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Collapse of Distance: Epistemic Strategies of Science and Technoscience[1]

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Danish Yearbook of Philosophy, 41, 2006, pp. 7-34

Introduction

Already the title of this paper shoulders too heavy a burden of proof. By contrasting science and technoscience it alludes to an epochal break or fundamental shift in the culture of research. "Science" refers to theoretical representations of nature as we know them primarily from the history of physics and primarily from a tradition that begins with Einstein and ends with Weinberg or Hawking. It is supposed to be succeeded by technoscience, mode-2 research, post-academic, entrepeneurial, finalized, or post-normal science as we know it from pharmaceutical research, nanotechnology, ICT, and, of course, synthetic chemistry or materials research. Any such suggestion of an epochal break is vulnerable to objections. Of these, the most obvious perhaps is that there was no historical break but merely a shift of attention. Instead of focusing on the continuing inquiries by theoretical physicists and evolutionary biologists we are now foregrounding those disciplines that have always operated in a "technoscientific" or "entrepeneurial" manner (Elzinga 2002). This objection can be answered here only by suggesting that this shift of attention does not owe to the whim of historians and philosophers of science but corresponds to a shift in societal expectations and in the way researchers even at universities conceive of themselves: Chemistry and materials research have displaced theoretical physics at the pinnacle of the sciences, we increasingly look to them and the various nano-, bio-, or information technologies if we want to know what science is

[1] This is the revised version of a plenary lecture at the annual meeting of the Danish Philosophical Association Copenhagen, March 2006.

and does. Accordingly, the definition of "technoscience" that is operative in the following reflections does not rest on the claim that scientific practice has undergone a profound change – though, with the advent of the computer, new techniques of experimentation, visualization, and simulation there may well have been such a change, too. Instead, my definition of technoscience posits a shift in the self-understanding and epistemic values of science, adding to this only that such a shift in self-understanding will be consequential in that it serves to orient practice differently.

For the purposes of this paper, I define "technoscience" rather simply in reference to Ian Hacking's distinction of "representing" and "intervening" (Hacking 1983): *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.[2]

All extant definitions of "technoscience" have in common that they view it is a hybrid or monster of sorts – something that defies classification because it does not fit the classical dichotomies of nature and culture, science and technology, representing and intervening. 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, we encounter the hybrid "technoscience" where theoretical representation becomes entangled with technical intervention.[3] But as soon as one encounters this hybrid technoscience and interprets it as a sign of the times, one discovers that such hybridities characterize the entire history of modern science, that nature and culture, science and technology have never been cleanly separate.[4] What appeared at first to be a hallmark of a profound transformation soon emerges as just another way of seeing the past.

Therefore, the most important words in my definition are the words "even in principle": In technoscientific research, the business of theoretical representation cannot be dissociated, *even in principle*, from the material conditions of knowledge production. Consider, for example, that 18th century theories of gases and airs referred to phenomena that were technically produced in the

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2 This, for example, would be a typical definition of "nanoscience" which justifies the label "nanotechnoscience": "Nanoscience studies effects that can be produced at the nanoscale and, in particular, the surprising novel properties of nanoscale materials and artefacts." – For a more elaborated characterization of technoscience see Nordmann 2004.

3 Andy Pickering explores this entanglement as a *Mangle of Practice* (Pickering 1995).

4 This is particularly evident in the title of Donna Haraway's book that revisits the "modest witness" of 17th century gentlemanly science at the end of the second millenium (Haraway 1997).

receiver of a vacuum pump. Even if these theories claimed to provide representations of nature, the "natural" phenomena were artificially produced. And yet, it still made sense to speak, as I just did, of natural phenomena that were technically produced. It was possible in principle and common intellectual practice to conceive of the airpump as a platform or theater that merely served as a stage where nature is prompted to act and show her tricks.[5] Conceptually, at least, scientists were able to dissociate their technical intervention from the subsequent business of producing a theoretical representation.[6] This in-principle-possibility does not obtain in the case of research with the onco mouse – to cite one of Donna Haraway's most prominent examples of technoscientific research objects (which, as we will see, should more properly be called research subjects).

A living organism that is genetically programmed to develop a certain kind of cancer differs from the airpump in that it cannot be conceived merely as a vessel in which natural processes unfold. But why not – what is the difference between airpump and onco mouse that makes the difference? Bruno Latour, Donna Haraway, Andy Pickering have a hard time answering that question and sometimes seem quite content to lump them together (Latour 1987, Haraway 1997, Pickering 1995). For the moment, a few descriptors of the onco mouse must take the place of a criterion: Onco mouse is a product of the knowledge economy, it is reproducible only to the design specifications of its distributors, it does not represent the disease process of breast cancer as it might occur in a human female but it *is* that disease process. The mouse does not exhibit a phenomenon in isolation, does not present the phenomenon as an object of learning about nature more generally. Instead of extracting general facts *from* onco mouse and then applying the lessons learned *to* humans, researchers learn to control and finally cure onco mouse as an entirely self-sufficient dynamic system. What, if anything, onco mouse models or represents therefore becomes an issue only when mouse-inquiry ends and clinical research begins, that is, when one needs to learn how to implement mouse-knowledge in a related biological system.[7]

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5 According to Joseph Priestley, "the experiments by the air pump, condensing engine and electrical machine [...] exhibit the operations of nature and the nature of God himself" (Priestley 1761, pp 27f.). John Robison remarks about these experiments: "We are now admitted into the laboratory of nature herself, and instructed into some of those great processes by which the author of this fair world makes it a habitable place" (Robison 1803, p. lvi).

6 The conviction that this distinction can be made, in principle and if only with the help of sophisticated methodological reasoning, still underwrites Nancy Cartwright's account of nature's capacities and the exhibition of concrete causal processes (Cartwright 1989).

7 To be sure, the genetic designers of onco mouse know precisely how it does and does not represent the genome of human breast cancer patient. However, the tools of technoscience are opaque even to their users. I will talk below about the work it takes for researchers to recover this information and thus to re-establish the animal model as a representational device. – If in technoscientific research one cannot, in principle, distinguish between representation and intervention, wouldn't that apply also to classic basic research like Mendel's pea-experiments? I cannot anticipate how many such "counterexamples" might be produced but this one is not compelling: Quite like the airpump that serves as a stage for the exhibition of natural phenomena, Mendel's field exhibits a statistical phenomenon (even though, indeed, the individual plants are products inextricably of nature and human craft).

I. Constructions of immediacy

My characterization of technoscience presented the question whether or not the animal model onco mouse represents anything, whether it is a model as models have been conceived by Heinrich Hertz or Ludwig Boltzmann and nowadays Nancy Cartwright, Margaret Morrison, or Mauricio Suárez, and others (Hertz 1956, Boltzmann 1974, Cartwright 1983, Morrison 1999, Suárez 2006) .

I would like to probe more deeply at this point what the transition from classical modern science to the technosciences amounts to. I will argue that it is a transition from "artful constructions of immediacy" in modern science to a "collapse of distance" in the technosciences. This main thesis of the present discussion has a mostly critical thrust since the collapse of distance signifies methodological forgetfulness, missing critical awareness or lack of nervousness regarding reality and artefact and the limits of knowledge or control. Peter Galison refers to this as "ontological indifference" but goes on to appreciate how and why technoscience can afford such indifference (Galison 2006). Also, we will see that the transition in question is not absolute or irreversible. Even after the collapse of distance researchers can shift perspective and re-assert the artful construction and representational rôle of a model. Indeed, the transition diagnosed here produces ambivalence and critical discussion within the scientific community itself. The traditional self-understanding of science is by no means reconciled with technoscientific practice.[8] But regardless of how conflicted individual researchers may be, the collapse of distance signals a real difficulty and calls for considerable effort to recover and reflect the artful construction of immediacy. Finally, my thesis assigns a new role to the philosophy of science. The ontological indifference of the technosciences needs to be complemented by a philosophical concern for the constructions of reality. Indeed, I hope to show that it is only through philosophical reflection that one can speak of technoscientific objectivity.

The significant step from artful constructions of immediacy to the collapse of distance involves only a small transition among the strategies required to deal with a paradoxical situation regarding representation. The very idea of representation presupposes, after all, that there is a distance between a representation and its object. This distance is that of aboutness: Our theories and representations show and tell us something *about* the world. At the same time, the acknowledgment of this distance undermines the notion that there could and should be some sort of agreement between a representation and its object. Ideally, in order to speak of "agreement" we need to

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[8] This ambivalence often takes the following form: Though they no longer insist on maintaining the difference between representing and intervening and though they acknowledge the increasing proximity of their research with engineering and design practices, scientists still claim for themselves the title of "basic researchers" who creatively go where their intellectual interests take them.

conceive or construct aboutness in such manner that one can determine without artifice and mediation but somehow immediately that this statement agrees with that fact. Ideally, agreement or disagreement should be pretty much self-evident, something that we can judge by simple routines, perhaps even just by looking.[9]

This construction of immediacy is a delicate matter also in that it can go too far by collapsing the distance between a representation and its object altogether. If our representational tools become so persuasive and if we become so immersed in a representation that we take it for the thing itself, the representation ceases to be a representation and we are no longer speaking about the world but are caught up in a self-referential system.[10] Modern science and philosophy of science produced artful constructions of immediacy that maintain the aboutnes-relation if only by clearly specifying the conditions that allow us to speak of "agreement". In contrast, the collapse of distance is a hallmark of technoscience and amounts to vague and half-acknowledged epistemological confusion. While constructions of immediacy construe agreement in terms of a coordination that does not require physical similarity or a likeness between the representation and what it represents, similarity and likeness overwhelm critical distance in technoscience. It is the story of that small but significant transition which I want to outline in the following sketch. It begins – how could it be otherwise – with Immanuel Kant.

II. Representations on the battlefield of metaphysics

When Immanuel Kant began working on the *Critique of Pure Reason*, he wrote to Marcus Herz about his discovery of a new question that in his long metaphysical studies he and others "had failed to pay attention to and that, in fact, contains the key to the whole secret of hitherto still obscure metaphysics." The question was: "What is the ground of the relation of that in us which we call representation to the object?"[11]

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9 In 1915, Danish philosopher Harald Høffding distinguished between "visualist" and "motorist" philosopher-scientists (see Lützen 2005, 188). Heinrich Hertz and, of course, Ludwig Wittgenstein belong to the former group. Their account of models, images, representations is geometrically inspired and shows how one can immediately see that this agrees with that, compare Nordmann 2005b from which sections 3 and 4 below are adapted.

10 Mauricio Suárez draws on art theorist Ernst Gombrich to reflect upon this: "Gombrich employs the analogy of a hobby horse, which children play with in a similar substitutional fashion. [...] In these activities children can sometimes lose track of the fictional nature of the entity – in fact there is a sense in which for it to perform its function correctly, it is essential that the fictional nature of the entity be in some ways suppressed. Although in substitutional representation we are not required to gain the (false) belief that the fictitious entity itself exists, it seems that we are required to display at least some attitudes towards the fiction that we would display towards the real entity" (Suárez 2006, see Gombrich 1984). Suárez's account of scientific practice suggests that there is a proper (artful) attitude towards a model: While suppressing to some extent its fictional nature, scientists will not mistake it for reality. Here, I argue that this balance is easier to lose and more difficult to regain in technoscientific practice.

11 The letter dated February 21, 1772 is quoted in Paul Guyer and Allen Wood's introduction to their edition of *The Critique of Pure Reason* (Kant 1997, pp. 47f., compare A58 in the *Critique*).

Nine years later Kant explained in his preface to the first edition of the *Critique of Pure Reason* how the problem arose in the first place and why it has become so important to critically investigate the relation of our representations to their objects. In the course of experience arises quite unavoidably the warranted conviction that our representations usually conform to the objects: When we describe what we see, we assume safely and naturally that our descriptions agree with some object out there, namely the object we saw. Upon this conviction our reason rises "ever higher, to more remote conditions" and begins to inquire into the grounds of our conviction. How is it possible, we may ask, that our descriptions agree with some object out there? The two are of very different stuff, after all. Our descriptions take the form of thoughts or sentences and exist entirely inside our minds, while the objects are material things that exist independently in the external world, indifferent to how we think of them. Moreover, we are directly acquainted only with perceptions and sensations, with feelings and thoughts, not with the objects themselves. So, what makes us think that there can be agreement between entities as dissimilar as our representations (which we know very well because we constructed them with our own conceptual tools) and the objects (with which we have no immediate acquaintance and which we did not produce)?

It is the very success of human reason and the experience of making correct representations that gave rise to this question in the first place. But in order to answer it, reason would have to do the impossible and "surpass the bounds of all experience." It would have to step outside of human cognition and assume a divine perspective, one that would allow a direct comparison of our representations with their objects.[12] From this predicament arise profound disagreements and "the battlefield of these endless controversies is called metaphysics."[13] The combatants on this battlefield are dogmatism and skepticism.

Dogmatism here refers to a rationalism that catapults reason well beyond the bounds of experience. Indeed, it uses reason to construct a kind of divine perspective from which we can be reassured that our representations agree with the external world. The Cartesian scientist therefore begins by withdrawing from the world and in solitary meditation constructs a vantage-point for a reconstruction of how things must be. Especially in the opening of his *Meditations*, Descartes himself gave us a portrait of the investigator who beholds an object in thought such as a piece of wax. His scientific method dictates a particular way of relating to objects of acquaintance, namely by retreating from them and from a distance substituting for them a construction of the mind. If Archimedes needed to step back just far enough to unhinge the world by force of the lever, Descartes is also in need merely of a firm standpoint from which to force together by force of

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[12] It is a recurring theme in Kant's philosophy that such a (divine) intelligence might be possible and superior to human understanding that "requires images" (Kant 2000, paragraph 77).

[13] This quotation and the preceding paraphrase come from the very first paragraphs of the first edition of Kant's *Critique of Pure Reason* (Kant 1997).

reason our perceptions and the external world. Accordingly he appeals to a principle of sufficient reason to argue that to differences of perception must correspond real differences of real properties. This specific argument parallels his general appeal to the benevolence of a perfect being or God who would not systematically deceive us regarding the veracity of our perceptions.[14]

While dogmatism thus employs metaphysical contrivance to force together the inner and the outer world, skepticism pries that union apart. John Locke and David Hume, in particular, showed that for all its exertions, reason cannot transcend experience but is stuck with sensory impressions. It does not achieve knowledge of causal laws, for example, because it cannot traverse the distance from the sensory experience of constant conjunctions all the way to necessary cause-effect relations. Instead, connections in the mind are forged by the sheer strength of impression. Instead of Descartes' portrait of a perfectly dissociated thinker who reinvents the world from scratch, one now gets the famous painting by Joseph Wright of Derby. It is rooted in Birmingham's Lunar Society and late 18th century British empiricism and shows the object of experience overwhelming its beholders. There is no possibility of rational ascent in the painted scene from sensory impressions to general laws. Indeed, the one experiment performed demonstrates various phenomena at once and the experiments in waiting (see the Guericke spheres on the table, the barometer, candle and watch) do not suggest a research program whereby experiments build upon each other to establish a theoretical point. And yet the experiment is compelling. In the absence of rational persuasion, what compels here is a fact so striking that it affects not only the spectators within the painting but extends to the beholder of the painting. The experiments with the airpump overwhelm the spectator, they spread enlightenment by literally displacing darkness by light (Baird and Nordmann 1994).

Joseph Wright of Derby (1768) *An Experiment on a Bird in the Air Pump*

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[14] For a less caricatured, more faithful and appropriately detailed account see Gaukroger 2002.

> This rapid process of knowledge, which, like the progress of a wave of the sea, of sound, or of light from the sun, extends itself not this way or that way only, but *in all directions*, will, I doubt not, be the means [...] of extirpating *all* error and prejudice, and of putting an end to all undue and usurped authority in the business of *religion*, as well as of *science*. (Priestley 1790, xxiii)

These words of a Birmingham scientist and member of the lunar society may well serve as a description of the painting, especially its treatment of light. They also make the Lockean point that the formation of representations is part of a natural process as impressions propagate like waves of light, leave their mark, destroy false ideas, and gradually establish the truth.

III. Artful construction

Immanuel Kant opened the door for a third approach and articulated a kind of immediacy that requires neither rational(ist) reconstructions, nor a surrender to overwhelming sensory impressions. According to Kant, dogmatism and skepticism tried to answer the wrong question by asking "Can reason bridge the gulf between our representations and their fundamentally dissimilar objects?" Between dogmatic attempts to answer yes and the skeptical reminders that the answer must be no, emerged a critical philosophy which did not provide an answer at all but removed the question: The *Critique of Pure Reason* demonstrates that there is no gulf between inside representations and outside objects. Instead of asking how our representations can agree with the objects, Kant famously proposed that we find out in which ways the objects must agree with our representations. We experience everything as given in time and space, thus susceptible to mathematical treatment. We also experience every event as the effect of a prior event and as the cause of a later event, thus susceptible to scientific or causal treatment. Time, space, causality, and other categories do not adhere to the things in themselves, they transform what is given to the senses into an object of experience that is given to the mind.

The relation between representations and their objects is thus an internal relation between entities that, far from being radically dissimilar, are actually made for each other. In a Wittgensteinian manner of speaking, what representations and their objects have in common is a grammar of construction. Ideally, this is a mathematical construction and the ideal case of agreement is therefore that between a predicted and a measured value. When Kant and his successors demand that all true science is mathematized, they privilege this quantitative agreement between numbers. Ideally again, this agreement is as immediate as the mere identity between two numbers: There is no ontological gap to be bridged and the agreement of thought and world requires neither construction nor interpretation – there is no need for a hermeneutics of science.[15]

In the history of science, hardly anyone represented this ideal as explicitly as Antoine Lavoisier who introduced precision measurement into chemistry, who transformed the chemical laboratory to the requirements of the balance and the calculation of weights, and who claims to have obtained measurements that agreed to several decimal points with his theoretical predictions (Holmes 1989, see also 1985).

Jacques-Louis David (1788) *Portrait of Monsieur Lavosier and his Wife.*

Especially in contrast to Wright of Derby's near contemporary painting, the portrait of Lavoisier and his wife by Jacques Louis David exemplifies how a scene of representation is instituted. The aesthetic attitude of beholding the object is here so subtle and nuanced and involves such a precarious balancing act that it becomes clear why I should speak of an "artful" construction of immediacy.[16]

From among the many relevant differences between the two paintings I want to emphasize that in the portrait of Lavoisier the instruments are subservient to the main activity of writing and thinking. And here, the Enlightenment's light of reason takes a view from nowhere to illuminate the entire scene. Lavoisier and David show that it requires an artful construction to behold a scene in

[15] For the need to keep interpretation out of science, see the Hobbes-Boyle dispute as reconstructed by Shapin and Schaffer 1985. More below on the historical fact that, of course, the intended exclusion of dissension and interpretation never worked, that predicted and measured values "agree" only approximately, that an interpretation of data is always necessary, and that this recognition requires a different, hermeneutic philosophy of science.

[16] For a more extensive treatment of ths balancing act see Nordmann 2005a. It shows how the scientist Lavoisier and the painter David confront (and solve) a specific problem of representation.

this manner. Instead of implicating and overwhelming the viewer in the violent propagation of impressions, the view from nowhere presents the scene as a scene, the object as an object, that is: from a distance. At the same time it is not dissociated from the spectator but offers this scene as one that absorbs us or holds our interest, that can be entered and explored. Where Wright of Derby's painting radiated outward, this one invites us in. But to enter this picture is a delicate and highly inferential procedure that consists in transformations of perspective that derive from and implicity preserve the rational perspective of the view from nowhere.

For example, Lavoisier is known to have transformed the laboratory by configuring it to the balance and more generally to measurement methods. Quantitative predictions could thus be confirmed by the verdict of a measurement. Therefore, aside from getting theory and experiments right, Lavoisier had to give the balance jurisdiction over chemical theories, he had to create a public space in which authority was ceded to its verdict. It no longer was to be a mere instrument for the determination of weights, nor to be vaguely associated with ideas of social or natural equilibrium. Like the scales of justice, upon weighing the evidence it would tilt to one side or the other, unambiguously determining right from wrong. In the case of chemical experimentation, it was failure to establish an equality of weight before and after a reaction which would tilt the balance against a hypothesis. Bernadette Bensaude-Vincent eloquently describes this employment of the balance:

> In the act of weighing Lavoisier sought to create an experimental space that was entirely under the experimenter's control. Once balanced with weights on Lavoisier's scale, substances were transformed from objects of nature to objects of science. The balance divested substances of their natural history. Their geographical and geological origins, their circumstances of production made little difference. They were transformed into samples of matter made commensurable by a system of standardized weights. (Bensaude-Vincent 1992, 222f.)

A seeming paradox arises from this description. Lavoisier created an experimental space "entirely under the experimenter's control," at the same time one in which the balance functioned "as an instrument of persuasion in an agonistic field." Thus, for the balance to be an instrument of persuasion the experimenters first had to persuade themselves that, for all their control, the testimony of the balance was not controlled by them at all. Bruno Latour formulates this paradox as a constitutional mandate of modern science: "[E]ven though we construct Nature, Nature is as if we did not construct it" (Latour 1993, 32). The employment of the balance in Lavoisier's new experimental space not only transformed objects of nature into objects of science, it also transformed natural historians, pharmacists, metallurgists, pneumatic chemists into that community of experimental scientists that ceded authority to the balance. In terms suggested by Michael Fried, they became absorbed into Lavoisier's experimental and rhetorical space of persuasive and arresting proof while maintaining the illusion that there is nothing theatrical about that space and that they themselves play no part in it.[17] According to the art historian Fried, the paradox of the balance (as generalized by Latour) challenged more generally the art of representation in the age of Diderot, Lavoisier, and David:

> [A] painting, it was insisted, had to attract the beholder, to stop him in front of itself, and to hold him there in a perfect trance of involvement. At the same time [...] it was only by negating the beholder's presence that this could be achieved: only by establishing the fiction of his absence or nonexistence could his actual placement before and enthrallment by the painting be secured. [...] What is called for, in other words, is at one and the same time the creation of a new sort of object – a fully realized tableau – and the constitution of a new sort of beholder – a new "subject" – whose innermost nature would consist in the conviction of his absence from the scene of representation. (Fried 1980, 103f.)[18]

As the beholders or scientific observers are drawn into the representation of nature and into a community of investigators, they become invisible to themselves and each other. Madame Lavoisier, for example, identifies her own location in the laboratory; in her drawing of experiments on respiration she is the woman to the right who is creating an objective representation of the scene. The standpoint of objectivity, however, is absent from the scene of representation, divorced from the true perspective of the observer; it is a hypothetical view from nowhere and as such a hypothetical viewpoint that can be assumed by anyone. Madame Lavoisier thus transforms her visual presence as an actor in the laboratory into an idealized absence, one that qualifies her as an invisible but objective scientific observer.[19]

By considering the art criticism of Diderot, Michael Fried shows that the balancing act between absorption and theatricality is not achieved simply by adopting the view from nowhere. In order for its beholders to willingly enter the scene and to forget its theatrical frame, the scene itself must appear unforced and "natural," corresponding to Lavoisier's emphasis on an arrangement of the givens such that we arrive at a certain conclusion through a natural chain of reasoning.

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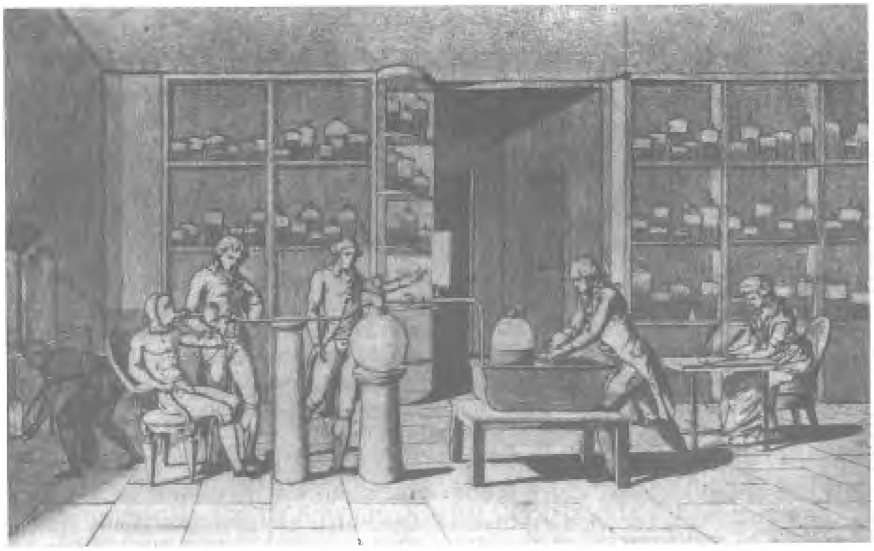
[17] In Priestley's culture of research (as depicted by Wright of Derby) it was not necessary to maintain such an illusion: Overwhelmed by experimental evidence we are swept away and deprived even of the opportunity to ask about its theatricality.

[18] Fried's work is controversial among art historians because he fails to persuade that the paintings of the period actually respond to this problem. For the present purpose it is enough to agree that Fried has identified a problem of representation as it was formulated in that period.

[19] In her interpretation of this drawing by Madame Lavoisier, Lissa Roberts draws on Fried's *Absorption and Theatricality* and refers to Diderot's notion of the 'pregnant moment' (Roberts 1991, 111f.). I am here following further down the tracks that were laid by her.



Marie-Anne Pierette Paulze
(Madame Lavoisier) (c. 1793)
An Experiment on Respiration

With Lavoisier and David, Latour and Fried we get a rather subtle account of scientific representation, modeling, experimentation, and objectivty. It goes beyond Kant's framing in thought of the immediate internal relation of object and representation to demonstrate a specific manner of instituting this relation in the laboratory and the academy. This includes a consideration of the aesthetic and rhetorical demands upon an artlessly artful construction of a scene. As in 18th century painting, so in science: What we see must coerce or compel us without appearing contrived or forced, it needs an air of naturalness. In science, this refers primarily to the experiment as a scene that takes place in the laboratory, it might also include exhibits at a museum or the aquarium as an artificial site for a spectacle of nature, it also includes the dynamic models of Heinrich Hertz that display a behavior over time. In all these cases as in genre scenes of 18th century painting, the model or display has a reality of its own while it represents another reality. We are therefore in a state of limbo, simultaneously present and absent from that scene – its witnesses but not its creators. The human observers are silent and simply accept the verdict of nature, quite irrespective of the fact that only they have given nature the language to speak through the experiment. This dialectic of absorption and theatricality, that is, of an absorption that is theatrically produced but simultaneously negates its character as theater, is characteristic for modern science and appears in many variants.[20]

A further decisive feature of Kant's account of the construction of immediacy suggests itself here: On the one hand, the distance between representations and their objects is reduced to the immediacy of an internal relation. On the other hand, this immediacy is possible only within a critical investigation of the limits of reason. The internal relation obtains because in our thinking we cannot venture anyway beyond the phenomena to the things themselves – it obtains because we can

[20] See, for example, discussions by Eric Winsberg and Mauricio Suárez of fictions in model-construction (Winsberg 2003, for Suárez see note 10 above).

know the world only as it is given to us and not as it is in and of itself. This, of course, is the punchline of Kant's philosophy: The limits of knowledge are constitutive of knowledge – the very idea of agreement between a representation and its object makes sense only where experience is nothing but a more less contingent system for the representation of phenomena as phenomena.

The Kantian strategy for the construction of immediacy was taken a step further by the physicist Heinrich Hertz and by Ludwig Wittgenstein. By emphasizing that the agreement between representations and their objects involves no similarity between the two, they underscore firstly Kant's focus on quantitative agreement and secondly that this agreement becomes possible only within definite limits of knowledge and language.

In the *Tractatus Logico-Philosophicus* Wittgenstein reduces the ontological gap between sentences and facts by treating sentences as facts (TLP 4.021, 2.141). A sentence is a configuration of words just like a state of affairs is a configuration of things. There is no qualitative similarity or physical likeness between these two kinds of facts, but there is a possibility of coordination that permits a simple and immediate decision regarding the agreement or disagreement between a sentence and a state of affairs. Here Wittgenstein follows Heinrich Hertz who spoke in very similar terms of the agreement between mind and world as that between two systems which model each other by way of coordination rather than physical similarity. Here is just one quote from Hertz's remarks on dynamical systems, a passage that is cited by Wittgenstein in the *Tractatus*:

> [I]t is generally impossible to carry our knowledge of the connections of natural systems further than is involved in specifying models of the actual systems. We can then, in fact, have no knowledge as to whether the systems which we consider in mechanics agree in any other respect with the actual systems of nature which we mean to be considering, than in this alone, — that the one set of systems are models of the others.
> The relation of a dynamical model to the system of which it is regarded as the model, is the same as the relation of the pictures our mind forms of things to these things. [...] The agreement between mind and nature can therefore be compared to the agreement between two systems which are models of one another, and we can even account for this agreement by assuming that the mind is capable of making actual dynamical models of things and of working with them. (Hertz 1956, paragraphs 427 and 428)

The story goes on with further developments or variants to the Kantian strategy for constructions of immediacy within a framework of critical restraint. From the representatives of the Vienna Circle, in the accounts of Nelson Goodman or Donald Davidson, all the way to sociologists of scientific knowledge like Andy Pickering, one encounters expressions of the same basic idea: Once we give up all attempts to mirror the world, to reproduce in our models the exact workings by which nature effects things, we become free to make full use of our conceptual resources. By surrendering the claim that we can know how things really are, we increase our powers of representation and of creating images or theoretical models that agree with observed and measured data.

This increase in powers of representation is thus qualified by a positivist disclaimer, by an implicit and generalized footnote that accompanies all scientific work. It states that we know nothing of reality because all we have are models that are constructed by us.

IV. A NEW ANIMISM

I would now like to contrast this positivist disclaimer of classical modern science with the animistic suggestion of technoscience: Technoscientific work is accompanied by the vague suggestion that we know everything of reality because the dynamic system in front of us is a self-sufficient reality in its own right – where this self-contained, non-referential dynamic system may be a computer simulation, a self-organizing algorithmic structure, or a model organism like the onco mouse.[21]

The positivist disclaimer consists in the qualification that all our knowledge is limited to how things appear to us in our representations. The agreement between the representation and its object or among representations allows no inference to nature as it exists beyond the constitution of objects in scientific experience. In contrast, the animistic suggestion of technoscience takes its objects as being endowed with powers that participate in the order of nature.[22] Somewhat like a voodoo doll, the onco mouse does not represent the disease process of breast cancer as it might occur in a human female but it *is* cancer or *is* the cursed object. The causal or referential connection between tumors in a onco mouse and in a diseased person remains opaque. As Donna Haraway points out, onco mouse symbolizes the patient with breast cancer such that our actions in regard to onco mouse substitute for actions in the treatment of cancer — onco mouse suffers for us and through its suffering promises healing and salvation (Haraway 1997, 79-85). In this respect still like a voodoo doll, onco mouse is not so much an object but a research subject that is vested with intentionality, it embodies the powers of cancer that are fought and must be defeated here. One works on and with it on the assumption that it simply *is* an incarnation or embodiment of cancer, and it therefore takes work to recover its representational features and to relate our mastery of this perfectly self-sufficient reality (a rodent breast cancer patient quite in its own right) to human patients or cancer in humans. Only this work of moving from one system to the next, of having to

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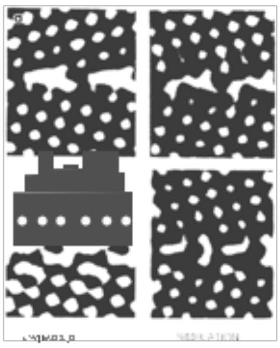
21 I am here listing three candidates for more detailed case studies (or reviews of case studies). Perhaps one can add to this list uncontrolled field experiments, the visualizations obtained by scanning tunneling microscopy, etc.

22 The term 'animism' was suggested to me by Mikael Hård. I hope that it will make increasingly good sense as I go along.

relearn mastery for each system reminds us that onco mouse might serve as a representation of sorts that establishes a correspondence of certain aspects of tumor growth in the mouse to that in humans.[23] The notion of the voodoo doll or onco mouse as a model or representation of anything is displaced and forgotten during the manipulation of the model or simulation. It needs to be actively remembered and reconstructed only as problems arise from the symbolic substitution of a dynamic system of nature by a technologically constructed dynamic system.

We may not know much about cancer, but the powers of cancer are present in the self-sufficient reality before us. Accordingly, the animistic strategy of collapsing distance replaces the immediacy of quantitative agreement between predicted and measured values by a qualitative agreement between calculated and experimental images. Their agreement consists primarily in the absence of visual clues by which to hold them apart. The 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 microscope), the other presents a dynamic simulation of the process he might have been observing – for this to be readable, the simulation software produces a visual output that looks like output from an electron 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.[24]



Experimental and calculated images of atoms at the grain boundaries in two structures (Merkle and Smith 1987)

This story of qualitative agreement or symbolic substitution warrants closer scrutiny regarding the loss of aboutness and the entanglement in similarities. Here, the “construction of immediacy” effects only the immediacy while its constructedness within the limits of language and knowledge drops from sight. Thus, the relation of aboutness collapses entirely and there appears nothing

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23 The most superficial and powerful indicator of the tenuously representational character of animals models comes from pharmaceutical research and the large failure-rate as one moves from animal testing to clinical trials.

24 This fairly early example is indicative also of the fact that such qualitative comparisons require considerable sophistication and power of judgement: “This procedure gives reasonably good agreement between experimental and calculated images. However, minor differences, particularly in the appearance of the open spaces at the core, can be noted and will be discussed below.” This eludes typical classical conceptions of modeling (in terms of coordination, projection, fitting) and challenges epistemology to make sense of statements like the following: “Atomic models which are consistent with these observed images can be verified by comparison with image simulations” (Merkle and Smith 1987, 2888).

arbitrary, conventional, or hypothetical about the relation between calculated and experimental images. Accordingly, the contrast between artful and deliberate constructions of immediacy and collapse of distance can be summarized (or: caricatured) as follows:

(1) In classical modern science (vaguely characterized by transcendental, empiricist, or positivist attitudes), nature was explained by way of conceptual or mental constructions that, qua constructions, were well-understood – but because they were such rational constructions that relied merely on coordination with real systems, scientists found it difficult to believe that this is how things really are. Thus, when 19th century chemists used stick-and-ball models to represent molecular structure, they were extremely aware of the crude and obvious constructedness of their models, and therefore thought of them as mere didactic tools that need to be disssociated from any implied realism (Meinel 2004). Further, since they did not assume that anything corresponds to the internal machinery of explanatory models, scientists became increasingly aware of their contingency: other models might work, too, as long as they generated predictions with equal success. Philosophy of science tended to strengthen this sense of contingency by attempting to explain the success of science on the weakest possible assumptions.[25]

(2) In the technoscientific "animistic" employment of computer simulations, animal models, algorithmic structures, and other substitutive uses of dynamic systems, those systems can be controlled without an understanding of their construction. This is evidenced quite simply by the fact that their scientific users do not actually make the requisite hard and software (and for the most part would not know how to make it). Rather than explicitly represent other ("real") systems by way of a specifiable coordination with them, they are symbolic substitutes for these, and the substitution includes the dynamic features that make the "real" system real.[26] When the system under study (the onco mouse, the computer simulation) refers to another system of interest (the human cancer patient, the molecular process), what distinguishes these two systems is not their reality or lack

[25] This "minimalist" philosophy of science was deductivist or syntactic and remained ontologically agnostic – because it could not be ontologically indifferent, dogmatic, or skeptical. As such, it comes historically and systematically before the semantic turn and an ontologically concerned philosophy of science that attended to miracle-barring arguments and debated scientific realism.

[26] The term "symbolic" is adequate in the ethnographic context since the notion of symbolic substitution agrees with the designation of this practice as a kind of animism. However, in terms of Peirce's distinction between iconic, indexical, and symbolic signs, the classical models appear indexical (by way of more or less rigid coordination) and the technoscientific dynamic systems iconic (the signs are thought to share features with the signified). For example, if the observed complexity can be modeled in terms of non-linear complex dynamics as a self-organizing system, the "power" of self-organization is thought to be equally present in (or shared by) the computer simulation and the referenced "real world situation" – even if this attribution is intractable. (The priests "know" that what they are doing to the voodoo doll they are doing also to the person for which the doll serves as a symbolic substitute – but this joint participation in a single underlying regime of powers is not transparent to them.)

thereof. They are tangible, complete onto themselves (discrete worlds with their internal dynamics), they are experientially rich, textured or “thick,” and not at all schematic. Their intimation of reality is underscored by the fact that technoscientific images tend to look alike, without visual markers to distinguish models, simulations, and real experiments. In addition to the black-boxed character of the imaging tools and the reality of the dynamic processes internal to the imaged systems, these systems can't be understood as representations because they are opaque for reasons of complexity. The system is opaque to its users for the same reason that it was developed in the first place as a self-sufficient substitute for the "real" system, namely because the real systems are too complex to be understood by the cognitive means available to humans. Instead of "understanding" in the manner of referring intellectually tractable particulars to general concepts, technoscience acquires a feeling for the system's behavior, probes its sensitivities to parameter variations, and the like, then transfers this knowledge as best one can from the isolated model systems to the integrated "real" systems.[27] For an example that updates the 19th century stick-and-ball constructions, today's molecular modeling software offers an interactive, seemingly cinematic journey into the inside of a molecule. Here, one finds it difficult to believe that what one sees might not be reality pure and simple.

This idealized contrast between classical and technoscientific models was anticipated in 1905 by Ludwig Boltzmann when he distinguished between the theoretical models of physics and the scale models of engineering.[28] The former serve constructions of immediacy along the lines suggested by Hertz. Through appropriate coordination we can determine unambiguously that this is a model of that (and vice versa). This determination, in turn, holds within set limits of knowledge that preclude us from knowing anything about the similarity between the model that serves as representation and the object that is modeled. In contrast, the scale models of engineering rely strongly on similarity. Paradoxically perhaps, for all their apparent likeness they do not permit an unambiguous, unmediated decision regarding their agreement or disagreement with situations in the world. This is not only because these can agree only in selected respects that require specification.[29] This is also because they need to be corrected for scaling effects – in order to preserve physical truth one cannot

[27] Johannes Lenhard has focused on this limit to human understanding conceived as tracking through a system of calculations causal mechanisms or the effects of parameter variations (e.g., Lenhard 2004).

[28] Boltzmann’s distinction is apt, since technoscience can be characterized as (fundamental) research in an engineering or design mode.

[29] Since the theoretical models of physics are constituted entirely by specifying unambiguously how their coordinates are mapped to the systems they represent, there arises for them no problem of interpretation or of identifying the relevant aspects of similarity and dissimilarity.

simply scale down uniformly but must introduce distortions that compensate for the scaling effects. For example, to construct a scale model of a ship in a harbor, one needs to scale down the water (and its waves) as well as the size of the ship. But in order to get the resistance of the ship right, the size of the ship needs to be factored differently than its velocity, they can't be diminished on the same scale – the ship in the model must be relatively larger.[30] Here, then, the very intimation of realism can work against the reliability and robustness of the model, and demands critical scrutiny. Engineers or technoscientists engaged in scale modeling pay attention to the ways in which a model becomes fitted, calibrated, or tuned to reality. This process can but need not involve a reconstitution of the aboutness-relation, now in highly contextualized, localized, qualitative terms.[31] Under the aegis of ontological indifference and the new animism, simulations are frequently tuned to agree with visualizations of data primarily to produce a compelling visual argument for the notion that simulation and observation partake in a shared underlying dynamics and that therefore one can substitute for the other.

Another pertinent distinction was introduced more recently by Rom Harré. Leaving aside conceptual or theoretical models altogether, he contrasts scientific instruments that serve as probes into causal processes with modeling apparatus (including simulations) that domesticates or produces phenomena. 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 (Harré 2003, p. 33 et passim). As the metaphor of domestication and Harré's conception of an apparatus-world complex suggest, such a causal inference from the apparatus to the world may be required only for

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30 Compare Nancy Cartwright's *How the Laws of Physics Lie*: "Adjustments are made where literal correctness does not matter very much in order to get the correct effects where we want them; and very often [...] one distortion is put right by another. That is why it often seems misleading to say that a particular aspect of a model is false to reality: given the other constraints that is just the way to restore the representation" (1983, 140).

31 This refers again to the "hermeneutic" approach by Nancy Cartwright and others that view models as mediators (Cartwright 1983, 1990, Morgan and Morrison 1999, see Nordmann forthcoming). These accounts of modeling were offered to reconstruct the practice of classical modern science and thus to undermine idealized Hertzian or deductivist conceptions. If these accounts apply also to Boltzmann's engineering models this would suggest that there is perhaps no difference between scientific and technoscientific modeling, after all (this has been argued by Carrier 2004a). However, it is one thing to expose all of the work that goes into artful constructions of immediacy, and quite something else to undo a technoscientific collapse of distance in order even to recover the problem of representation. Moreover, it may well turn out that the details of the mediations are different when the construction aims for coordination and when it aims for substitution. This may affect the alignment between theoretical resources, paradigm engineering practices, models and devices, world, and the dynamic system under investigation.

special theoretical purposes that are characterized by a concern for reality. In the meantime and for most practical purposes, the very fact that the apparatus *is* nested in the world underwrites a continuity of principles and powers and the affordance of ontological indifference.[32]

Boltzmann, Harré, and the current proposal drive a wedge between theoretical understanding through artful coordination of detached models and animistic control by way of substitution of one bit of reality by another. This juxtaposition is epistemologically significant but its significance is normally visible only from one side of the divide, namely from the point of view of a positivist concern or apprehensiveness regarding reality, but not immediately from the point of view of an ontologically indifferent animism.[33] This indicates a new task for the philosophy of science.

Even where it sets out to better understand how technoscience achieves robust knowledge, the philosophy of science must do battle against the models and images of technoscience by making explicit their implicit claims to represent and by showing where these claims run into difficulty. It is too easy, of course, to view the collapse of distance as merely deficient in comparison to the highly self-aware and artful procedures of classical modern science and its hyperbolic self-image as rigorously anti-metaphysical. Clearly, technoscientific practice deserves a rich account of "evidence for use" and perhaps its own theory of confirmation.[34] But it is an important feature of technoscientific research that it does not seek methodological self-awareness – even if it remains incomplete without it. It is thus left to the philosophy of science to restitute and make subject to critical deliberation the aboutness-relation, the representation *and* its object *and* their relation. It is in this sense that without philosophy of science there is no technoscientific objectivity.[35]

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32 As far as I can tell, Harré did not himself draw these conclusions from his analysis.

33 Remember that, according to Galison, ontological indifference is characteristic of those endeavors that are not concerned to establish what exists, that do not seek out fundamental praticles or construct a hierarchy of matter, and that do not aim for a theoretical representation or best explanation of how things are. – To be sure, as a matter of fact most researchers currently inhabit both sides of the divide. Cognizant of the tension, many worry about the new animism.

34 "Confirmation" may be a misleading term, suggesting as it does some formal relation between theory and evidence. Instead, technoscience may need a theory of robustness. The term "evidence for use" refers to Cartwright (forthcoming) and her proposal that more work should be done in this area.

35 Martin Carrier argues that technoscience does not need such outside help because it will inevitably discover its objects, its representational commitments and difficulties – just as soon as things go wrong and the tools or instruments of technoscience become subject to scrutiny (Carrier 2004b). Carrier might underestimate here just how long one can carry on without things going wrong – especially since technoscience can exploit the tremendous plasticity of its theoretical and procedural resources. This raises the question whether mistakes and failures direct technoscientific attention to underlying assumptions and causal structures, or whether they serve as a call for more tinkering and fine tuning of functional relations. The latter approach would exemplify the technoscientific sentiment that we know so much already that we will tend to get it right. This sentiment makes it quite difficult even to raise questions about current or in-principle limits of understanding and control.

V. Technoscientific objectivity

The problem of objectivity is solved by the artful constructions of classical modern science. Here, the object is constituted as an object of experience and something like the agreement *among* our representations *of* the object is normally taken as sufficient for the achievement of objectivity. With the collapse of distance and thus of the aboutness-relation, technoscientific objectivity requires a philosophical impulse that prompts a shift in the beholder, namely a shift from immersion within a substitute reality to absorption in a constructed scene.[36]

In order to elaborate this last point, the technoscientific manner of beholding its subjects needs to be compared to the three portraits of scientists at their business of representation by Descartes, Wright of Derby and Jacques-Louis David. I have shown how each of these three portraits responds to a problem of representation and that this is problem is shared by scientists and artists: If only God or reason can vouchsafe the agreement of thought and world, how far do we need to step back in order to reconstruct what is right in front of us? In the absence of an inferential ascent, are impressions strong enough to establish the truth? Once we have the laboratory as a theater of proof, how can we ensure that the laboratory phenomena appear natural rather than constructed? Each of these questions and the responses to them characterize a culture of representation and its institutions of specific modes of beholding. This wider cultural context is particularly apparent in the way in which technoscience beholds the world, rather: interacts with it – for here, the characteristic mode of beholding has been instituted in the immersive and substitutive aesthetics of video games.

The transition from artful constructions of immediacy to collapse of distance corresponds aesthetically to the transition from absorption to immersion. When one becomes absorbed into a scene (as described above with reference to Michael Fried), one remains a spectator of that scene, indeed one can only become absorbed on the condition that one doesn't claim any presence in the scene. Immersion, in contrast, abandons the spectatorial perspective but claims a physical presence in the midst of things. It does not assume a view from nowhere but demonstrates that it can go everywhere. The observer is the camera and the camera is the observer that performs a fly-through of a landscape, that looks from the inside-out just as easily as from the outside-in. There is no privileged vantage point, only pictures referring to other pictures.

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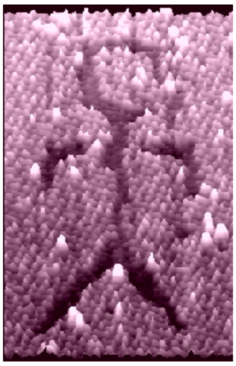
[36] Another approach would consist in developing an alternative conception of objectivity, one that reflects on the presence of things in the construction of material apparatus-world systems as opposed to their absence in propositional representations of the world. This alternative approach does not view the objects as “mere objects” (of discourse) but endows them with a kind of agency, including the power to validate material constructions.

Wolfgang Heckl is one of Germany's best known nanotechnology researchers, director of the esteemed Deutsches Museum for the history of technology, and a hobby artist who engages in molecular painting (Heckl 2003). Looking for a contemporary equivalent to Wright of Derby's or David's portraits of science, one might take this self-portrait of a nanoscale researcher as it appears on Heckl's website.



Molecular *NanoMan* logo (line thickness 1-3nm), written with STM into a layer of self assembled molecules. Adapted from the webpage of the Scanning Probe Microscopy Group (Prof. Wolfgang Heckl) at the Ludwig-Maximilians-Universität (LMU), Munich www.nano.geo.uni-muenchen.de/external/research/topics/Nanomanipulation/structuring_STM/molecular_writing/molecwrite.html (accessed December 29, 2006)

Three images add up to a bigger picture on this page. There is the schematic of a technique, an image obtained with this technique, and a videoclip that dramatizes and idealizes the process. Indeed, the videoclip provides an aesthetic standard or norm for the perfection of control that ought to be achieved at the nanoscale, namely the production of straight lines, right angles, and the like. However, the portrait of NanoMan is less than perfect and falls short of this norm (Nordmann 2006). Taken together, the three pictures serve not as the representation of some state of affairs but as a demonstration of capability. They lack an aboutness-relation as it obtains between a representation and its object, and they are clearly not images *of* a human being, *of* a molecular landscape, *of* an STM-tip, or *of* a writing tool.[37] Instead, they partake in the constitution of an object, partake in natural processes, partake in a culture of producing images just like these (including the popular practice of writing on the nanoscale the names and logos of laboratories and universities), and they partake in a general exchange or circulation of pictures that strive for photographic objectivity (full bodied, continuous, colored objects).

It remains for a more detailed analysis to show how the immersive character of these images is related to the new animism postulated above. Just one hint must suffice here: It concerns the surrender of the view from nowhere and the identification of the "observer" with the "eye" of a virtually or actually moving camera. This fusion of the observer with the moving camera produces a

[37] Such images as well as simulations give us an object but that object is only what was constituted by the image, the object is not pictured but produced by the image. Indeed, some of the objects exist only for the moment that the image was made (and for the purpose of the image). Can one go as far as saying that nanoscale phenomena are made in the image of their images? For a partial elaboration of this suggestion see Nordmann 2006.

loss of proportion. As Felice Fraenkel has pointed out, pictures of the nanoscale are aesthetically powerful in part because we cannot tell by looking at them just how big or small things are – we are to be unmoored by them and this is one way in which they serve as "destabilizing stabilizers" (Frankel 2004, Kaiser and Mayerhauser 2005). These images demonstrate the powers of nanotechnology by demonstrating its power of visualizing what no one has seen before. The beholders of these images are in awe, reminded that "any sufficiently advanced technology is indistinguishable from magic" (Clarke 1962). With central perspective they are also abandoning a classical position of power from which the world becomes transparent and proportionate to human interests and needs. Instead, the immersed beholders of technoscientifc visualizations are surrendering to a "reenchantment of the world through technology." This return to a magical relation to the world (paradoxically, through the rational and rationalizing means of technology) is a hallmark not only of technoscience but also of the new animism.

VI. Conclusions

In conclusion, I have arrived at a point where an investigation from the inside of technoscientific research joins up with outside public perspectives on technoscience. The opacity of the aboutness-relation, of visualization tools, of epistemic standards and ontological concerns corresponds to an attitude of wonder at the accomplishments of technoscience. Rather than insist on technology that rationalizes the world and enhances control, the public is left with marveling at where technoscience can go, what it can visualize, and all that it effects.

It is not at all obvious that these perspectives join up. In order to explain this, the investigation would have to go on and show that researchers and the public are in not at all dissimilar positions towards the artefacts that surround them, the tools they use, the networks of credulity and trust they rely on.

In the meantime, the claim of a new animism is bound to appear exaggerated at best, wholly inappropriate at worst. Surely, our control of phenomena in the natural world is more robust than the manipulation of a voodoo doll, even if we cannot dissect its complexity into a fully detailed causal story. And this is surely because the components of which we build our technoscientific voodoo dolls partake in the real dynamics of our natural world in a much deeper, more sustained way: These components, after all, are tried and true algorithms that have been developed in scientific contexts, that belong to established theoretical frameworks and tool-kits. Again, there is more of the story to be told here, namely how an assemblage of such robust components achieves a robustness of its own. Here, the focus was on the limits of understanding, the systematic neglect of the aboutness relation, the disappearance and thus the need for recovery of the object in technoscientific objectivity.

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Captions

Figure 1:
Joseph Wright of Derby (1768) *An Experiment on a Bird in the Air Pump*

Figure 2:
Jacques-Louis David (1788) *Portrait of Monsieur Lavoisier and his Wife*

Figure 3:
Marie-Anne Pierrette Paulze (Madame Lavoisier) (c.1793) *An Experiment on Respiration*

Figure 4:
Experimental and calculated images of atoms at the grain boundaries in two structures (Merkle and Smith 1987)

Figure 5:
Adapted from the webpage of the Scanning Probe Microscopy Group (Prof. Wolfgang Heckl) at the Ludwig-Maximilians-Universität (LMU), Munich www.nano.geo.uni-muenchen.de/external/research/topics/Nanomanipulation/structuring_STM/molecular_writing/molecwrite.html (accessed December 29, 2006)