of a current through an organic-inorganic molecular complex, for example, might be reconstructed quantum-chemically or in the classical terms of electrical engineering – and yet, the two accounts do not compete against each other for offering a better or best explanation [20]. Armed with theories that are closed relative to the nanoscale, researchers are well equipped to handle phenomena in need of explanation, but they are also aware that they bring crude instruments that are not made specifically for the task and that these instruments therefore have to work in concert. Indeed, nanoscale research is characterized by a tacit consensus according to which the following three propositions are to hold true simultaneously:

1. There is a fundamental difference between quantum and classical regimes such that classical theories cannot describe quantum phenomena and such that quantum theories are inappropriate for describing classical phenomena.
2. The nanoscale holds intellectual and technical interest because it is an “exotic territory” [14]

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[7] Note that the term “complexity” is used here in a deliberately non-technical manner. It does not refer to phenomena that fit the constraints of non-linear complex dynamics, “complexity-theory,” or the like. The complexity at the nanoscale is one of great messiness, too many relevant variables and properties, and multiple complicated interactions. This becomes apparent especially in contrast to the comparatively neat world of the laboratory phenomena that underwrite classical and quantum physics. In its complexity, the “real-world situation” of the nanoworld is precariously situated between classical and quantum regimes.

[8] Here is another way to characterize this contrast between “applying” theory by fitting and by stretching: In the standard case of fitting theory to reality and *vice versa*, the problem concerns ways to compensate for the idealizations or abstractions that are involved in formulating a theory and constructing a model. However, classical theories do not abstract from nanoscale properties and processes, nor do they refer to idealizations of nanoscale phenomena. In this case, the challenge is that of crossing from the intended domain of a classical theory into quite another domain. – Like all attempts to systematically distinguish the new nanotechnoscience from old-fashioned “science and engineering,” this one is vulnerable to the critique that the two notions of “application” (bringing phenomena into the domain of application, stretching the domain of application to areas for which the theory has not been made) are not categorically distinct but differ only by degree. I would like to thank Eric Winsberg for suggesting this line of thought.

where classical properties like color and conductivity emerge when one moves up from quantum levels, and where phenomena like quantized conductance emerge as one moves down to the quantum regime.

3. Nanoscale researchers can eclectically draw upon a large toolkit of theories from the quantum and classical regimes to construct explanations of novel properties, behaviors, or processes.

Taken together, these three statements express a characteristic tension concerning nanotechnology, namely that it is thought to be strange, novel, and surprising on the one hand, familiar and manageable on the other. More significantly for present purposes, however, they express an analogous tension regarding available theories: They are thought to be inadequate on the one hand but quite sufficient on the other. The profound difference between classical and quantum regimes highlights what makes the nanocosm special and interesting – but this difference melts down to a matter of expediency and taste when it comes to choosing tools from classical or quantum physics. Put yet another way: What makes nanoscale phenomena scientifically interesting is that they cannot be adequately described from either perspective, but what makes nanotechnologies possible is that the two perspectives make do when it comes to account for these phenomena.

Available theories need to be stretched in order to manage the tension between these three propositions. How this stretching actually takes place in research practice needs to be shown with the help of detailed case studies. One might look, for example, at the way in which theory is occasionally "stuck in" to satisfy an extraneous explanatory demand.[9] A more prominent case is the construction of simulation models where integrations of different levels of theoretical description are tuned to the actual behavior of a nanoscale system or process [22,23]. This implies also that the very meaning of theories is stretched especially where they account for causal structure behind the observed phenomena: As these theories are applied in situations that are taken to be far more complex than the one for which the theories were developed, the causal story offered by them takes a backseat to the contributions they can make towards a description of the phenomena. In other words, algorithms descriptive of a certain dynamics become detached from the causal explanation they originally helped to provide, since it is the initial or structural conditions precisely that are not

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[9] See, for example, a publication in *Science* on observed effects (large on-off ratios, negative differential resistance) in a molecular device. Asked by peer reviewers to offer an explanation of the observed effect, the authors suggest a somewhat arbitrary but plausible candidate mechanism and call for theories and future experimental work to "elucidate the transport mechanisms" [21]. This discussion was introduced reluctantly since it is clearly unnecessary for the point they wish to make (namely that they can consistently pass a current where no one had done so before), and because it is obviously easy to come up with a sufficiently credible explanation from the toolkit of available theory. The authors implicitly acknowledge that another explanation could easily substitute for theirs.

thought to hold continuously from macro to nano to quantum regimes.[10]

There is quite another symptom of the ways in which theories and concepts are stretched as they are applied to the nanoscale. The nanoworld is taken to be complex, self-organizing, full of surprises – a world characterized by chemical and biological activity. The aspirations of nanotechnologies therefore emphasize the construction of active rather than merely passive devices.[11] The so-called first generation of nanotechnological achievements was limited to the generation of new materials (passive structures), the second generation is supposed to incorporate molecular activity into nanotechnical systems.[12] However, from the point of view of theories that are closed relative to the nanoscale, one cannot "see" any of that novel activity and liveliness but only what has become stabilized in the formulations and formalisms of those theories. Several descriptive or programmatic terms for nanoscale phenomena therefore strain to reach beyond their actual meanings. A prime example of this is the term "selective surface" which attributes agency to something that remains quite passive: Cells may attach to a given surface differentially, but the surface is not therefore doing anything to favor or disfavor certain cells; the selection is entirely on the side of the engineer who selects that surface in order to achieve some functionality. The same holds for "self-cleaning surfaces," "smart materials," "autonomous (self-propelled) movement," the different conceptions of "self-assembly," or "soft machines."[13] All these terms have a specific meaning and at the same time refer to something more visionary, more genuinely "nano" that transcends their pedigree in theories that come from outside the nanoworld.[14]

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[10] At the panel "Ontologies of Technoscience" of the October 2006 Bielefeld conference ("Science in the Context of Application"), Bernadette Bensaude-Vincent showed that in the development of materials science and nanotechnologies the focus on structure-function relations (Crick's dogma that scientific understanding requires that function is referred to underlying structure) gives way to analyses of dynamic patterns in the observed functions and properties. Davis Baird offered as an example of this a particular nanotechnological detection device that physically instantiates factor analysis and therefore statistically infers underlying causes from observed properties (in other words, it does not perform a physical or chemical analysis to identify the presence of what is measured). Nicole Karafyllis finally suggested that (nano)technologies are now entering into a novel relation to biology as they design function not through construction (e.g. from structural principles) but by way of growth (e.g. by way of harnessing of self-organization).

[11] Regarding the prestige of the device *vis-a-vis* the material, see Nordmann 2005 and forthcoming on Herbert Gleiter as a pioneer of nanotechnology.

[12] The trope of first/second generation passive/active devices was established and reproduced especially by Mihail Roco of the National Nanotechnology Initiative. This paper remains quite agnostic as to whether the second generation will ever be attained.

[13] Since the publication of Richard Jones's book on *Soft Machines*, that concept has been subject of an emerging discussion [25, 26]. It concerns the question whether the term "machine" retains any meaning in the notion of a "soft machine" when this is thought of as a non-mechanical, biological machine (while it clearly does retain meaning if thought of as a "concrete" machine in the sense of Simondon).

[14] This is especially true, perhaps, for the concept "self-assembly," which has been cautiously delimited for example by George Whitesides [27] but which keeps escaping the box and harks backwards and forwards to far more ambitious notions of order out of chaos, spontaneous configurations at higher levels, etc.

(3) Mute Complexity

So far, the notion of stretching what we know in one regime to phenomena in another one, has been taken descriptively to characterize nanoscale research. Here, however, arises an occasion for critical questioning by scientists, citizens, concerned policy makers. To the extent that one cannot see the specific complexity from the point of view of theories closed relative to the nanoscale, we may find that the difficulties of understanding and controlling nanoscale phenomena are not adequately expressed. By stretching closed theories one recovers partial explanations of phenomena and thereby partial stories only of success. In other words, the assurance that much is amenable to explanation from the large toolkit of available theories finds ample expression, but there is no theoretical framework for the actual struggle of taming and controlling nanoscale phenomena – this part of the story remains untold, locked up in the laboratory.[15] Put bluntly, one might be doing years and years of interesting research only to discover that most of the phenomena one is tinkering with, that one is stabilizing and probing in the laboratory, will never be robust enough to serve as components in nanotechnological devices. There is no language, in other words, to identify specific limits of knowledge and control.

Having arrived at this point in a rather roundabout manner, one might ask whether the limited ways to speak of limits of understanding and control can be shown more straightforwardly. A telling illustration or example is provided by nanotoxicology. It is finding out the hard way that physico-chemical characterization does not go very far, that even the best methods for evaluating chemical substances do not REACh all the way to the nanoscale [28].[16] In other words, the methods of chemical toxicology go only so far, will be able to tell only a small part of the toxicological story – though regarding chemical composition, at least, there are general principles, even laws that can be drawn upon. In regard to the surface characteristics and shape of particles of a certain size, one has to rely mostly on anecdotes from very different contexts, like the story of asbestos. For lack of better approaches, therefore, one begins from the vantage point of chemical toxicology and

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[15] To be sure, it is a commonplace that laboratory practice is more complex than the stories told in scientific papers. Traditional scientific research often seeks to isolate particular causal relations by shielding them against interferences from the complex macroscopic world of the laboratory. Whether it is easy or difficult to isolate these relations, whether they are stable or evanescent is of little importance for the scientific stories to be told. The situation changes in respect to nanotechnoscience: Its mission is to ground future technologies under conditions of complexity. In this situation, it becomes significant that scientific publications tell stories only of success.

[16] The pun is intended: REACh refers to the new style of regulating chemical substances in and by the EU. It is widely acknowledged that it does not apply where properties depend not only on chemical composition but also on surface characteristics, size, shape, perhaps also engineered functionality and the specificities of their environments. (Along similar lines, Joachim Schummer [29] has argued that REACh does not even reach to the products of conventional synthetic chemistry.)

confidently stretches available theories and methods as far as they will go – while the complexities of hazard identification, let alone risk assessment (one partially characterized nanoparticle or nanosystem at a time*?!*) tend to be muted.[17]

There is yet another, again more general way to make this point. Theories that are closed relative to the nanoscale can only introduce non-specific constraints. The prospects and aspirations of nanotechnologies are only negatively defined: Everything is thought to be possible at the nanoscale that is not ruled out by those closed theories or the known laws of nature. This, however, forces upon us a notion of technical possibility that is hardly more substantial than that of logical possibility. Clearly, the mere fact that something does not contradict known laws is not sufficient to establish that it can be realized technically under the complex conditions of the nanoregime. Yet once again, there is no theoretical framework or language available to make a distinction here and to acknowledge the specificities and difficulties of the nanoworld – since all we have are theories that were developed elsewhere and that are now stretched to accommodate phenomena from the nanosphere.[18] However, failure to develop an understanding also of limits of understanding and control at the nanoscale has tremendous cost as it misdirects expectations, public debate, and possibly also research funding.

III. FROM SUCCESSFUL METHODS TO THE POWER OF IMAGES

(1) (Techno)Scientific Methodology: Quantitative vs. Qualitative

As was shown above, Heisenberg considered "a question of success" the extent to which phenomena of experience can be fitted to closed theories [10]. This suggests the question what "success" amounts to in nanoscale research, that is, what it takes to satisfy oneself that one has reached a sufficiently good understanding or control of the phenomena under investigation.

For Heisenberg and any philosopher of science who is oriented towards theoretical physics, this question boils down to the predictive success of a quantitative science. Here, "quantitative" means more than the employment of numbers and even of precision measurements. The characteristics of quantitative approaches include the following: First, predicted numerical values are compared to

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[17] Sabine Maasen and Monika Kurath have shown that this difficulty for chemical toxicology creates interesting new opportunities for nanotoxicology [31]. – For another illustration of the predicament, one might recall that carbon nanotubes were "discovered" in the 1980s, that for a good number of years they are being commercially manufactured, and that researchers are still complaining that no two batches are alike.

[18] I have been urging that more attention be paid to limits of understanding and control at the nanoscale. If I am right in this section, I have been asking for something that cannot be done (as of now) in a straightforward way.

values obtained by measurement. The reasonably close agreement between two numbers thus serves to establish the agreement of theory and reality. Second, this quantitative agreement emphatically makes do without any appeal to a likeness or similarity between theoretical models and the real-world systems they are said to represent. Quantitative science rests content if it reliably leads from initial conditions to accurate predictions, it does not require that all the details of its conceptual apparatus (every term in its algorithms) has a counterpart in reality. Both characteristics of quantitative science are familiar especially from 20th century theoretical physics – but do they serve to characterize also nanotechnoscience [31]?

In light of the extremely heterogeneous research practices under the general heading of "nanoscience and nanotechnologies" there may not be a general answer to this question. Yet it is fair to say that much nanotechnoscientific research is qualitative. Its epistemic success consists in constructions of likeness.[19]

The shift sounds innocent enough but may have significant consequences: The agreement of predicted and measured quantities is being displaced by an agreement of calculated and experimental images. The latter qualitative agreement consists primarily in the absence, even deliberate suppression of visual clues by which to hold calculated and experimental images apart. Indeed, the (nano)technoscientific researcher frequently compares two displays or computer screens. One display offers a visual interpretation of the data that were obtained through a series of measurements (e.g. by an electron or scanning probe microscope), the other presents a dynamic simulation of the process he might have been observing – and for this simulation to be readable as such, the simulation software produces a visual output that looks like the output for an electron or scanning probe microscope. Agreement and disagreement between the two images then allows the researchers to draw inferences about probable causal processes and to what extent they have understood them. Here, the likeness of the images appears to warrant the inference from the mechanism modeled in the simulation to the mechanism that is probably responsible for the data that were obtained experimentally. Accordingly (and this cannot be done here) one would need to

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[19] Here, a case study of Jan Hendrik Schön might show that he was caught between quantitative and qualitative methodologies. He was "caught cheating," after all, when it was discovered that for different experiments he included an exactly identical plot of current-flow. This diagram is supposed to be generated from a series of measurements but the characteristic shape of the curve is also a qualitative short-hand expression for "current is flowing." In a culture of research that is moving increasingly to produce effects, Schön may well have "written" this diagram as it is generally "read" – without regard to the particular values but as a symbol for a certain type of event. Overall, Schön's case is less innocent and more complicated than this [32]. But perhaps in other regards, too, it is symptomatic of the ambivalence that results from the transdisciplinary qualitative orientation of nanotechnoscience even as nanoscale research continues to be informed mostly by rigorously quantitative disciplinary traditions.

show how nanoscale researchers construct mutually reinforcing likenesses, how they calibrate not only simulations to observations and visual representations physical systems but also their own work to that of others, current findings to long-term visions. This kind of study would show that unifying theories play little rôle in this, unless the common availability of a large tool-kit of theories can be said to unify the research community. Instead of theories, it is instruments (STM, AFM, etc.), their associated software, techniques and exemplary artefacts (buckyballs, carbon nanotubes, gold nanoshells, molecular wires) that provide relevant common referents [33, 34, 35].

(2) "Ontological Indifference": Representation vs. Substitution

This is also not the place to subject this qualitative methodology to a sustained critique. Such a critique is easy, in fact, from the point of view of rigorous and methodologically self-aware quantitative science [31]. Far more interesting is the question why, despite this critique, a qualitative approach appears to be good enough for the purposes of nanoscale research. As Peter Galison has pointed out, these purposes are not to accurately represent the nanoscale and, in particular, not to decide what exists and what doesn't exist, what is more fundamental and what is derivative. He refers to this as the "ontological indifference" of nanotechnoscience [5]. Why is it, then, that nanotechnological research can afford this indifference? For example, molecular electronics researchers may invoke more or less simplistic pictures of electron transport but they do not need to establish the existence of electrons. Indeed, electrons are so familiar to them that they might think of them as ordinary macroscopic things that pass through a molecule as if it were another material thing with a tunnel going through it [20]. Some physicists and most philosophers of physics strongly object to such blatant disregard for the strangely immaterial and probabilistic character of the quantum world that is the home of electrons, orbitals, standing electron waves [36, 37]. And indeed, to achieve a practical understanding of electron transport, it may be necessary to entertain more subtle accounts. However, it is the privilege of ontologically indifferent technoscience that it can always develop more complicated accounts as the need arises. For the time being, it can see how far it gets with rather more simplistic pictures.[20]

Ontological indifference amounts to a disinterest in questions of representation and an interest,

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[20] A particularly interesting and challenging example of this is Don Eigler's famous picture of a quantum corral that confines a standing electron wave. The picture's seemingly photographic realism suggests that the quantum corral is just as thing-like as a macroscopic pond. It brazenly bypasses all discussions regarding the interpretation of quantum mechanics and thus displays its ontological indifference. Nevertheless, it is an icon of nanotechnoscience, testimony to new capabilities of manipulation and visualization, and a down-payment of sorts on the promise that technical control does not stop at the threshold to quantum effects.

instead, in substitution.[21] Instead of using sparse modeling tools to economically represent salient causal features of real systems, nanoresearchers produce in the laboratory and in their models a rich, indeed over-saturated substitute reality such that they begin by applying alternative techniques of data reduction not to “nature out there” but to some domesticated chunk of reality in the laboratory. These data reduction and modeling techniques, in turn, are informed by algorithms which are concentrated forms of previously studied real systems, they are tried and true components of substitute realities that manage to emulate real physical systems [38].[22] In other words, there is so much reality in the simulations or constructed experimental systems before them, that nanotechnology researchers can take them for reality itself [39]. They study these substitute systems and, of course, have with these systems faint prototypes for technical devices or applications. While the public is still awaiting significant nanotechnological products to come out of the labs, the researchers in the labs are already using nanotechnological tools to detach and manipulate more or less self-sufficient nanotechnological systems which “only” require further development before they can exist as useful *devices* outside the laboratory, devices that not only substitute for but improve upon something in nature.

(3) Images as the Beginning and End of Nanotechnologies

Again, it may have appeared like a cumbersome path that led from qualitative methodology and its constructions of likeness to the notion that models of nanoscale phenomena do not represent but substitute chunks of reality and that they thereby involve the kind or constructive work that is required also for the development of nanotechnological systems and devices. For more immediate illustration of this point, we need to consider only the rôle of visualization technologies in the

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[21] Compare Peter Galison’s suggestion above that the relevant contrast is that between demonstrating existence and building things. Yet, as we will be shown in section 4 below, “building” is too narrow and too “technical” a notion. It does not do justice to the intellectual engagement, even passion for the challenges encountered at the nanoscale.

[22] Rom Harré contrasts scientific instruments that serve as probes into causal processes and modeling apparatus (including simulations) that domesticates or produces phenomena. It is this modeling apparatus that underwrites epistemic success in constructions of likeness: Instruments typically obtain measurements that can be traced back down a causal chain to some physical state, property, or process. As such, the instruments are detached from nature – measurements tell us something *about* the world. Physical models, in contrast, are part of nature and exhibit phenomena such that the relevant causal relations obtain within the apparatus and the larger apparatus-world complex. Whether it domesticates a known phenomenon like the rainbow or elicits an entity or process that does not occur “naturally,” it does not allow for straightforward causal inference to the world within which the apparatus is nested [38]. As the metaphor of domestication and Harré’s conception of an apparatus-world complex suggest, causal inference from the apparatus to the world may be required only for special theoretical purposes that are characterized by a specific concern for reality (for example, when something goes wrong and one wants to explore the reasons for this). At the same time, the very fact that the apparatus *is* nested in the world delivers an (unarticulated) continuity of principles and powers and the affordance of ontological indifference.

history of nanotechnological research.[23] Many would maintain, after all, that it all began for real when Don Eigler and Erhard Schweizer created an image with the help of 35 xenon atoms. By arranging the atoms to spell “IBM” they did not represent a given reality but created an image that replaces a random array of atoms by a technically ordered proto-nanosystem. Since then, the ability to create images and to spell words has served as a vanguard in attempts to assert technical control in the nano-regime – the progress of nanotechnological research cannot be dissociated from the development of imaging techniques that are often at the same time techniques for intervention. Indeed, Eigler and Schweizer’s image has been considered proof of concept for moving atoms at will. It is on exhibit in the STM web-gallery of IBM’s Almaden laboratory and is there quite appropriately entitled “The Beginning” – a beginning that anticipates the end or final purpose of nanotechnologies, namely to directly and arbitrarily inscribe human intentions on the atomic or molecular scale.

Images from the nanocosm are at this point (early 2007) still the most impressive as well as popular nanotechnological products. By shifting from quantitative coordinations of numerical values to the construction of qualitative likeness, from the conventional representation of reality to the symbolic substitution of one reality by another, nanotechnosciene has become beholden to the power of images. Art historians and theorists like William Mitchell or Hans Belting, in particular, have emphasized the difference between conventional signs that serve the purpose of representation and pictures or images that embody visions and desires, that cannot be controlled in that they are not mere vehicles of information but produce an excess of meaning that is not contained in a conventional message [40, 41].

The power of images poses some of the most serious problems of and for nanoscience and nanotechnologies. This is readily apparent already for “The Beginning.” As mentioned above, it is taken to signify that for the first time in history humans have manipulated atoms at will, and thus as proof of concept for the most daring nanotechnological visions and by the most controversial nanotechnological visionaries such as Eric Drexler. This was not, of course, what Eigler and Schweizer wanted to say. Their image is testimony also to the difficulty, perhaps the limits of control of individual atoms. But the power of their image overwhelms any such testimony.

Here arises a problem similarly as above in section 1.3. The specificity, complexity, and difficulty of work at the nanoscale do not have a language and do not find expression. The theories imported from other size regimes can only carve out an unbounded space of unlimited potential,

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[23] It is no accident that this is perhaps the best-studied and most deeply explored aspect of nanotechnologies.

novelty, possibility, and the pictures from the nanocosm show us a world that has already been accommodated to our visual expectations and technical practice.[24] Ontologically indifferent, nanotechnoscience may work with simplistic conceptions of electron transport, and it produces simplistic pictures of atoms, molecules, standing electron waves which contradict textbook knowledge of these things. For example, it is commonly maintained that nanosized things consist only of surface and have no bulk. This is what makes them intellectually and technically interesting. But pictures of the nanocosm invariably show objects with very familiar bulk-surface proportions, a world that looks perfectly suited for conventional technical constructions. And thus, again, we might be facing the predicament of not being told or shown what the limits of nanotechnical constructions and control might be.

The power of images also holds another problem, however. In the opposition of conventional sign and embodied image the totemistic, fetishistic, magical character of pictures comes to the fore. To the extent that the image invokes a presence and substitutes for an absence, its kinship to voodoo-dolls, for example, becomes apparent. This is not the place to explore the analogy between simulations and voodoo-dolls [31], but it should be pointed out that nanotechnologies in a variety of ways cultivate a magical relation to technology – and their imagery reinforces this. Indeed, in the history of humankind we might have begun with an enchanted and uncanny nature that needed to be soothed with prayer to the spirits that dwelled in rocks and trees. Science and technology began as we wondered at nature, became aware of our limits of understanding and yet tamed and rationalized nature in a piece-meal fashion. Technology represents the extent to which we managed to defeat a spirited, enchanted world and subjected it to our control. We technologized nature. Now, however, visitors of science museums are invited to marvel at nanotechnologies, to imagine technological agency well beyond human thresholds of perception, experience, and imagination, and to pin societal hopes for technological innovation not on intellectual understanding but on a substitutive emulation that harnesses the self-organizing powers of nature. We thus naturalize technology, replace rational control over brute environments by magical dependency on smart environments, and we may end up rendering technology just as uncanny as nature used to be with its earth-quakes, diseases, thunderstorms [42, 43].[25]

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[24] Compare note 13 above.

[25] This is a strong indictment not of particular nanotechnologies but of certain ways of propagating our nanotechnological future. Considered another way, it is simply an engineering challenge to design nanotechnology for the human scale.

IV. FROM DEFINITIONS TO VISIONS

(1) Wieldly and Unwieldly Conceptions

The first two sections gave rise to the same complaint. After surveying the rôle of theories and methodologies for the construction of technical systems that can substitute for reality, it was noted that this tells us nothing about the specificity, complexity, difficulty of control at the nanoscale. The nanocosm appears merely as that place from where nanotechnological innovations emanate, and so far it appears that it can be described only in vaguely promising term: The domain of interest to nanoscience and nanotechnologies is an exotic territory that comprises all that lies in the borderland of quantum and classical regimes, all that is unpredictable (but explicable) by available theories and all that is scale-dependently discontinuous, complex, full of novelty and surprise.[26]

However, as one attempts a positive definition of nanotechnoscience and its domain of phenomena or applications, one quickly learns how much is at stake. In particular, definitions of "nanotechnology" can postulate as unified a program so heterogeneous and diverse that we cannot intellectually handle or manage the concept anymore. By systematically overtaxing the understanding, such definitions leave a credulous public and policy makers in awe and unable to engage with "nanotechnology" in a meaningful manner. The search for a conceptually manageable definition is thus guided by an interest in specificity but also by a political value – it is to facilitate informed engagement on clearly delimited issues. In purely public contexts, therefore, it is best not to speak of nanotechnology in the singular at all but only of specific nanotechnologies or nanotechnological research programs [44]. In the present context, however, an effort is made to circumscribe the scope or domain of nanotechnoscience, that is, to consider the range of phenomena that are encountered by nanoscience and nanotechnologies. This proves to be a formidable challenge.

(2) Unlimited Potential

There is an easy way to turn the negative description of the domain into a positive one. One might say that nanoscience and nanotechnologies are concerned with everything molecular or, a bit more precisely, with the investigation and manipulation of molecular architecture (as well as the properties or functionalities that depend on molecular architecture).

Everything that consists of atoms is thus an object of study and a possible design target of

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[26] Tellingly, the most sophisticated definition of nanoscience is quite deliberate in saying nothing about the "nanocosm" at all. Indeed, this definition is not limited to nanoscale phenomena or effects but intends a more general nanoscience of scale-dependently discontinuous behaviors at all scales: Nanoscience is everywhere where one encounters a specific kind of novelty or surprise [6].

nanoscale research. This posits a homogeneous and unbounded space of possibility, giving rise, for example, to the notion of an all-powerful nanotechnology as a combinatorial exercise that produces the “little BANG” [45] – since bits, atoms, neurons, genes all consist of atoms, since all of them are molecular, they all look alike to nanoscientists and engineers who can recombine them at will. And thus comes with the notion of an unlimited space of combinatorial possibilities the transgressive character of nanotechnoscience: Categorial distinctions of living and inanimate, organic and inorganic, biological and technical things, of nature and culture appear to become meaningless. Though hardly any scientist believes literally in the infinite plasticity of everything molecular, the molecular point of view proves transgressive in many nanotechnological research programs. It is particularly apparent where biological cells are redescribed as factories with molecular nanomachinery. Aside from challenging cultural sensibilities and systematic attempts to capture the special character of living beings and processes, nanotechnoscience here appears naively reductionist. In particular, it appears to claim that context holds no sway or, in other words, that there is no top-down causation such that properties and functionalities of the physical environment partially determine the properties and behaviors of the component molecules.[27]

This sparsely positive and therefore unbounded view of nanoscale objects and their combinatorial possibilities thus fuels also the notion of unlimited technical potential along with visions of a nanotechnological transgression of traditional boundaries. Accordingly, this conception of the domain of nanoscience and nanotechnologies suffers from the problem of unwieldiness – it can play no rôle in political discourse other than to appeal to very general predispositions of technophobes and technophiles [46].

Three further problems, at least, come with the conception of the domain as “everything molecular out there.” And as before, internally scientific problems are intertwined with matters of public concern. There is firstly the (by now familiar) ”scientific” and “societal” problem that there is no cognizance of limits of understanding and control – as evidenced by a seemingly naive reductionism. There is secondly the (by now also familiar) problem that technoscientific achievements and conceptions have a surplus of meaning which far exceeds what the research community can take responsibility for – the power of images is dwarfed by the power of visions (positive or negative) that come with the notion of unlimited potential. And there is finally the

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[27] I cannot pass judgement on these claims. However, even Richard Jones’s *Soft Machines* [32] with its vivid appreciation of the complexities of “biological nanotechnology” does not reflect the findings of developmental biologists regarding environmental stimuli to gene expression. Recent work on adult stem cells appears to reveal that they can be reverted to earlier states but that they nevertheless “remember” what they were. Such findings complicate immensely the apparently unbounded promise that nanotechnology can solve all problems at the level of molecules.

problem of the relation of technology and nature.

Martin Heidegger, one of the sharpest critics of modern technology chastised it for treating all of nature as a mere resource that is “standing in reserve” to be harnessed by science and industry [47]. The power of his argument derives precisely from the fact that he saw all of modern technoscience as one: It is a scaffolding or harness (the German word is *Gestell)* that recruits humans and nature into a universal scheme of production. Rather than accept as a gift what nature, poetry, or craft brings forth, it demands the deliverance of what it has learned to rationally expect from the study of nature as a calculable system of forces. Conceived as a unified enterprise with an unbounded domain of “everything molecular,” nanotechnology fits the bill of such an all-encompassing modern technology. It does so because it employs what one might call a thin conception of nature. Nature is circumscribed by the physical laws of nature. All that accords with these laws is natural. Thus, nanotechnology can quickly and easily claim for itself that it always emulates nature, that it manufactures things nanotechnologically just as nature does when it creates living organisms. This conception, however, is too “thin” or superficial to be credible and it suffers from the defect that the conditions of (human) life on earth have no particular valence in it: From the point of view of physics and the eternal immutable laws of nature, life on earth is contingent and not at all necessary. The laws predate and will outlive the human species. In contrast, a substantial, richly detailed or “thick” conception of nature takes as a norm the special evolved conditions that sustain life on earth. Here, any biomimetic research that emulates nature will be characterized by care and respect as it seeks to maintain these special conditions. This involves an appreciation of how these conditions have evolved historically. On this conception, context holds sway and a molecule that occurs in a technical system will not be the same as one in a biological system, even if it had the same chemical composition.

It is an open question and challenge to nanoscience and nanotechnologies, however, whether it can embrace such a thick or substantial conception of nature.

(3) A Formidalbe Challange

Just because it is easy to identify at least four major problems with the commonly held view that the domain of nanotechnological research encompasses “everything molecular” does not mean that there is compelling way to avoid those problems. In particular, it appears to defy common sense and the insights of the physical sciences to argue that molecules should have a history or that they should be characterized by the specific environments in which they appear. Is it not the very accomplishment of physical chemistry ever since Lavoisier that it divested substances of their local origins by considering them only in terms of their composition, in terms of analysis and synthesis [48]? And should one not view nanoscience and nanotechnologies as an extension of traditional physics, physical chemistry, and molecular biology as they tackle new levels of complexity? All this appears evident enough, but yet there are grounds on which to tackle the formidable challenge and to differentiate the domain of nanoscientific objects.[28]

As noted above, bulk chemical substances are registered and assessed on the grounds of a physico-chemical characterization. Once a substance is approved, it can be used in a variety of contexts of production and consumption. On this traditional model, there appears no need to consider its variability of interactions in different bio-chemical environments [but see 30]. Though the toolkit of nanotoxicology is still being developed, there is a movement afoot according to which a carbon nanotube is perhaps not a carbon nanotube. What it is depends on its specific context of use: Dispersed in water or bound in a surface, coated or uncoated, functionalized or not – all this is toxicologically relevant. Moreover, a comprehensive physico-chemical characterization that includes surface properties, size, and shape would require a highly complex taxonomy with too many species of nanoparticles, creating absurdly unmanageable tasks of identification perhaps one particle at a time. Instead, the characterization of nanoparticles might proceed by way of the level of standardization that is actually reached in production and that is required for integration in a particular product – with a smaller or larger degree of variability, error-tolerance, sensitivity to environmental conditions, as the case may be for a specific product in its context of use. Nanotoxicology would thus be concerned with product safety rather than the safety of component substances. On this account the particles would indeed be defined by their history and situation in the world, and thus thickly by their place within and their impact upon nature as the specific evolved conditions of human life on earth.[29]

There is another, more principled argument for a thickly differentiated account of the objects that make up the domain of nanoscience and nanotechnologies. The unbounded domain of "everything

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[28] One might argue that a definition requiring scale-dependent discontinuities already does offer such a differentiation [6]. This is not the case, however. It is a beginning at best. As shown above, this definition excludes certain phenomena and processes from nanoscience and thus claims specificity, but it leaves nanotechnology entirely undetermined: Nanoscience tends to certain novel or surprising properties and processes, nanotechnology is *whatever* one can make of these properties and processes. More significantly, however, the appearance of scale-dependent novel properties can be claimed rather generically. Not every property at the nanoscale is discontinuous in respect to scale. However, for every substance one can claim that it may or will have *some* such properties simply in virtue of the proportion of atoms in the boundary layers.

[29] Nanotoxicology in particular, nanotechnological research in general might thus become a "Social Science of Nature" [49].

molecular" includes not only the objects and properties that we now have access to and that we can now measure and control. It also includes those objects and properties that one may gain access to in the future. This way of thinking is indifferent to the problem of actual technical access also in that it does not consider how observational instruments and techniques structure, shape, perhaps alter the objects in the domain. On this account, the domain appears open and unlimited because it implicitly refers to an imaginary (future) state of a non-intrusive and perfectly perceptive presence of observers in the nanoworld. In contrast to this account, the domain could be delimited more concretely and its visionary surplus could be contained more effectively if it did not include all nanoscale objects "out there" but considers how these objects are constituted, how they become accessible to nanoscale research. Accordingly, the domain of objects and processes would consist of just those phenomena and effects that are disclosed by scanning tunneling microscopy and other specifically nanotechnological procedures [50, see also 51].

However, more so than the current attempt to formulate a philosophy of nanotechnoscience, this proposal by Peter Janich ascribes to nanotechnoscience a methodological unity or basis in common practice. He suggests a philosophical program of systematizing the operations by which nanoscale objects become amenable to measurement and observation. Such a systematic reconstruction of the domain of objects of nanotechnological research might begin by looking at length measurement or scanning probe microscopy. However, research practice is not actually unified in this manner. Even scanning probe microscopy – to many a hallmark or point of origin for nanotechnologies – plays a minor rôle in the work of many nanoscale researchers [52]. Also, the above-mentioned struggles to attain standard measures, to characterize nanomaterials testify to the unruliness of the objects of research. They are not constituted through methodical procedures that individuate objects and make them comparable throughout the scientific community. Instead, it appears that they are constituted through complicated interactions that are difficult to reproduce and that rely on proximate likeness.

Since Janich's approach faces considerable odds, all one can do perhaps is to generalize the previous lesson from nanotoxicology: The objects of nanoscale research are constituted through their specific histories – histories that concern their origin (in a tissue sample, in the earth, in a chemically produced batch), that include nanotechnological interventions as well as their location finally in a technical system. This would promote, of course, the fragmentation of "nanotechnology" into as many "nanotechnologies" as there are nanotechnological devices or applications. A nightmare vision for some, this may be an ineluctable prospect for others. If this is so, it becomes impossible to uphold the idea of carbon nanotubes as all-purpose technical components. If they contribute to the performance of some product, then they are individuated or characterized as being carbon-nanotubes-in-that-product, and they are as safe or unsafe as that product is. By the same token, they are no longer conceived as molecular objects that are combinable in principle with just about any other. The open space of unlimited potential differentiates into a manifold of specific technological trajectories.

The formidable challenge has not been met by this proposal. It does help dramatize, however, the inherent tension in the commonly held view of nanotechnological objects, as well as the difficulties (once again) of prediction and control at the nanoscale.

V. FROM EPISTEMIC CERTAINTY TO SYSTEMIC ROBUSTNESS

(1) What do Nanoscientists Know

The previous sections considered research practices of nanotechnosciences – how theories are stretched to the complexities at the nanoscale, how a qualitative methodology serves the construction of likeness and inferences from that likeness, how the research objects are individuated and encountered. All these practices contribute to the generation of knowledge but it remains to be explored in which sense this is "objective knowledge." As in traditional science, the findings of nanotechnoscientific research are published in scientific journals, so the questions is, more concretely, what kind of knowledge is expressed or communicated in a nanoscientific journal article. To answer this question properly, contrasts need to be established and particular publications compared. Here, a summary must suffice.

A typical research article of classical science states a hypothesis, offers an account of the methods, looks at the evidence produced, and assesses the hypothesis in light of the evidence. It participates in a public process of evaluating propositions, of finding certain beliefs or statements true or false, and of seeking certainty even where it is impossible to attain. In contrast, a technoscientific research article provides testimony to an acquired capability. It offers a sign or proof of what has been accomplished in the laboratory and tells a story of what has been done. The telling of the story does not actually teach the capability but it offers a challenge to the reader that they might develop this capability themselves. As opposed to epistemic knowledge (concerned with truth or falsity of propositions), nanoscale research produces skill knowledge. This is not an individualized skill, however, or tacit knowledge. Acquired capabilities can be objective and public, specifically scientific, and communicable. They grasp causal relations, and establish habits of action. They are assessed or validated not by the application of criteria or norms but by being properly entrenched in a culture of practice. One cannot judge their truth or falsity (skills aren't true or false) but by the robustness of demonstrability: If one has acquired a capability, one can more or less consistently do something in the context of an "apparatus-world complex" [38]. As opposed to the truth or falsity, certainty or uncertainty of hypotheses, the hallmarks of technoscientific knowledge are robustness, reliability, resilience of technical systems or systematic action.

(2) The Knowledge Society

This account of skill knowledge presses the question of where the "science" is in "technoscience." The answer to this question can be found in the very first section of this article: It is in the (closed) theories that are brought as tools to the achievement of partial control and partial understanding. Nanotechnoscience seeks not to improve theory or to change our understanding of the world but merely to manage complexity and novelty. As such, nanotechnoscience is just technical tinkering, just product development, just an attempt to design solutions to societal problems or to shape and reshape the world. However, the conceptual and physical tools it tinkers with do not come from ordinary experience, from common sense and a craft tradition but concentrate within them the labors of science. So, the "science" of "nanotechnoscience" is what goes into it. What comes out is skill knowledge and it does not rely on a corresponding scientific understanding. As long as one can produce an effect in a reasonably robust manner, it does not really matter whether scientific understanding catches up. Indeed, the complexities may be such that it cannot fully catch up.[30]

The standard example of technology being ahead of science is the steam engine which was developed without a proper understanding of the relation between heat and work [53]. This understanding came much later and, indeed, was prompted by the efficient performance of the steam engine. The steam engine itself was therefore not applied science but the result of technical tinkering. It was made of valves, pumps, gears etc. of which there was good non-scientific craft-knowledge – and it worked just fine before the advent of thermodynamics. In a sense, it didn't need to be understood.

As opposed to the steam engine, nanotechnological devices (whatever they may be), genetically modified organisms, drug delivery systems are offsprings of the knowledge society. They are not made of valves and pumps but assembled from highly "scientized" components such as algorithms, capabilities acquired by scientifically trained researchers, measuring and monitoring devices with

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[30] This diagnosis is not entirely novel or surprising. Technology, writes Heidegger, is always ahead of science and, in a deep sense, science is only applied technology [47]. By this he means not only that laboratory science requires instruments and experimental apparatus for stabilizing the phenomena. He means more generally that a technological attitude informs the scientific way of summoning phenomena to predictably appear once certain initial conditions are met.

plenty of knowledge built in [39]. The science that goes into the components is well-understood, not so the interactions of all the components and their sensitivities in the context of the overall technical system. Still, like the steam-engine it may work just fine without being fully understood. And though one cannot attain positive knowledge from which to derive or predict its performance, we may learn to assess its robustness.

(3) Social Robustness

The shift from hypotheses that take the form of sentences to actions within techno-cultural systems, from epistemic questions of certainty to systemic probes of robustness has implications also for the "risk society" that looks to government mostly for protection from risk [54].[31]

Expectations of certainty and assurances of safety will not be met by nanotechnologies. Other technologies already fail to meet them. Certainty about the safety of a new drug, for example, is produced by the traditional method of a clinical trial that establishes or refutes some proposition about the drug's efficacy and severity of side-effects. A far more complex and integrated mechanism is required where such certainty is unattainable and where robustness needs to be demonstrated. Here, several activities have to work in tandem, ranging from traditional toxicology, occupational health, and epidemiology all the way to the deliberate adoption of an unknown risk for the sake of a significant desired benefit. If this integration works, social robustness will be built into the technical system along with the robustness of acquired skills, tried and true algorithms, measuring and monitoring apparatus. The fact that nanoscale researchers demonstrate acquired capabilities and that they thus produce "mere" skill knowledge, creates a demand for skill knowledge also in a social arena where nanotechnological innovations are challenged, justified, and appropriated.

VI. WHAT BASIC SCIENCE DOES NANOTECHNOLOGY NEED?

The preceding sections provided a survey of nanotechnoscience in terms of disciplinary questions (a complex field partially disclosed by stretching closed theories), of methodology (constructions and qualitative judgments of likeness), of ontology (a thin conception of nature as unlimited potential), and of epistemology (acquisition and demonstration of capabilities). This does not exhaust a philosophical characterization of the field which would have to include, for example, a sustained

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[31] The precautionary principle refers to the certainty and uncertainty of knowledge regarding risks. Where technology assessment shifts from truth of sentences about risk to the robustness or resilience of emerging technical systems and their interaction with other technical systems, the precautionary principle is not applicable and a different kind of prudential approach is required – for example, Dupuy and Grinbaum's "ongoing normative assessment" [55].

investigation of nanotechnology as a conquest of space or a kind of territorial expansion.[32] Also, nothing has been said so far about nanotechnology as an enabling technology that might enable, in particular, a convergence with bio- and information-technologies. Finally, it might be important to consider nanotechnoscience as an element or symptom of a larger cultural transition from scientific to technoscientific research.

This survey is limited in other ways. It glossed over the heterogeneity of research questions and research traditions. And it focused exclusively on the way in which nanotechnological research has developed thus far. There is nothing in the preceding account to preclude profound reorientations of nanoscience and nanotechnologies. Indeed, one reorientation might consist in the whole enterprise breaking apart and continuing in rather more traditional disciplinary settings – with “nano” ceasing to be a funding umbrella but becoming a prefix that designates a certain approach. Thus, under the sectoral funding umbrellas “food and agriculture,” “energy,” “health,” “manufacturing,” or “environment” researchers with the “nano”-prefix would investigate how problems and solutions can be viewed at the molecular level. Their work would then have to be integrated into more comprehensive approaches to the problem at hand.

Alternatively, nanotechnological researchers may pursue and promote disciplinary consolidation and unification.[33] In that case, they might be asking the question “what kind of basic science does nanotechnology need?” From quantum mechanics, hydrodynamics, etc. derive the (closed) theories that serve as the toolkit on which nanoscale research is drawing. While these are basic sciences, of course, they are not therefore the basis of nanoscience. What, then, is the basic scientific research that needs to be done in order to properly ground nanotechnologies or to establish nanoscience as a field in its own right? There are no attempts so far to address this question in a systematic way.[34] And obviously, one should not expect any consensus regarding the following list of proposed basic research for nanotechnology.

In terms of empirical grounding or a theoretical paradigm, some call for general theories of (supra-)molecular structure-properties relations, others imagine that there will be a future science of

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[32] One implication of this is that nanotechnology should not be judged as the promise of a future but, instead, as a collective experiment in and with the present [56].

[33] The field of “nanomedicine” appears to be moving in that direction by distinguishing its research questions and paradigms from “medical nanotechnologies.” It is not at all clear yet whether nanomedicine will emerge from this with a disciplinary identity of its own, including perhaps a unique body of theory.

[34] To be sure, there are piecemeal approaches. One might say, for example, that a theory of electron transport is emerging as a necessary prerequisite for molecular electronics (but see [57]). Also, the giant magnetoresistance effect might be considered a novel nanotechnological phenomenon that prompted “basic” theory development [13].

molecular and nanotechnical self-organization.[35] Following the suggestion of Peter Janich (see above, section 3.2), one might identify and systematize how nanoscale phenomena are constituted through techniques of observation and measurement – this might render theories of instrumentation basic to nanoscience.[36]

Another kind of basic research, entirely, would come from so-called *Bildwissenschaft* (image or picture-science) that could provide a foundation for image-production and visualization practice in nanotechnoscience. Such investigations might contribute visual clues for distinguishing illustrations from animations, from simulations, from visualizations of microscopically obtained data. It might also investigate image-text relations or develop conventions for reducing the photographic intimations of realism while enhancing informational content.[37]

Finally, one might ask, whether nanotechnoscience can and should be construed as a "social science of nature."[38] As an enabling, general purpose, or key technology it leaves undetermined what kinds of applications will be enabled by it. This sets it apart from cancer research, the Manhattan project, the arms race, space exploration, artificial intelligence research, etc. As long as nanotechnoscience has no societal mandate other than to promote innovation, broadly conceived, it remains essentially incomplete, requring social imagination and public policy to create an intelligent demand for the capabilities it can supply. As research is organized to converge upon particular societal goals [61], nanoscience and nanotechnology might be completed by incorporating social scientists, anthropologists, philosophers in its ambitions to design or shape a

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[35] See, for example, [15]. In [14] Michael Roukes calls for the identification of the special laws that govern the nanoscale. To be sure, there is profound skepticism in the scientific community a) that there can be laws of structure-property relations at the nanoscale, and b) that they are needed in order to pursue nanotechnological research. On this latter view, the account provided in the first four sections of this paper provides quite sufficient "grounding" of nanotechnology.

[36] See, for example, [58] on modeling of measurements at the nanoscale. Can this kind of theory development and modification serve to constitute a nanoscale research community – or does it belong to a special tribe of instrument developers that merely enters into a trade with other nanotechnology researchers [59]?

[37] Compare the suggestion by Thomas Staley (at the conference *Imaging Nanospace*) that visualizations of data could be constructed like maps with graphic elements even text imposed upon the quasi-photographic image [60]. This might break the animistic spell of the powerful image (see above) and restrict the image to the scientific community.

[38] See notes 3 and 22 above. The term *Soziale Naturwissenschaft* was coined in the context of the finalization thesis and could be designated more literally as a social natural science – science of a nature that is socially shaped through applied science, technology and human action. It is thus not social science but an integrated approach that acknowledges the social character of the world. Here, this proposal is taken up in two ways. Materials (as opposed to matter) and molecules defined by their history and situation are social entities, as such objects of this socials science of nature. Secondly, nanotechnoscience is a program for shaping and reshaping, designing and redesigning, for reforming the world. To the extent that this is also a social reform it is systematically incomplete without societal agenda-setting: What are the projects, the problems to be solved, the targets and design norms of nanotechnoscience?

world atom by atom.

Nanotechnologies are frequently touted for their transformative potential, for bringing about the next scientific revolution. This paper did not survey a revolutionary development, but pragmatic and problematic integrations of pre-existing scientific knowledge with the novel discoveries at the nanoscale. If one expects science to be critical of received theories and to produce a better understanding of the world, if one expect technology to enhance transparency and control by disenchanting and rationalizing nature, these pragmatic integrations appear regressive rather than revolutionary. Once one makes the shift from epistemic certainty to systemic robustness, these pragmatic integrations hold the promise of producing socially robust technologies. In the meantime, there is little incentive and no movement to seriously consider the question of a disciplinary reorientation and consolidation of the nanosciences and nanotechnologies. A nanotechnological revolution has not happened yet, we may be waiting for in vain, and this is probably a good thing.[39]

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