The Advancement of Ignorance

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1. A Baconian Opening

Francis Bacon's *The Advancement of Learning* (1605) is a founding document not only of modern science but also of modern society. It forged a connection between scientific and social progress, between the accumulation of knowledge and of wealth (Krohn 1987). To Bacon we can trace the productive illusion as well as expectation that societies flourish through the continuous increase of knowledge. Even as the illusion is exposed and ignorance makes its appearance in every corner of today's so-called knowledge societies, the expectation persists in the form of anxiety: Ignorance is seen as a shortcoming in the process of modernization (Beck 1996). Even when it is acknowledged as inevitable and productive, it is treated at least as a problem, if not as a threat to the fabric and even the foundation of social life. In the face of ignorance, conceptions of human progress and general enlightenment become questionable.

Upon closer scrutiny, however, Bacon provides an instructive irritation. His advancement of learning cannot simply be equated with the advancement of scientific knowledge and of understanding the world intellectually. In his *Novum Organon* Bacon develops a conception of learning that builds on the knowledge of artisans who labor in the making of works, who do not win battles in the court of opinion but attain power through works and deeds, who do not contemplate the order of things but successfully participate in it (Bacon 1990: 41, 43, 79, cf. Bono 1995, Gaukroger 2001, Smith 2004). In other words, Bacon's advancement of learning is not tied to the intellect and its requirement of intelligibility or conceptual understanding. On the contrary, what the mind can learn is constrained by what the hand can do – manual operations suggest ideas of causation that cannot penetrate any deeper than these operations themselves (Bacon 1990: aphorisms 1 to 3):

> Towards the effecting of works, all that man can do is to put together or put asunder natural bodies. The rest is done by nature working within. (Bacon 1990: aphorism 4)

On Bacon's account, then, the advancement of learning is the advancement of mastery in the order of things. In this lies his break with conceptions of science and theoretical knowledge that are rooted in antiquity. *Theoria* informs the conceptions also of modern science and the Enlightenment project. As opposed to Bacon, the criteria for theoretical knowledge and for the advancement of learning answer to the questions of Plato and Aristotle and their concern with true belief. Here, knowledge consists in the achievement of human understanding and in the intellectual tractability of the models and theories that represent the world of observable phenomena. Modern science aims for the agreement of mind and world, theory and reality, and for justfied true belief – it is thus situated in the sphere of ideas and opinions where true understanding may produce a foundation for technical agency but technical agency as such does not constitute knowledge. In the world of modern science, intellectual understanding is viewed as a necessary condition for technical control, and inversely, technical control cannot by itself be a sufficient condition for the possession of knowledge (Bunge 1966).

This is Bacon's instructive irritation: From the received point of view of basic and applied science, Bacon's advancement of learning is tantamount to the tolerance of ignorance and, indeed, might involve the deliberate advancement of ignorance in respect to theoretical understanding, intellectual tractability and intelligibility by the human mind.

The following pages explore the productive tension that arises when we acknowledge that there is an *Advancement of Learning* which is in terms of the human intellect an *Advancement of Ignorance*. In the modern world of science and technology, of transparency, accountabilty and regulatory action it would appear inconceivable to consider progress as the deliberate production of ignorance not as as an unintended consequence but as a precondition for the achievement of technologically embodied knowledge that is not constrained by the requirements and limitations of the human mind. And yet, it appears ever more evident that citizens in the age of technoscience (Nordmann, Radder, Schiemann 2011) are not only coming to terms with, but embracing the hitherto inconceivable surrender of intellectual claims to knowledge.[1]

2. Scientific and Technoscientific Knowledge Societies

The ambitiously forward-looking book on *The Advancement of Ignorance* will never be written – it would require a kind of pathos which is lacking in *TechnoScienceSociety*. And yet, if one takes *TechnoScienceSociety* seriously and seeks to distinguish it from the scientific knowledge societies of first and second modernity, one cannot help but note that it is built around the accommodation of ignorance as a necessary evil and as a matter of course. It comes with the abdication of the intellect in favor of the reliable and robust working order of a sociotechnical machinery.

In order to substantiate this claim, what is needed first of all is a definition of technoscience and an account of how it gives rise to today's technoscientific condition. From there it is only a small step to exhibit or exemplify the advancement of ignorance. Accordingly it will be first encountered neither in individual decision-making under conditions of uncertainty or ignorance, nor in regulatory institutions that are confronted with a lack of action-guiding scientific knowledge about, for example, toxicological thresholds. Instead, the production of ignorance as absence of theoretical understanding takes place first and foremost in academia's technoscientific research laboratories. It is technoscientific knowledge production that rejects the demands of the human intellect and links the promise of innovation to the advancement of ignorance.

Our familiar stories of science and society are rooted in the Enlightenment and the institution of scientific communities, academies, and journals. From Kant to Habermas, these are stories of methodological commitments in the republic of scholars or intellectual public sphere producing the emancipation from dogma and prejudice and, thereby, clearing the ground for political and economic emancipation as well. According to *EnlightenmentScienceSociety*, history and theory asymptotically progress towards the unattainable ideals of truth, eternal peace, and a well-ordered, just society. In this context, science provides a theoretical description of the world. It puts forward hypotheses or ideas that aspire to truth, and it is the unending quest of the scientific community to ascertain whether these claims to truth can be justified. Accordingly, criticism becomes an essential feature of science, Enlightenment, and modern societies alike.

If this conception of science and society is a mere conceit, it is nevertheless a powerful conceit as witnessed by the standing to this day of philosophers like Karl Popper or Jürgen

Habermas. And even where the conceit is questioned or undermined, this is done in the idiom of modern science as producer of representations, descriptions, ideas. Constructivists, for example, suggest that claims to representational truth are not discovered and justified but socially produced and sanctioned. But irrespective of realist, empirist, or social constructivist accounts of the success of modern science, its knowledge claims remain subject to revision, and on all these conceptions the job of science is to make knowledge available such that society can draw upon or expand it for technological or administrative purposes.

Similarly, when Ulrich Beck, Anthony Giddens, and Scott Lash began to speak of reflexive modernization in second modernity (1994), they spoke of modernity becoming reflexive in the sense of successful modernization turning upon itself and creating unanticipated problems of its own. These are problems that arise from knowing the world as envisioned by modern science. With the increasing complexity of socio-technical systems, for example, it becomes more difficult to assess risks or anticipate failure. And with increasingly probabilistic or statistical interpretations of data, rational decision-making routinely takes place under conditions of uncertainty or ignorance. These new sources of ignorance at the very core of *EnlightenmentScienceSociety* provide for the theorists of reflexive modernization the occasion to reflexively question forms of knowledge and control, and thereby to attain a kind of self-knowledge. So, even as they show that the advancement of learning produces new forms of ignorance, they treat this as a problem of knowledge with the inherent goal to overcome or sublimate ignorance.

Accordingly and for the most part, the recent slate of books on *Agnotology* (Proctor and Schiebinger 2008) or *Ignorance: How it Drives Science* (Firestein 2012) draw attention to systemic sources of ignorance so we might better address them – be it in the form of secrecy or the suppression of indigenous knowledge or the Socratic confession of ignorance as initiation to a search for truth. The slogan “Not Ignorance but Ignorance of Ignorance is the Death of Knowledge” graces the cover of the recent *Handbook on Ignorance Studies*. The slogan is indicative of the wide range of topics that is covered in this collection of essays. It deals with ignorance in the modernist mode of gesturing at the ineffable that lies beyond the limits of knowledge of which a long tradition of thinkers and writers were painfully aware (Franke 2015). It shows that ignorance is vital for knowing and acting as it becomes incorporated in advanced conceptions of rational choice, as it provides a strategic resource for claiming “needs to know” and as it serves to motivate science and science education (Gross and McGoey 2015).

Ignorance appears quite differently on the stage of *TechnoScienceSociety*. This other kind of knowledge society is not built around the advancement of learning for the purpose of empowerment and criticism and thus for the emancipation of individuals and societies from dogma and prejudice. Science is not considered the hallmark or vanguard of social and political progress. Instead, by tying technoscientific research into the procedures and processes of contemporary society, technoscience becomes embedded within a socially and technologically robust working order. This reversal was first discussed under the heading “mode 2” knowledge production with its attendant “new social contract of science and society” (Nowotny and Scott and Gibbons 2001). When the machinery runs well and the sociotechnical working order is well-composed, it becomes easy to abandon intellectual claims to knowledge of truth and easy to accept ignorance as to how and why things work as they do.

One example of this provides a very different perspective on the familiar diagnosis of a second modernity which cannot provide properly science-based risk assessments. The trend towards miniaturization and technical control over ever smaller constituents of matter provides a story *par excellence* of the advancement of learning. When reaching the nanoscale, however, this advancement of learning turns upon itself by producing a new kind of ignorance: The properties of nanoparticles are subject to such minute variations that it becomes exceedingly difficult to perform a scientific risk analysis on whole classes of nanoparticles, whereas it would be futile to assess one nanoparticle at a time. The most optimistic predictions speak of many years, if not decades until proper risk assessment becomes feasible. This, one might expect, would put nanotechnology on hold until an adequate knowledge base has been attained. Instead, however, we witness ways to accept and work around this deficit (Nordmann 2010): The focus shifts on ways of being precautionary, prudent, and productive, with risk assessment replaced by risk management, with hard regulation and monitoring of thresholds replaced by an institutional regime of permanent vigilance. The problem of a lack of scientific knowledge disappears in the construction of a robust socio-technical machinery. In its place ermerges a managerial or technical knowledge of how to accommodate risk in real-time under conditions of presumably irreducible, pressumably harmless ignorance.

All of this implicitly suggests a conceptual structure that needs to be elaborated. Evidently, it is not sufficient to speak of different science-society relations or different conceptions of knowledge in order to appreciate the shift from mode-1 Enlightenment science to mode-2 technoscience. This also requires a sustantial conception of technoscientific research as consisting not in representing the world by means of theory, but in developing working knowledge of how things can work together and of how to make things work for us. This working knowledge, in turn, is not the opposite of ignorance: We can know how to make things work without knowing how they work. On the face of it, this may sound paradoxical, which is all the more reason to now turn to the technoscientific production of working knowledge and its attendant advancement of ignorance – and then, of course, to provide examples of this.

3. Accommodating Ignorance

More so perhaps than *EnlightenmentScienceSociety,* this volume's *TechnoScienceSociety* captures the peculiar character of today's "knowledge societies." If that term were to highlight that societal institutions, their technical, economic, administrative capabilties were based in knowledge of some kind or another, "knowledge society" would designate all societies at all times. The term gains specific meaning only in that it refers to the production and management of knowledge and ignorance in some but not all contempory societies. These are knowledge societies because they appreciate the value of knowledge and are equipped to make knowledge available where profitable or necessary, and to offer work-around solutions where knowledge is not necessary or available. Indeed, citizens of the knowledge society are deeply aware that knowledge is scarce, that it is hard to come by and to sort out once things become sufficiently complex (Böschen and Kastenhofer et al. 2010; Janich, Nordmann, Schebek 2012: 7-20). They are well aware that knowledge as resource and commodity takes on a wholly different value and character as we transtion fom the world of the classical sciences to the world of biomedical and nanotechnological research, of information and communication technologies or synthetic biology.

The predicament of the technosciences and the so-called emerging technologies is this: On the one hand, there is plenty of useful knowledge, though it is quite general and not tailored as yet to the specific demands of the highly complex processes and phenomena that need to be modeled, manipulated, predicted and controlled. On the other hand, there is a lot that we can't know or at least won't be able to know for quite some time – due to that very same complexity and its attendant limits of knowledge. But finally and perhaps fortunately, one discovers that we really don't actually need to know what we can't and won't know.

This predicament owes to what might be the main epistemological difference between science and technoscience: Science seeks to reduce ignorance by reducing complexity. Technoscience accomodates ignorance in order to generate complexity. The search algorithm of science is to discover how things are, so as to make them technologically useful. The search algorithm of technosience is to discover how far we can get technologically with what little or much we already know.

This may sound like a bold characterization of "technoscientific research," especially since one will be hard-pressed to find researchers who are willing to admit that they have abandoned the search for knowledge. That is why it is important to qualify the claim: It is not that curiosity is over and done with, that theoretical understanding is not valued where it can be had, or that the quest for theoretical knowledge and the reduction of ignorance is over. Instead, the argument is that technoscientific research proceeds on a substrate of ignorance, that it welcomes and, indeed, seeks out short-cuts, work-around solutions, black-boxed modules, and data-management routines. And indeed, there are plenty of indications that tolerance of ignorance is necessary to succeed in contemporary technoscientific research. Many of these are properly subject of a sociology of technoscientific knowledge. After mentioning these only briefly, somewhat more sustained attention will be given to the role of ignorance in knowledge generation and explanation, that is, to two questions for a philosophy of technoscience.[2]

While scientists are usually thought of as champions of criticism, the criticisim of theories and hypotheses requires the framework of a discipline, of shared concepts, paradigms, methodologies, theoretical frameworks. In the world of technoscience, however, the most attractive projects involve multiple disciplines – and in order to recruit a multidisciplinary research team, mutual trust is necessary and some degree of credulity becomes a virtue. Moreover, since everyone knows just how difficult one's own piece of the work is, one would like to imagine that that of the others is comparatively easy. Indeed, this kind of wishful thinking might be a prerequisite for convincing oneself that real progress towards achievement of a project goal is possible at all.[3]

Another reason why researchers need to accommodate ignorance as a normal part of their daily lives comes with the instruments they use. The insides of their instruments are as opaque to most researchers as are the insides of computers to most of their users. Indeed, some of these instruments are useful precisely because they work beyond the limits of what the human mind can manage – as witnessed by the current interest in "data-intensive science" and a somewhat morbid fascination in popular culture with the rule of "algorithms," "self-learning" and "A.I." When such instruments, moreover, render data sets in a pictorial way, they intimate immediate visual access to the objects of research. Highly processed data is thus presented as if the instrument merely opened a window to the world. This offers neither incentive nor point of entry to critical questions about instrumental artefacts or alternative ways of rendering the data. Indeed, some instruments render obsolete even the very idea of an observer's perspective, a perspective that serves as a reminder of the need to constructedness of representations and the epistemological difficulty of relating one's detached standpoint to a remote world "out there." Instead, some instruments beckon researchers to become fully immersed, conflating real and virtual worlds as one flies through and interacts with molecular or cellular systems, exploring them as if from within (Nordmann 2006). All of this suggests that technoscientific researchers must be tolerant of ignorance and willing to „black-box" bothersome detail. As Eran Tal has pointed out, this is not just a matter of reluctantly paying the prize for the increasing complexity of research technologies: Technoscientific researchers gratefully embrace and appreciate instruments, tools, or routines that allow them to be ignorant of the precarious construction and maintenance of these instruments. Standards and measures, for example, are maintained by an international community of metrologists who take care of the uncertainties that are associated with the various parameters that might influence a measurement. They thereby create the conditions that render measurements intelligible and comparable around the world – by "affording ignorance" metrologists render their own work invisble to those who perform measurements (Tal 2013).[4]

With Tal's analysis, we have moved from rather more sociological to rather more epistemological considerations. And it might now be worth considering how ignorance enters into the very process of generating knowledge. At first glance this appears to be paradoxical since knowledge is thought to be the opposite of ignorance such that each new item of knowledge displaces some blind spot of previous ignorance. The air of paradox vanishes just as soon as one conceives of different kinds of kowledge – intellectual and technical – and different kinds of problems – representational and effectual. A representational problem of accurately describing the world challenges us to fill a gap in our intellectual understanding. This problem signifies something for which we have no satisfactory account as yet. By supplying the proper theories, hypotheses, explanations one produces intellectual understanding and thus reduces ignorance. In contrast, to solve the effectual problem of reliably bringing something about often takes the form of creating a thing that exhibits a desired property or behavior – for example, to write software that emulates expert judgement, or to model global weather patterns, or to increase the productivity of an ecoystem, or to build a more efficient engine or solar cell. Here, the solution of the problem will generate technical knowledge but frequently without a corresponding gain in intellectual understanding or theoretical knowledge. Indeed, it can be rational not to wait for theoretical understanding before setting out to expand and achieve technical control.

A rational strategy for establishing technical control in the absence of detailed knowledge of all the relevant processes is the design cycle that has been explicated in software engineering and that informs the construction of expert systems, of simulation and climate models, of biological entities and processes in synthetic biology, and implicitly the creation of many experimental systems and technical artefacts.[5] If the target or end-point of the design process is some entity or system with desired properties or behaviors, one begins, of course, with the assembly of a model that incorporates the relevant available knowledge. Based on an analysis of the task, a first protoytype is constructed. So far, then, this conforms to the normal expectation that theoretical descriptions underwrite technical constructions: When we study the initial protoype we find our own knowledge reflected in the principles of its construction. In the next step along the design cycle, the performance of the prototype needs to be considered and compared to the desired behavior. Typically the prototype either doesn't work at all or falls short of desired performance goals. Here, then, the discrepancy needs to be bridged which requires an analysis in its own right, not of the original task but of the behavior of the prototype. We systematically probe the prototype and introduce corrections, patches, additional routines of various kinds. These corrections are also based on knowledge and experience, of course, but this is knowledge of the technical systems, of the design process, of tried and tested algorithms, of software modules or technical adjustments that usually get the job done. One tweaks the prototype, in other words, observes it again, tweaks it again, and thus the process of approximating the desired performance supports a process of optimization, of fine-tuning, or calibration. Iterating this cycle again and again, one keeps adding elements, writing new code, altering conditions in such a way that the prototype gains complexity: It incorporates more and more bits of knowledge and practice such that, as a whole, its is no longer a transparent instance of our theories and principles. The technical achievement now eludes intellectual tractability and we are to some and perhaps to a considerable extent ignorant of what we made.

It is by no means a novel phenomenon that our technical creations can get ahead of our theoretical understanding. In some cases – most famously, the steam-engine and perhaps the computer – science will catch up with the new devices. In other cases – most famously, nuclear weapons – it has been suggested that we will never be able to fully comprehend the potential effects and implications of our own technologies.[6] If there is something decidedly novel about optimization in a design cycle, it is that this production of technical knowledge occurs at the forefront of technoscientific research and that it purposefully drives a wedge between explanation and prediction as the two-pronged goals of science. According to standard accounts of scientific knowledge, one needs good explanatory theories in order to render the world increasingly predictable and subject to technical control. Inversely, the testing of predictions allows us to assess the quality of our explanatory theories. In the current technoscientific „culture of prediction“ (Johnson and Lenhard 2011) one demands that models and other technical constructions behave predictably and allow for the successful control of behaviors or events – and this functions as a technical criterion which does not presuppose intellectual understanding or theoretical explanation. By iterating the design cycle one can optimize the retrodictive and predictive performance of a model without requiring an articulated conception of how the predictions are generated or precisely what role the various theoretical components of the model play in the process. Indeed, computer models are mostly used to relieve resesarchers of having to know any of this – that is, as ignorance affordances.

In the long run, the dissociation of explanation and prediction in *TechnoScienceSociety* valorizes predicitive control and the technological agenda of building the machines that do the knowing for us. Though we regulate and, through fine-tuning, maintain the capacity of these machines to accurately model and predict phenomena and processes, we do not know and need not know how an “e-scientific” computer model or expert system knows what will happen next, nor can we predict what it will predict.

This is not the place to discuss the long-term viability of this development. Though the process of iteration and incremental optimization is meant to overcome limits of complexity, it may well encounter limits of its own. To the extent, however, that the technical achievement of predictive control takes priority over the intellectual achievement of a satisfactory theory or tractable explanation, it is evidence for the tolerance of ignorance at the forefront of contemporary research.

Undoubtedly, some will object to this account by pointing out that explanations are constantly produced, that most research publications offer explanations of their findings, and that predictive and explanatory capabilities still seem to grow together. Modelling, they will contend, is at least as much about explanation as it is about prediction. However, though explanation has a place also in the culture of prediction, what an explanation is and what counts as an explanation is not the same in a culture of prediction as it was traditionally. Indeed, it is further testimony to the tolerance and promotion of ignorance in *TechnoScienceSociety* that even so-called explanations can be inscrutable and opaque: When pharmacologists, materials scientists, nanotechnology researchers, or synthetic chemists discover an interesting feature, promising behavior, or surprising property, they exhibit it in the laboratory with the help of their apparatus. They thereby arrive at measurements, perhaps a visual output, an observable effect, something that works better than placebo, or the like. Having found that this is a robust and repeatable finding, they may well be content to publicize it as is, foregoing explanation altogether. They might also walk down the hall to the theorists in their department and ask them to produce an explanation. More often than not, these theorists will seek to reproduce the finding once more. However, they do not reproduce it in a petri-dish, a population of cells, or an atomic-force microscope. Instead of materially reproducing it in an experimental system, they reproduce it in the physical system of a computer. In order to reproduce *in silico* what the experimenters have produced *in vivo* or *in vitro*, the theorists or modelers assemble bits of theory (*e.g.*, in the form of algorithms) to piece together a process that appears to be quite like the one that was observed in the lab.[7]

Once the process can be modeled *in silico*, one speaks of an "explanation" – which is now the ability to obtain a phenomenon by theoretical means in the computer model, that is, by building into the model bits and pieces of theory. Accordingly the model reflects technical rather than intellectual knowledge in that explanation now consists in the capability of producing a phenomenon with the means of theory. Technoscientfic explanation is not constrained by the requirements of human understanding, that is, it does not trace the phenomenon back to general principles or laws, it does not exhibit entailment relations or show that the phenomenon was to be expected, nor does it allow the retracing step by step of a causal mechanism. Accordingly, the question of truth does not arise, with no one asking whether this *in silico* model provides the only explanation, the best explanation, or the one that should be preferred over others? Instead, all we get is a proof of principle, namely that one can use available knowledge to account for the phenomenon, with explanations showing only *that* a process or a phenomenon can be reconstituted with the help of theory. And given the computational complexity of these explanations, they tell us that the phenomenon might be inscrutable but nevertheless lies within the reach of human technical control. Moreover, these explanations allow us to explore technical alternatives: If we get the observed phenomenon by assembling such and such bits of theory into our model, perhaps we can get quite another phenomenon if we change this or that parameter.

4. Technoscientific Rationality

TechnoScienceSociety advances a model of knowledge production that bypasses intellectual limitations. It ascertains technical control of systems that are too complex so as to be tractable by the human mind. It thereby bypasses also the established knowledge requirement for public deliberation, regulatory safeguards, or accountability for impacts on the environment, human health, or the social fabric. Here, tolerance for ignorance may result in toxicology by computer simulation or iterative processes of social learning from collective experiments. And instead of aspiring to a state of certainty of truth from which to make judgements or take regulatory action, *TechnoScienceSociety* cultivates a state of permanent vigilance - seeking to monitor potential hazards in real time and through a large network of informational institutions (Nordmann 2010).

Technoscientific research thus supports contemporary knowledge societies not only in their quest for innovation but also regarding their ability to deal with ignorance. Where we do not have knowledge, we can still have something like robustness. And when we cannot satisfy our intellect or achieve a reasonable degree of certainty about risks, we can develop new governance mechanisms and adaptive management tools to detect and respond to emerging risks.

To be sure, epistemic virtues are themselves subject to public debate and might be adjudicated in the terms of political theory and constitutional principles. For example, whether simulation toxicology will ever be allowed to underwrite regulatory actions does not depend on its ability to meet the technical challenge of managing the requisite complexity. It depends much rather how the ambivalence and political conflict between modern *EnlightenmentScienceSociety* and *TechnoScienceSociety* will be settled or resolved. What is commonsensical from the point of view of *TechnoScienceSociety*, may well appear unprincipled, if not cynical from an Enlightenment perspective. This holds for the delegation to machines of judgements about potential harm to humans, and it holds more generally to questions of knowledge and ignorance and whether one should let sleeping dogs lie.

There are things that we don't know, things that we can't know, things that we are not supposed to know, things that we don't need to know, things that we don't want to know. Curious seekers of enlightenment are bothered by what they do not know, technoscientific rationality requires only that we know just what we need to know, no more and no less. Technoscientific builders and makers might even go to some lengths to determine just how little knowledge or theoretical understanding is sufficient to get along just fine – even if it means surrendering here and there the notion that the intellect should always and everywhere be the arbiter of human affairs.

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[1] Bacon began with a diagnosis of the pitiful state of theoretical knowledge which – as opposed to the knowledge of artisans – had stagnated for centuries. It came easy for him to jettison this ideal of knowledge. Today and before the backdrop of the amazing success story of modern science it appears far less likely and far more unpalatable to surrender the demand that there ought to be an intellectual grasp of the technological conditions of the world.

[2] The brief survey of features of contemporary research that require a tolerance of ignorance draws on Nordmann 2008.

[3] To be sure, the question of trust was at issue also in the gentlemanly science of the 17th and 18th centuries. In the 20th century, it was mostly Karl Popper who maintained the ideal of the scientist who takes nothing for granted and questions everything, while Ludwig Wittgenstein or Thomas Kuhn showed that mutual critique requires a shared language or paradigm that must be taken on trust. Compare Shapin 1994 and 2008.

[4] From a very different standpoint Mario Bunge noted that applied scientists “can afford to ignore” the details of theories (1966, 333, cf. also Bowker 2005).

[5] Arguably, it plays a major role in metrology as well (Chang 2007). It is fair to say, perhaps, that it inhabits the vast middle ground between ab initio constructions that implement a theoretically derived blueprint and haphazard trial and error tinkering (Nordmann 2014).

[6] Günther Anders speaks here of the discrepancy between what we can produce (*herstellen*) and what we can conceive, survey, take responsibility for (*vorstellen*), see Anders 1956. This may also hold, albeit along different lines, for formal systems or computer models that instantiate complex non-linear dynamics and that offer a new kind of technically produced entity for investigation, one that cannot be fitted easily to the requirements of human understanding.

[7] The iterations of the design cycle once again play a role here as one seeks to produce a close match between the experimental and the simulated versions of the process.