Philosophia Scientiæ

Travaux d'histoire et de philosophie des sciences

23-1 | 2019

Y a-t-il encore de la place en bas ?

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Electronic version

URL: <http://journals.openedition.org/philosophiascientiae/1773>

DOI: 10.4000/philosophiascientiae.1773

ISSN: 1775-4283

Publisher

Éditions Kimé

Printed version

Date of publication: 18 February 2019

Number of pages: 99-119

ISSN: 1281-2463

Electronic reference

Alfred Nordmann, "NanoTechnoScience for Philosophers of Science", *Philosophia Scientiæ* [Online], 23-1 | 2019, Online since 01 January 2021, connection on 31 March 2021. URL: <http://journals.openedition.org/philosophiascientiae/1773> ; DOI: <https://doi.org/10.4000/philosophiascientiae.1773>

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NanoTechnoScience for Philosophers of Science

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Résumé: Au cours des dernières décennies, la philosophie des sciences est devenue la philosophie des sciences particulières. En conséquence, certaines des questions majeures de la philosophie des sciences sont adressées à la recherche en nanosciences et technologie. C’est le cas notamment des questions concernant la nature de la connaissance, le rôle de la théorie, les pratiques expérimentales et observationnelles. Ces questions habituelles suscitent des réponses inattendues, suggérant que la nanotechnoscience est un exemple non pas d’une science mais d’une technoscience.

Abstract: In recent decades, the philosophy of science has become philosophy of the special sciences. Accordingly, some of the main questions of the philosophy of science are brought to nanoscale research. These are questions regarding the nature of knowledge, the role of theory, accounts of experimental and observational practice, and others. As it turns out, however, the familiar questions elicit unfamiliar answers, suggesting that nanotechnoscience is an instance not of science but of technoscience.

“Nanotechnoscience” is more than shorthand for “nanoscience and nanotechnologies” but signifies a mode of research that is neither science nor engineering¹. Peter Galison, for example, speaks of an “engineering way of being within the sciences” when he characterizes nanotechnological research:

A focus on novel effects, materials, and objects, but constructed through an engineering way of being that values the making and linking of structures with little regard for the older fascination with existence for its own sake. [Galison 2017, 25]

Philosophia Scientiæ, 23(1), 2019, 99–119.

1. This text integrates, revisits, updates, and revises two earlier publications: “Philosophy of Nanotechnoscience” [Nordmann 2008], and “Philosophy of Technoscience in the Regime of Vigilance” [Nordmann 2010].

Along such lines, science and technoscience can be distinguished as follows: Science uses experiments, measurements, research technologies in order to produce representations and forge an agreement between theory and reality, mind and world. Technoscience uses theories, models, and scientific knowledge in order to achieve predictive and technical control and make things work [Bensaude-Vincent, Loeve *et al.* 2017, 3–5]. As for the philosophy of science and the philosophy of technoscience, they ask many of the same questions but answer them differently. This will now be shown in a cursory way for the philosophy of nanotechnoscience and its seven unfamiliar responses to seven familiar questions:

1. What is the role of theory and theory-development in nanoscale research, and what kinds of theories are needed for nanotechnological development?
2. What are the preferred modes of reasoning, methods and associated tools in nanoscientific research?
3. What is the domain of objects that are of interest to nanotechnoscience?
4. What kind of knowledge do nanotechnoscientific researchers typically produce and communicate?
5. What kind of basic science could provide a foundation for nanotechnoscience?
6. What sorts of experiments are performed in nanotechnological research, what is its mode of experimentation?
7. What is observation, how do nanotechnology researchers observe their experiments and see with and through their instruments?

All seven questions are of primarily epistemological and methodological significance—they tell us what NanoTechnoScience *is* in terms of presuppositions and aspirations, epistemic values and practices. And yet, the answers to these questions have societal dimensions and implicate ethical or political values. Here, these will only be hinted at by way of a closing remark at the end of each section.²

1 Closed theories

In the late 1940s, physicist Werner Heisenberg introduced the notion of “closed theories” [Heisenberg 1974]. In particular, he referred to four closed theories:

2. While there may be such a thing as pure or value-free science, there is no pure technoscience. For a more extensive consideration of the intersection between epistemology and ethics, broadly conceived, see the publications cited in the previous note.

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 [Heisenberg 1974].

All this holds for nanotechnoscience: It draws on an available repertoire of theories that are closed in regard to the nanoscale, and it is concerned neither with the critique or further elaboration of these theories, nor with the construction of theories of its own.³ This is not to say, however, that closed theories are simply “applied” in nanotechnoscience.

When Heisenberg refers to the hermetically closed domain of closed theories, he states merely that the theory will be true where its concepts *can* be applied and leaves quite open the domain of its actual applicability. 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” [Heisenberg 1974]. 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. 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 into the domain of the theory such that its concepts can be applied to them.

This notion of “application” has been the topic of recent discussions—but it does not capture the case of nanotechnoscience. Here, researchers are not

3. There is more to be said about the lack of theory development in and for nanotechnoscience. One counterexample might be the discovery and subsequent theoretical work on the giant magnetoresistance effect [Wilholt 2006]. Also, there have been calls for the development of theory specifically suited to the complexities of the nanocosm [Roukes 2001], [Eberhart 2002]. These voices remain isolated, however. Also, if there were theories of and for nanotechnology, would they describe an underlying structure and reality, or would they anticipate a world that can arise only under conditions of perfect technical control at the vanishing point of engineering [Nordmann 2017]?

trying to bring nanoscale phenomena into the domain of quantum chemistry or fluid dynamics or the like. They are 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 accounting for this complexity, no theories, for example, of structure-property relations at the nanoscale.⁴ 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 in such a way 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.⁵ A particular measure of the flow of current through an organic-inorganic molecular complex 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 [Nordmann 2004].

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 to bear that are not made specifically for the task. Accordingly, the business of explanation becomes transformed into one of re-construction. Rather than offering a theoretical description that satisfies the human intellect, there is a demonstration that bits and pieces of theory can be joined together or modularized so as to yield the observed event in a computer model. If the language of “fitting” derives from a representational idiom of making a picture that fits the situation and *vice versa*, this practice of “stretching” emphasizes that theories provide modular components for the re-construction of a process *in silico*. Indeed, nanoscale research is characterized by a tacit consensus according to which the following three propositions 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.

4. The term “complexity” is used here in a deliberately non-technical manner. The complexity at the nanoscale is one of great messiness, of too many relevant variables and properties, and multiple complicated interactions.

5. There is another dimension to this: 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. Instead, in nanotechnoscience the challenge is that of crossing from the intended domain of a classical theory into quite another domain.

2. The nanoscale holds intellectual and technical interest because it is an “exotic territory” [Roukes 2001], 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 re-construct—by stretching rather than fitting—novel properties, behaviors, or processes.

Taken together, these three statements express a characteristic tension concerning nanotechnology, namely that on the one hand it is thought to be strange, novel, and surprising while on the other hand it is familiar and manageable. 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 boils down to a matter of expediency and taste when it comes to choosing modular bits and pieces of theory from the perspectives of classical or quantum physics. Put 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 classical and quantum approaches prove resourceful enough when it comes to reconstructing these phenomena.

As for the societal dimensions of all this—theories that are closed relative to the nanoscale and stretched to provide explanations, do not suggest limits of what is technically possible. Especially in the early days of nanotechnology, this gave rise to an image of nanotechnology as an unlimited storehouse of goods.

2 Qualitative reasoning

As was shown above, Heisenberg considered the extent to which phenomena of experience can be fitted to closed theories as “a question of success” [Heisenberg 1974], and one can consider the extent to which elements of closed theories can be stretched to account for phenomena of experience in the same terms. This suggests the follow-up question as to what “success” amounts to in nanoscale research: What does it take to satisfy oneself that one has reached a sufficiently good understanding or control of the phenomena under investigation?

For Heisenberg himself and those philosophers of science who follow the paradigm of theoretical physics, the question boils down to the predictive success of quantitative science. Here, “quantitative” means more than the employment of numbers or precision measurements. The characteristics of

quantitative approaches include the following: First, predicted numerical values are compared to values obtained by measurement. The reasonably close agreement between two numbers then 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 is satisfied if it reliably leads from initial conditions to accurate predictions, it does not require that all the details of its conceptual apparatus or every term in its equations has a counterpart in reality. Both characteristics of quantitative science are familiar especially from 20th century theoretical physics—but do they hold for nanotechnoscience?

Although there may not be a general answer to this question, it is fair to say that much nanotechnoscientific research is qualitative. To be sure, phenomena are measured and described with the utmost quantitative precision. And yet, epistemic success consists in constructions of likeness or similarity. In other words, in nanotechnoscience the quantitative agreement of predicted and measured quantities is replaced by a qualitative agreement of calculated and experimental images. One hallmark of the achievement of likeness or similarity is the absence, even deliberate suppression of visual clues by which to hold calculated and experimental images apart. Instead, there has been a pronounced tendency to blend and even fuse them: The mere fact of a seamless transition between them serves as an argument of sorts according to which the calculated image or model captures the relevant structure or dynamics of the experimentally observed entity or behavior.

Since an extensive analysis of this practice cannot be provided here, a description must do. It starts with (nano)technoscientific researchers comparing two seemingly distinct images on their displays or computer screens. One of the displays 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 observed process—and for this simulation to be readable as such, the simulation software has produced a visual output that is designed to look like the output of an electron or scanning probe microscope. Agreement between two similarly processed images gives the researchers license to draw inferences about probable causal processes and to suggest that they understand these processes, perhaps creating and participating in them. The mere likeness of the images appears to warrant inferences from the mechanism modeled in the simulation to the mechanism responsible for the experimentally obtained data. Accordingly—and this has not been done as yet—one could investigate how nanoscale researchers construct mutually reinforcing likenesses, how they calibrate not only simulations to observations and visual representations to physical systems, but also their own devices to extant devices, their own work to that of others, and current findings to long-term visions. This kind of study would show that the community of researchers is not unified by an overarching paradigm or theoretical framework but by the availability of a large

tool-kit of theories, concepts, strategies, and techniques. Instead of theories, it is instruments (STM, AFM, etc.), their associated software, techniques and exemplary artefacts (buckyballs, carbon nanotubes, gold nanoshells, molecular wires, graphene), that provide relevant common referents [Mody 2004], [Hennig 2006], [Johnson 2006], [Marcovich & Shinn 2014].

Peter Galison has referred to this qualitative orientation as “ontological indifference”: Nanoscale research does not seek to decide what is and what is not, what are fundamental features of the world and what is inferred or derived [Galison 2017]. Since such questions are central in physics with its fundamental particles and hierarchical composition of matter, how is it that nanotechnological research can afford to do without? For example, molecular electronics researchers may invoke more or less simplistic pictures of electron transport but they do not reflect much on the nature and 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 [Nordmann 2004]. Many physicists and philosophers of physics would object to such blatant disregard for the strangely immaterial and probabilistic character of the quantum world that is the home of electrons, orbitals, and standing electron waves [Scerri 2000], [Vermaas 2004]. 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.⁶

Ontological indifference amounts to a disinterest in questions of representation and an interest, instead, in substitution and immersion. Rather than use 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. Accordingly, only after generating a highly complex system from simple parts (e.g., a simulation model or experimental system), they then begin to reduce complexity by observing the behavior and parameter-dependencies not in “nature out there”, but in some domesticated chunk of reality in the computer or 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 tested components of substitute realities that manage to emulate real physical systems [Harré 2003]. In other words, there is so much reality in their simulations or constructed experimental systems, that nanotechnology researchers can take them for reality itself [Winsberg 2009]. They study these substitute systems and, of course, these systems provide prototypes for technical devices or applications. While the public is still awaiting significant

6. A particularly interesting and challenging example of this is Don Eigler’s famous image 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.

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.

Instead of producing a symbolic picture of reality, researchers learn to inhabit an artefactual or manufactured reality that displaces the observed reality. At the height of contemporary scientific and technological development, we therefore encounter a mode of thought which is characteristic of prescientific magical thinking. The pseudo-science of physiognomy, for example, is based on the idea that there is a meaningful likeness between the facial features and the character of a person—both participating in the same reality of which they are only two different aspects. With the reappearance of such forms of reasoning, societies will need to reassess the classical ideal of critical science in the service of Enlightenment.

3 The objects of interest

Any field of research is directed at a certain domain of objects and what unifies this domain is a particular way of conceiving these objects. Mechanics, for example, looks at all phenomena of motion. Everything that can be assigned coordinates in time and space and that has mass is an object of mechanics and is of interest in regard to those properties that make it an object of motion. The philosophy of science articulates this world-view of mechanics and asks, for example, to what extent certain conceptions of time and space prejudice the investigation of objects in motion. If one now asks about nanotechnological research, the philosophy of technoscience may offer something like the following characterization of its domain of objects: Nanotechnological research considers properties, traits, or features in regard primarily to their potential technical function, and in regard only incidentally to structure.

On a first approach, 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 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” (ETC Group 2003)—since bits, atoms, neurons, genes all consist of atoms and all of them are molecular, they all look alike to nanoscientists and engineers who can recombine them at will. And thus, categorial distinctions of living and inanimate, organic and inorganic, biological and technical things, of nature and culture appear to become meaningless with the notion of an unlimited

space of combinatorial possibilities. Though hardly any scientist believes literally in the infinite plasticity of everything molecular, the molecular point of view proved transgressive in many nanotechnological research programs. It is particularly apparent where biological cells are described as factories operating 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 does not usually acknowledge any influence of the context or environment of molecular structures, thereby excluding top-down causation from wholes to parts that would determine the properties and behaviors of component molecules.⁷

Conceived as a unified enterprise with an unbounded domain of “everything molecular”, nanotechnology fits the bill of an all-encompassing modern technology along the lines of Heidegger’s *Gestell* that treats everyone and everything as a material resource for the achievement of technical control. It does so because it employs what one might call a “thin” conception of nature: Nature is circumscribed by the physical laws of nature and 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 failing that the conditions of (human) life on Earth have no particular place 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. These laws predate and will outlive the human species.

In contrast, a substantial, more 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 derives from an attitude of care and respect as it seeks to maintain these special conditions. This would involve an appreciation of how these conditions have evolved historically. On this conception, a molecule that occurs in a technical system will not be the same as one in a biological system, even if they share the same chemical composition. Instead of considering the nature or essence of objects in terms of structure-property relations, nanotechnology is interested in their power or potency—what they can or what they will be.⁸ However, it once again remains an open question and challenge to nanoscience and nanotechnologies whether they can really integrate such a thick or substantial conception of nature.

7. Even Richard Jones’s *Soft Machines* [Jones 2004] with its vivid appreciation of the complexities of “biological nanotechnology” does not reflect the epigenetic findings of developmental biologists regarding environmental stimuli to gene expression. These findings complicate immensely the promise of robust nanotechnology.

8. This ontological conception of (not only) nanotechnology’s attractive objects was the subject of the GOTO project on the Genesis and Ontology of Technoscientific Objects [see Bensaude-Vincent, Loeve *et al.* 2017].

If the thin conception of “everything molecular” yields a fantastically broad domain of objects, and if a more contextual, thick conception appears to be too challenging and perhaps too limiting, a third attempt to limit the domain of objects would foreground instrumental and experimental practice: The domain of objects and processes does not include all nanoscale objects “out there” but consists of just those phenomena and effects that are revealed by scanning tunneling microscopy and other specifically nanotechnological procedures. It was Peter Janich, in particular, who ascribed to nanotechnoscience a methodological unity based on common practice [Janich 2006], [see also Grunwald 2006]. He suggested 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. Unfortunately, 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 role in the work of many nanoscale researchers [Baird & Shew 2004]. Also, the struggles to attain standard measures, or to characterize nanomaterials, testify to the unruliness of the objects of research.

In light of the shortcomings of all three approaches, what remains is the idea that the specific rather than envisioned objects of nanoscale research are constituted through their particular 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. 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. 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.

For technology assessment and especially the assessment of risk and safety, this would imply a shift of perspective from component materials to integrated systems or devices—a carbon nanotube would be as safe or unsafe as the product in which it appears.

4 From epistemic certainty to systemic robustness

The previous sections considered research practices of the nanotechnosciences—how theories are stretched to deal with the complexities at the

nanoscale, how a qualitative methodology serves the construction of likeness and inferences from that likeness, and how the research objects are individuated and encountered. All these practices contribute to the production of knowledge, but the sense in which this is “objective knowledge” needs to be explored. As with more classical science, the findings of nanotechnoscientific research are published in scientific journals, so the question is, more concretely, what kind of knowledge is expressed or communicated in a nanoscientific journal article? Instead of answering this question in a properly detailed and differentiated manner, a somewhat schematic summary must suffice here [Nordmann 2012].

A typical research article in 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. In contrast to “hypothesis testing”, a technoscientific research article provides testimony for 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 the truth or falsity of propositions), nanoscale research produces working knowledge—that is, knowledge of how things can work together within a working order.⁹ Working knowledge can be objective and public, scientific and communicable. It grasps causal relations, and establishes habits of action. It is validated or assessed not by the application of criteria or norms but by being properly entrenched in a culture of practice. Only propositions can be true or false not attunement to a working order: by demonstrably acquiring a capability, one can more or less consistently effect something in an “apparatus-world complex” [Harré 2003]. As opposed to the truth or falsity, certainty or uncertainty of hypotheses, the hallmarks of technoscientific knowledge are robustness, reliability, and resilience of technical systems or systematic action.

This account of working knowledge pushes the question of where the “science” is in “technoscience” to the fore. The answer to this question can be found in the very first section above: 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 to manage complexity and produce novelty. As such, nanotechnoscience is technical tinkering, product development, search for design solutions to societal problems, an attempt to shape and reshape the

9. This particular notion of “working knowledge” originated in [Baird & Nordmann 1994]. It should be distinguished from thing knowledge on the one hand, from personal skill or tacit knowledge on the other hand. Even when it is non-propositional, it is based in public performances of construction, maintenance, or repair. It consists in a demonstrable grasp of how things can be brought to exhibit their capacities in the context of specific works of human art—as such subject to scrutiny, assessment, prodding.

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 in the theoretical tools that enter into the research process. What comes out is working knowledge which cannot be reduced to scientific understanding or a theoretical description of how things are. 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.

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 [Baird 2004]. This understanding came much later and, indeed, was prompted only 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 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 products, genetically modified organisms, or drug delivery systems are all 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 plenty of knowledge built in [Winsberg 2009]. The science that goes into the components is well-understood, but 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.

The fact that nanoscale researchers demonstrate acquired capabilities, and that they thus produce “mere” working knowledge, creates a demand for working knowledge also in a social arena where nanotechnological innovations are challenged, justified, and appropriated. The shift from propositional hypotheses to actions within techno-cultural systems, from epistemic questions of certainty to systemic probes of robustness has implications also for the production of socially robust technologies which requires working knowledge of how things work in a society.

5 Scientific foundations for an open science

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 investigation of nanotechnology as a conquest of space or a kind of territorial expansion.¹⁰ 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 exemplar 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. If there is to be a common denominator for the nanoscale research, this invites the speculative question: “What kind of basic science is required by and for nanotechnology?” From quantum mechanics or hydrodynamics derive the (closed) theories that serve as the toolkit for nanoscale research. While these are basic sciences, of course, they are not therefore the basis of nanoscience. What, then, is the basic scientific research that might properly ground nanotechnologies or establish nanoscience as a field in its own right? Interestingly, perhaps characteristically, there are no attempts so far to address this somewhat speculative question in a systematic way.¹¹ And obviously, one should not expect any consensus regarding the following proposals.

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 molecular and nanotechnical self-organization, for example [Eberhart 2002], or [Roukes 2001]. Following the suggestion of Peter Janich (see above), 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, for example [Clifford & Seah 2006], [Marcovich & Shinn 2014].

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 in nanotechnoscience. Its investigations might contribute clues for distinguishing visualizations of microscopically obtained data from animations and simulations. This science might also investigate image-text relations or develop conventions for reducing the photographic intimations of realism while enhancing informational content.

10. 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 [Nordmann 2007].

11. 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 Tao 2006]. Also, the giant magnetoresistance effect might be considered a novel nanotechnological phenomenon that prompted “basic” theory development [Wilholt 2006]. Compare also [Nordmann 2017].

A third possibility is to ask whether nanotechnoscience can and should be construed as a “social science of nature” [Böhme & Schäfer 1983].¹² 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, requiring social imagination and public policy to create an intelligent demand for its capabilities. As such a paradigmatically “open science”, it relies on social scientists, anthropologists, philosophers to realize its ambitions of shaping a world atom by atom.

A science of mesocosmic order, a science of instrumentation and imaging, a social science of nature can be conceived as basic to nanotechnological research. In fact, nanotechnology remains fairly indifferent to any such attempts of grounding it. What remains then, is the question not of basic science but of basic technoscience which establishes capabilities of measurement, intervention, visualization, and thus a mastery of complexity that remain irreducible to underlying theory.

Instead of a new systematic understanding of complexity at the nanoscale, nanotechnoscience achieves pragmatic and problematic integrations of pre-existing scientific knowledge with novel discoveries and capabilities. If one expects science to be critical of received theories in order to produce a better understanding of the world, and if one expects technology to enhance transparency and control by disenchanting and rationalizing nature, these pragmatic integrations appear regressive rather than progressive or even revolutionary. However, if instead of epistemic certainty one seeks systemic robustness, these integrations hold the promise of producing socially robust technologies.

6 Collective experimentation

Quite independently of what uses experiments are put to, they consist first and foremost in the stabilization of a phenomenon in a laboratory—experiments make something observable, measurable, and replicable that does not exist as such outside controlled laboratory conditions. This is surely what nanotechnological experiments do, too. But they do not end here.

12. The term *Soziale Naturwissenschaft* was coined in the context of the finalization thesis and refers to a “social science of nature” as well as a “science of social nature”. Here, this proposal is taken up in two ways. As opposed to matter, materials are social entities and, as such, objects of this social science of nature—as are molecules which are defined by their history and situatedness. Secondly, nanotechnoscience is a program for shaping and designing, that is, 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?

All the novel phenomena and surprising properties that are discovered in nanotechnological laboratories mark the beginning of a process of “delocalization” [Galison 1997]. Phenomena leave their place of origin and become delocalized by being stabilized in the laboratory, then rendered robust enough to be reproducible under varying conditions in other laboratories, then scaled up and moved out of the laboratory altogether into the world at large of technical devices. This process of delocalization aims for a seamless transition from laboratory to market-place as technical processes or phenomena become more robust or viable. It is therefore misleading to imagine that these processes and phenomena are brought to completion in the scientific laboratory and then handed over or “transferred” to engineers and commercial development. Instead, the world at large is just a larger laboratory in which these processes and phenomena can prove themselves.

In order to take literally the notion of collective experimentation in society as a laboratory, one needs to attend to the various features of experimentation writ large [Krohn & Weyer 1994], compare [Groß, Hoffmann-Riem *et al.* 2005], [Schwarz 2014]. As with all laboratories, this one is standardized in a variety of ways, and as with all experiments, these require systematic observation to support a learning process. In particular, the immersive aspect of experimentation in the laboratories of technoscience and society deserve to be explored. Where the experimenters and observers are also the guinea pigs and *vice versa*, where experiments do not serve the advancement of truth but the experience and management of surprising features and effects, the mode and manner of experiencing and observing the experiments is I believe crucially important.

For social learning from collective experiments to take place, proper institutions are required for their more or less systematic observation. In the case of nanotechnologies, the question of regulation is tied in with the search for such institutions. There is on the one hand the sceptical question whether current methods of data-collection and monitoring will prove to be adequate; and there is on the other hand the search for new instruments such as codes of conduct, observatories, public engagement exercises, citizens and consumer conferences, as well as “ELSA”-research or Responsible Research and Innovation. Though vaguely defined and lacking proper agency, these new institutions serve a general form of permanent vigilance.

7 Observatories and other agencies

Even for observation with the naked eye, it has been shown that it is neither passive nor neutral but, in the words of Norwood Russell Hanson [Hanson 2007], “theory-laden”. When we see the sun rising and setting, our observation corresponds to an implicit theory when we “should” be seeing the Earth turning against the sun. And when a lay-person looks at a prepared tissue

sample, she tends to see nothing at all, whereas the trained eyes of the pathologist comprehend the situation immediately and seemingly without an explicit act of interpretation. The difficult, perhaps intractable question of immediate, yet theory-laden observation becomes more difficult even in the case of technoscience and in the case of observing the collective experiment with nanotechnologies in society.

Ian Hacking famously asked “Do we see through a microscope?” [Hacking 1981]. Discussing light microscopy as well as electron microscopy, he argues that we do not see “through” an electron microscope as through a tube but that we see “with” advanced microscopes. We see with them because seeing is not merely passive or reactive but is based on strategic interventions: We literally throw light at what we are hoping to see and utilise laws of refraction to receive an image that we can interpret. Therefore, even in 19th century, light microscopy observation was wrapped up with an experimental intervention of sorts. But even though electron microscopy might appear more mediated and inferential than light microscopy, this does not make it less reliable. One of the ways in which electron microscopy is highly inferential is the fact that it is calibrated to light microscopy—it is set up in such a way that it agrees with light microscopy. So even where, in the end, one does not look through a lense but at a display screen, the display gives us a way of seeing the world much as a television set does. For the expert, then, scientific observation involves a technically contrived effortlessness or mediated immediacy—it is conceptually complicated and perceptually simple.

With regard to nanotechnologies, Hacking’s question should now be extended: “Do we see through a scanning tunnelling microscope?” One of the distinctive features of the STM is that it is used to intervene not only by making visible but also by way of manipulating the objects under observation. A second distinctive feature of STM microscopy consists in its twofold calibration. Its data set is calibrated to electron microscopy on the one hand, and on the other hand its visual output is calibrated to topographic software that is used in geography, simulation modelling and video gaming—this software is best suited for the representation of what goes on at the surface of a body. Aside from providing the pleasure of experiencing a very familiar-looking space that stands ready to be colonised by nanotechnology, it stacks the deck in favor of inferences from the likeness of STM-images and theoretical models in a computer simulation. Tellingly, these distinctive features make the STM conceptually even more complicated but perceptually even simpler than electron microscopy.

Philosophers tell different stories when they consider whether the case of the STM is just another small step in the history of microscopy or whether it poses entirely new questions, see, for example, [Pitt 2004], [Rehmann-Sutter 2014]. But they all agree that it involves an interplay between active intervention and passive submission or, to put it philosophically, between spontaneity and receptivity. Indeed, this attitude of the observer informs the general orientation towards objects of nanoscale research: interesting

properties that might provide technical functionality are actively sought out by researchers who are hoping to be surprised by the phenomena they produce. Also, the appearance of specific phenomena and processes requires hard work and careful control, but the familiar visual frame of the “surfacescape”, for example, opens up an unbounded space for the emergence of novelty and surprise.

So far, the history of “seeing with microscopes” revolves around realism or truth: Straightforward seeing is associated with seeing how things are, whereas a highly theory-laden and inferential mode of perception suggests that what we see is a construct of sorts. The reliability of a way of seeing—with the electron microscope, for example—was judged in comparison to apparently straightforward cases of immediate perception. But the two features, identified above, of the STM drive home that the reliability of the observation depends not on representational features but on the technical robustness and performance of the system. Though STM microscopy is even more inferential than electron microscopy, the fact that it is also an instrument of intervention and the fact of its twofold calibration indicate that it cannot be likened to a human observer who confronts an outside reality and wonders whether a mental image provides a truthful representation. Instead, the STM is coordinated with a multitude of other instruments and procedures and is judged by the way it agrees with and improves upon a whole system of observational and experimental techniques. Firmly entrenched in a variety of contexts and practices, the STM is not so much a method of seeing atoms on surfaces but an “apparatus-world complex” that affords perceptual and manipulative access to atoms on surfaces.¹³

Similarly, collective experimentation with emerging nanotechnologies also requires a robust system of observation that is tied to various institutions and interests and that is simultaneously a way of seeing and of acting in the world. Rather than simply registering potential hazards and public concerns, a systematic observation of our collective experiments should afford a kind of institutional robustness. When, for example, a commercial “nano”-product sends users to the hospital for respiratory distress, an observation of this event should do more than merely represent what happened—what did the media report, what did the toxicologists conclude, how did the stock market react? Instead, it needs to view this incident as an experimental situation that served to probe the robustness of the regime of vigilance that is to ensure a social learning process—how effectively did existing regulatory institutions, governmental agencies, public media and the scientific community respond to this incident, what was learned and what deficits can be identified? To

13. See Rom Harré for an account of the difference between instruments that function like probes (the thermometer, the light microscope) and a complex of apparatus and world that makes a phenomenon available for research and development, for observation and intervention. Of the latter complexes he says that they afford a phenomenon much like yeast, water and an oven afford us a loaf of bread [Harré 2003].

make these assessments, to raise and answer these questions, an appropriate institution is needed [Lösch, Gammel et al. 2009].

8 Parting shot

While there is more than this to the philosophy of nanotechnoscience, this initial survey might be sufficient to suggest that we should not become fixated on the imagined consequences of an emerging technology. If there is something special about nanotechnology and the challenges it poses, it is right in front of our eyes in the form of a very unusual research enterprise. The main challenge is to analyze, appreciate, and evaluate it.

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