

Computer Simulations and the Changing Face
of Scientific Experimentation

Edited by

Juan M. Durán and Eckhart Arnold

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P U B L I S H I N G

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Edited by Juan M. Durán and Eckhart Arnold

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CHAPTER FOUR

THE USE OF THE ‘MATERIALITY ARGUMENT’ IN THE LITERATURE ON COMPUTER SIMULATIONS

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Introduction

Much of the current philosophical interest in computer simulations stems from their extended presence in scientific practice. This interest has centered on studies of the experimental character of computer simulations and, as such, on the differences (and similarities) between computer simulations and laboratory experiments. The philosophical effort, then, has been primarily focused on establishing the basis of this contrast; specifically by means of comparing the epistemic power of a computer simulation with that of a laboratory experiment. The basic intuition has been that if computer simulations resemble laboratory experiments in relevant epistemic respects, then they too can be sanctioned as a means of providing understanding of the world.

The literature on the topic distinguishes computer simulations from laboratory experiments on both ontological and representational grounds. The fact that a computer simulation is an abstract entity, and therefore bears only a formal relation to the system being investigated, contrasts with a laboratory experiment, which typically has a causal connection to the target system. These ontological and representational differences have suggested to some philosophers that establishing external validity is a much more difficult task for computer simulations than for laboratory

experiments. For others, however, it has been a motivation to reconsider experimental practice, and see it as a broader activity that also includes simulations as a new scientific tool. These two approaches, I claim, share a common rationale that imposes restrictions on the epistemological analysis of computer simulations. In this paper I propose to discuss this claim.

The most well-known criterion for distinguishing between computer simulations and laboratory experiments is given by the so-called *materiality argument*. Parker has provided a helpful account of this argument:

In genuine experiments, the same 'material' causes are at work in the experimental and target systems, while in simulations there is merely formal correspondence between the simulating and target systems [...] inferences about target systems are more justified when experimental and target systems are made of the 'same stuff' than when they are made of different materials (as is the case in computer experiments). (2009, 484)

Two claims are being made here. The first is that computer simulations are abstract entities, whereas experiments share the same material *substratum* as the target system.¹ The second, which is essentially epistemic, is that inferences about empirical target systems are more justified by experiments than by computer simulations due to the material relations that the former bears with the world.

Current literature has combined these two claims into two different proposals: either one accepts both claims and encourages the view that being material better justifies inferences about the target system than being abstract and formal (Guala 2002, Morgan 2005); or one rejects both claims and encourages the view that computer simulations are genuine forms of experimentation and, as such, epistemically on a par with experimental practices (Morrison 2009, Winsberg 2009, Parker 2009). I claim that these two groups of philosophers, that superficially seem to disagree, actually share a common rationale in their argumentation. Concretely, they all argue for ontological commitments that ground their epistemic evaluations on computer simulations. I will refer to this rationale as the *materiality principle*.

¹ Some of the terminology in the literature remains unspecified, such as 'material' causes or 'stuff' (Guala, 2002). I here take them to mean *physical causal relations*, as described, for instance, by Dowe (2000). In the same vein, when I refer to *causes*, *causality*, and similar terms, they should be interpreted in the way here specified.

In order to show that the materiality principle is at work in most of the philosophical literature on computer simulations, I discuss three distinctive viewpoints:

- a) Computer simulations and experiments are ontologically similar (both share the same materiality with the target system); hence, they are epistemically on a par (Parker, 2009);
- b) Computer simulations and experiments are ontologically dissimilar. Whereas the former is abstract in nature, the latter shares the same materiality with the phenomenon under study; hence, they are epistemically different (Guala 2002, Giere 2009, Morgan 2003, 2005);
- c) Computer simulations and experiments are ontologically similar (both are ‘model-shaped’); hence, they are epistemically on a par (Morrison 2009, Winsberg 2009).

With these three viewpoints in mind, the materiality principle can be reframed from another perspective: it is due to the philosophers’ commitment to the abstractness (or materiality) of computer simulations that inferences about the target system are more (or less thereof) justified than laboratory experiments.

The principal aim of this paper is to show that philosophers of computer simulations do adhere, in one way or another, to the materiality principle. I am also interested in outlining some of the consequences of adopting this rationale. In particular, I am convinced that grounding the philosophical analysis on the materiality principle, as most of current literature seems to do, places a conceptual corset on the study on the epistemological power of computer simulations. The philosophical study on computer simulations must not be restricted to, not limited by, a priori ontological commitments. By analyzing themes in the literature, then, I show that the materiality principle does not engender a helpful conceptualization of the epistemic power of computer simulations. I will also give some suggestions as to how to circumvent this issue and address the epistemology of computer simulations at face value.

The paper is divided in a way that corresponds to the three uses of the materiality argument listed above. The section entitled ‘the identity of the algorithm’ discusses option a); the section entitled ‘material stuff as criterion’ addresses option b), which comes in two versions, the *strong*

version and the *weak version*; and finally option c) is addressed in the section entitled ‘models as (total) mediators.’

The Identity of the Algorithm

Wendy Parker’s formulation of the materiality argument has a prominent place in the recent literature on computer simulation. Following Hartmann (1995), Parker defines a computer simulation as a time-ordered sequence of states that abstractly represents a set of desired properties of the target system. Experimentation, on the other hand, is the activity of putting the experimental setup into a particular state by means of intervening in it, and studying how certain properties of interest in the setup change as a consequence of that intervention (Parker 2009, 486).²

Parker’s goal is to show that computer simulations and experiments share the same ontological basis, and to use this basis as justification for the claim that computer simulations and experiments are epistemically on a par. To her mind, the central problem is that current definitions of computer simulation do not qualify as an experiment because they lack the crucial intervening mechanisms. Indeed, it is the abstract character of the model that prevents computer simulations from serving as intervening systems. The solution to this issue consists in construing the notion of *computer simulation studies* as a computer simulation where an intervention is made into the physical computer itself. So defined, a computer simulation study does qualify as an experiment.

A *computer simulation study* [...] consists of the broader activity that includes setting the state of the digital computer from which a simulation will evolve, triggering that evolution by starting the computer program that generates the simulation, and then collecting information regarding how various properties of the computer system, such as the values stored in various locations in its memory or the colors displayed on its monitor, evolve in light of the earlier intervention. (2009, 488)

The notion of *intervention* is now defined as the activity of setting the initial state of the computing system and triggering its subsequent evolution. Thus understood, a computer simulation study is an experiment in a straightforward sense, for now the system intervened is the programmed digital computer (2009, 488). On this basis, Parker claims that there is ontological equivalency between computer simulations and

² ‘Intervention’ is conceived of as the manipulation of physical causal relations in the experimental setup.

experiments, and this in turn allows her to claim an equivalency in their epistemic power.

Notably, she does not explain what it means for a computer simulation study to be epistemically powerful. Instead, she limits the argument to asserting that an epistemology of computer simulations should reflect the fact that it is the observed behavior of the computer system that makes them experiments on a real material system (and therefore epistemically powerful).

The influence of the materiality principle can be made yet more explicit. First, Parker conceives of the digital computer as the ‘substratum’ for the simulated system, thus claiming ontological equivalence between computer simulation studies and experiments. Since the computer simulation study is the activity of putting the physical computer into an initial state, triggering the evolution of the simulation, and collecting physical data as indicated by prints-outs, screen displays, etc. (2009, 489), then the epistemic value of computer simulation studies also corresponds to that of experiments. The evolution in the behavior of the programmed computer represents material features of the simulated phenomenon. Our understanding of such a phenomenon, then, is justified by this evolution on the physical computer. Computer simulation studies and experiments are, then, ontologically on a par, and so is their epistemological power.

Here I have briefly outline Parker’s main claims. The problem is that it is still not clear which are the reasons for considering the materiality of the digital computer as the relevant player in the epistemology of computer simulations. Let me put this concern in other terms. To my mind, Parker’s motivations are to subvert the materiality argument by showing that computer simulations and experiments are ontologically on a par (and so is their epistemic power). This move, as I have argued, is grounded on a rationale behind the same materiality argument that she is trying to overthrow. The question, then, is what role does the materiality of the digital computer play in the evaluation of the epistemic power of computer simulation studies? Let me now reconstruct three interpretations of Parker’s argument.

First, Parker takes the materiality of the digital computer to play some relevant role in the interpretations of results (2009, 490). Under this interpretation, hardware failure, round-off errors, and analogous sources of miscalculation affect the results of the simulation in different ways. This is true of computers and of computation, and it does not call for any special terminology or treatment. It is then doubtful that Parker is grounding her ontological claim on the fact that a digital computer is prone to errors that might affect the final results.

A second possible interpretation is that the system of interest is the physical computer itself, regardless of the represented empirical system. In this scenario, the researcher runs her simulations as usual, only paying attention to the changes in the behavior of the physical computer. These behavioral changes become the substance of the scientist’s inquiry, whereas the target system is only regarded as the initial point of reference for the construction of the simulation model. In this context, the researcher learns first and foremost from collecting information on the properties of the physical computer—the values in its memory and the colors on the monitor (Parker 2009, 488).³ If this is the correct interpretation, then it is incumbent upon Parker to show that the scientist can cognitively access the various physical states of the computer, something that she fails to do. Philosophers have discussed whether it is possible to access different locations inside a computer—the memory, the processor, the computer bus, etc.—and the general agreement is that these are cognitively inaccessible for the unaided human. There is a guiding principle of epistemic opacity ascribed to computational process which rules out any possibility of cognitively accessing the internal states of the physical computer (see Humphreys 2004, 2009). Moreover, even if scientists could actually access these locations (say, if they were aided by another computer), it is still not clear why accessing these locations would be of any relevance for the understanding the simulated phenomenon.

To my mind, neither of the above interpretations is correct. Rather, Parker should be interpreted as taking the materiality of the digital computer as playing the fundamental role of ‘bringing about’ the target system (i.e., brings into causal existence the phenomenon simulated). In other words, the behavioral changes that the scientist observes in the physical computer are instantiations of the representations built into the computer simulation.⁴ Such representations are, naturally, representations *of* a target system. In this way, the digital computer behaves *as if* it were the empirical phenomenon simulated in the programmed computer. I refer

³ Eckhart Arnold (this volume, 50) interprets Parker in a similar way. As he puts it: “the data of a simulation usually does not convey any information about the computer on which it was produced, but only information about the simulated system.”

⁴ Note that appealing purely to the visual behavior of the machine is not enough for claiming that computer simulation studies are ontologically on a par to experiments. Moreover, Parker is clearly thinking of causal relations originating in the machine: “The experimental system in a computer experiment is the programmed digital computer (a physical system made of wire, plastic, etc.)” (2009, 488-489).

to this interpretation metaphorically as the ‘phenomenon in the machine.’ Let me now explore this possibility a little further.

No Phenomenon in the Machine

Parker’s main strategy consists in locating the notion of physical causality in the digital computer, and assuming that the evolution of the simulation (represented by the physical states of the digital computer) corresponds to the physical evolution of the target system. In the same vein, intervention in the computational system corresponds to intervention in the target system. Taking this interpretation to be correct, I will now object that there is a principle of multi-realizability in computer software that prevents us relating the physical states of the computer with the target system simulated. Unlike experiments, where the scientist assumes consistency in the causal relations at work in the phenomenon, the physical states of the computer are not constantly the same; rather, they change with each run and for each type of computer architecture. It follows that the physical computer cannot work as the basis for the target system in the same way as materiality works as the basis of the phenomenon.

Let me begin by pointing out some basic modes of operation of the computer. The physical state of the computer is understood as the electronic configuration that the computer has at a given time. Such a configuration is provided by the state of the memory, the state of the computer bus, the I/O devices, and of every other physical component of the computer. Parker refers to this electronic configuration as the *materiality of the computer*.

Now, Parker’s argument requires that a set of sufficiently similar physical states of the digital computer is instantiated by the same computer program. To put the same idea slightly different: a computer program must instantiate sufficiently similar physical configuration of the digital computer over each run of the program. This assumption must be met otherwise Parker has no grounds for claiming for the epistemological value of computer simulations (2009, 489). The misunderstanding from Parker is that the physical states of the digital computer are rarely, if ever, similar between multiple instantiations of the same computer program. Indeed, the simulation is not the only process running on the digital computer for it must share the digital computer with the operating system, the processes in charge of running the physical machine, and other user process. Moreover, with a computer processor switching back and forth among all the processes that are running, the rate at which a process

performs its computation is not uniform, and therefore not reproducible on the same machine (Tanenbaum and Woodhull 2006, 56).

To illustrate this point, consider the unique case of *one* computer program running *once* on the *same* machine. A general setup would be: let P_t be the logical state to which a computer program enters when running at time t . In this sense, P_t could be the *if ... then* clause, a loop, or simply an instruction for printing out some data. Since the computer process is implemented on the physical computer, P_t instantiates the physical state of the computer at time t , let us call it M_t . Now, there is a unique mapping relation from P_t to M_t described by F_t which takes as its argument the state of the computer program at time t and matches it with the physical state of the computer at the same time t (Tanenbaum and Woodhull 2006, 56).

Consider now the situation where the *same* computer program is executed on the *same* machine, although *multiple* times. This situation looks very much like Figure 4-1. Using the previous notation: there exists a P_t such that, for each execution $1 \leq i \leq n$ on M , and for each $F_{i,t}$, there exists an $F_{j,t}$, $1 \leq i \leq n$ and $i \neq j$, such that $F_{i,t} \neq F_{j,t}$ and $M_{i,t} \neq M_{j,t}$. In other words, if we run the same instruction on multiple occasions, the internal behavior of the computer will be to create different mappings to different physical states of the same machine.

If we were to draw an analogy with experiments, we would be envisaging something along the following lines: intervention on the same variables instantiates different causal relationships, despite which we obtain the same set of results. This is an unacceptable consequence, because it shows that it is impossible to identify one set of causal relations that is consistent for a given phenomenon.

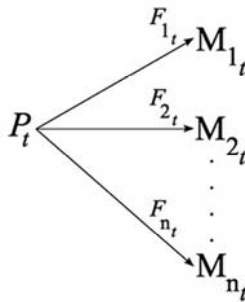


Figure 4-1: Program P at time t running on multiple occasions on the same machine M

Similarly, if the same computer program is run on different physical computers, there are no reasons for thinking that will instantiate the same physical state across the different machines. This situation is illustrated in Figure 4-2.

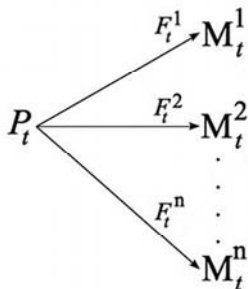


Figure 4-2: Program P at time t running on multiple machines $M^{1...n}$

In addition, it is a common practice to upgrade hardware by adding new components, or to completely renew the architecture of the computer. For this latter case, take M_t^i as the machine i running at time t . Then M_t^i differs from M_t^j , for all $1 \leq i, j \leq n$, $i \neq j$ (see Figure 4-2).

With these ideas in mind, any attempt to recreate the ‘phenomenon in the machine’ is fundamentally flawed for it contradicts basic principles of computer architecture. As I have said, however, this is only an interpretation of Parker’s central thesis. Whether correct or not, it should not affect our main claim that her account of computer simulation studies follows the dictates of the materiality principle. This is the case because, as I argued before, Parker takes it that the epistemology of computer simulations is restricted to the conditions imposed by laboratory experiments. The epistemological value of computer simulations is established, therefore, by arguing that the ontology of simulations is equivalent to the ontology of experiments.

Material ‘Stuff’ as Criterion

The idea of ‘material stuff as criterion’ is perhaps the most faithful account of the materiality argument.⁵ According to this view, there are

⁵ There is a generalized and, to my mind, imprudent use of the word ‘stuff’ in current literature. In this section, however, I use it in the same context and in the same sense as the authors.

fundamental and irreconcilable ontological differences between computer simulations and experiments, the latter being epistemically superior. There are two versions of this account: a *strong version* and a *weak version*.

The strong version holds that the causal relations responsible for bringing about the phenomenon must also be present in the experimental setup. This means that the experiment must replicate the causal relations present in the empirical system. According to the strong version, then, the experiment is a 'piece' of the world.

Take as an example a beam of light used for understanding the nature of the propagation of light. In such a case, the experimental setup is identical to the target system; that is, it simply *is* the empirical system under study. It follows that any manipulation of the experimental setup does address the same causes as the phenomenon, and that an insight into the nature of light can be delivered by our understanding of the controlled experiment (i.e., the beam of light (Guala 2002)).

Applied to computer simulations, the strong version takes it that the merely formal correspondence between the computer and the target system provides a sufficient basis for downplaying their status as epistemic devices. If there are no causal relations acting, then the epistemic power of inferences thereby made about the world is conceptually downgraded.

The weak version, on the other hand, relaxes some of the conditions imposed by the strong version on experimentation. According to this view, a controlled experiment requires only the set of relevant causal relationships that bring the phenomenon about. In this vein, the proponents of the weak version do not commit themselves to a complete reproduction of the phenomenon under study, as the strong version does, but rather to the set of relevant causes that characterize the behavior of the phenomenon.

Let us illustrate the weaker version with a simple example: a ripple-tank can be used as a material representation of light, thus providing insight into its nature as a wave. To the proponent of the weaker version, it is enough to have a representative collection of causal correspondences between the experimental setup and the target system in order for the former to provide some insight into the latter. The relation between the experiment and the real-world phenomenon, then, is one of causal similarity: a cloud chamber detects alpha and beta particles, just as a Geiger counter can measure them. But neither instrument is a 'piece' of the phenomenon under study nor fully interacts with all kinds of particles. It follows that experimental practice, as exemplified by the detection and measurement of particles, depends on a complex system of actual causal relations between the experimental setup and the target system.

Applied to the general evaluation of computer simulations, the weak version presents a more complex and rich picture, which affords of degrees of materiality being ascribed to computer simulations.

Despite these differences, however, both versions share the same viewpoint regarding computer simulations; namely, that they are epistemically inferior to experiments. This claim follows from the ontological conceptualization previously depicted, and stems from the same rationale as underlies the materiality principle. To show this, I discuss arguments provided by two authors.

The Strong Version

Francesco Guala champions the defense of the *strong version*. He assumes from the outset the existence of fundamental differences between computer simulations and experiments grounded on causality.

The difference lies in the kind of relationship existing between, on the one hand, an *experimental* and its *target* system, and, on the other, a *simulating* and its target system. In the former case, the correspondence holds at a ‘deep’, ‘material’ level, whereas in the latter the similarity is admittedly only ‘abstract’ and ‘formal’ [...] In a genuine experiment the same ‘material’ causes as those in the target system are at work; in a simulation they are not, and the correspondence relation (of similarity or analogy) is purely formal in character. (Guala 2002, 66-67)

Guala conceives the experiment as one that reproduces the causal relations present in the phenomenon. The author emphasizes the changes of materiality by appeal to the concepts of ‘same’ and ‘different stuff.’ The case of the ripple-tank is paradigmatic in this sense. According to Guala, the media in which the waves travel are made of ‘different stuff’ (and therefore so are the equations of force): while one medium is water, the other is light. The ripple-tank, then, is a representation of the wave nature of light only because there are similarities in the behavior at a very abstract level (i.e., at the level of Maxwell’s equations, D’Alambert’s wave equation, and Hook’s law). The two systems obey the same laws and can be represented by the same set of equations, despite their being made of ‘different stuff.’ However, water waves are not light waves (2002, 66), and a difference in the materiality presupposes a difference in the epistemic insight into nature. Indeed, Guala straightforwardly admits that the ontological difference between experiments and simulations grounds epistemological differences (2002, 63). His loyalty to the materiality principle is unquestionable: there is a clear distinction between what we

can learn and understand by direct experimentation and what we can learn by mediated simulation. The epistemic payoff of the latter is less than the former, and this is because, on this view, there is an ontological commitment to causality as epistemically superior that determines the downplaying of the epistemology of computer simulations.

Let me now consider a few objections to Guala's point of view. Parker has objected that his position is too restrictive for experiments, as well as for computer simulations (Parker 2009, 485). I agree with her on this point. Guala's conceptualization of experiments and computer simulations imposes artificial restrictions on both that are difficult to back up with examples in scientific practice. Moreover, and complementary to Parker's objection, I believe that Guala is adopting a perspective that takes both activities as chronologically mutually exclusive: that is, the computer simulation becomes a relevant tool when the experimentation cannot be implemented. STRATAGEM, a computer simulation of stratigraphy, provides us with an example here: when geologists are faced with difficulties in carrying out controlled experiments about strata formation, they appeal to computer simulations as the most efficacious replacement (2002, 68).⁶ Such a tendency towards a disjunctive assessment of the two activities is a natural consequence of taking computer simulations to be epistemically inferior to experimentation. In other words, it is a natural consequence of adopting the materiality principle.

The Weak Version

For a proponent of the *weak version*, I turn to the work of Mary Morgan. She has presented the richest and most exhaustive analysis currently to be found in the literature regarding the differences between experiments and computer simulations.

Morgan's primary concern is with so-called *vicarious experiments*, that is:

Experiments that involve elements of nonmateriality either in their objects or in their interventions and that arise from combining the use of models and experiments, a combination that has created a number of interesting hybrid forms. (2003, 217)

⁶ Guala allows that experiments and computer simulations are appropriate research tools, *knowledge-producers* as he calls them, although only for different contexts (2002, 70).

Having thus set out the features of vicarious experiments, she then turns to the question of how they provide an epistemic basis for empirical inference. Briefly, the more ‘stuff’ is involved in the vicarious experiment, the more epistemically reliable it becomes. In plain words, degrees of materiality determine degrees of reliability. As Morgan comments: “on grounds of inference, experiment remains the preferable mode of enquiry because ontological equivalence provides epistemological power” (2005, 326).

Morgan thus adheres to the weak version, because a vicarious experiment is characterized by different degrees of materiality, as opposed to the strong version that holds that experiments must be a ‘piece’ of the world. In terms of the materiality principle, however, there are no fundamental differences between the two versions: she also considers ontology to determine the epistemological value of computer simulations. The difference lies, again, in the detailed analysis of the different kinds of experiments involved in scientific practice. Let me now briefly address her account.

As noted above, vicarious experiments can be classified according to their *degree of materiality*; that is, the different degrees to which the materiality of an object is present in the experimental setup. Table 4-1 summarizes four classes of experiments: *Ideal laboratory experiment* (also referred as a *material experiment*), two kinds of *hybrid experiments*, and finally *mathematical model experiment*. As the table indicates, the classification is in terms of the kind of control exerted on the class of experiment, the methods for demonstrating the reliability of the results obtained, the degree of materiality, and the representativeness of each class.

The first and last classes are already well known to us: an example of an ideal laboratory experiment is the beam of light, for it requires effort by the scientist to isolate the system, rigorous attention to the control of the interfering circumstances, and intervention under these conditions of control. An example of the mathematical model experiment, on the other hand, would be the famous mathematical problem of the seven bridges of Königsberg; that is, a class of experiment whose control requirements are achieved by simplifying assumptions, whose demonstration method is via a deductive mathematical/logical method, and one whose materiality is, as expected, inexistent (2003, 218).

Among the number of ways in which these two classes of experiment differ, Morgan emphasizes those constraints imposed naturally via physical causality, and those imposed artificially via assumptions:

The agency of nature creates boundaries and constraints for the experimenter. There are constraints in the mathematics of the model, too, of course, but the critical point is whether the assumptions that are made there happen to be the same as those of the situation being represented and there is nothing in the mathematics itself to ensure that they are. (2003, 220)

	Ideal lab experiment	Hybrid experiments		Mathematical model experiment
		<i>Virtually</i>	<i>Virtual</i>	
<i>Controls on:</i>				
<i>Inputs</i>	experimental	experimental on	assumed	assumed
<i>Intervention</i>	experimental	inputs; assumed	assumed	assumed
<i>Environment</i>	experimental	on intervention and environment	assumed	assumed
<i>Demonstration</i>	experimental	simulation: experimental/		deductive
<i>method</i>	in laboratory	mathematical using model object		in model
<i>Degree of materiality of:</i>				
<i>Inputs</i>	material	semimaterial	nonmaterial	mathematical
<i>Intervention</i>	material	nonmaterial	nonmaterial	mathematical
<i>Outputs</i>	material	nonmaterial	non- or pseudo-material	mathematical
<i>Representing and Inference Relations</i>	representative of... ... to same in world representative for... ... to similar in world		representation of... ... back to <i>other</i> kinds of things in the world	

Table 4-1: Types of experiment: Ideal laboratory, hybrids, and mathematical models with representing relations (Morgan, 2003, 231)

Hybrid experiments, meanwhile, can be conceived as experiments in-between the other two: they are neither material nor mathematical.⁷ The class of *virtually experiments*, then, are understood as those “in which we have nonmaterial experiments on (or with) semimaterial objects,” whereas *virtual experiments* are those “in which we have nonmaterial experiments but which may involve some kind of mimicking of material objects”

⁷ “By analyzing how these different kinds of hybrid experiments work, we can suggest a taxonomy of hybrid things *in between* that include virtual experiments (entirely nonmaterial in object of study and in intervention but which may involve the mimicking of observations) and virtually experiments (almost a material experiment by virtue of the virtually material object of input)” (2003, 232).

(2003, 216). Table 4-1 again summarizes the properties of all four kinds of vicarious experiments showing their representing and inference relations.

The differences between virtually and virtual experiments can be illustrated with the example of a cow hipbone used as surrogate for the internal structure of human bones. In this context, there are two alternatives: one can use a high-quality 3-D image of the hipbone that creates a detailed map of the bone structure, or, alternatively, a computerized 3-D image of the stylized bone; that is, a computerized 3-D grid representing the structure of the stylized bone. According to Morgan, the 3-D image has a higher degree of verisimilitude to the structure of the real hipbone because it is a more faithful representation of it, as opposed to the mathematization represented by the computerized 3-D grid (2003, 230). The former is referred to as *virtually an experiment*, whereas the latter are called *virtual experiments*.

What are the differences among the kinds of experiment? As expounded in Table 4-1, whereas a virtually experiment is semi- or nonmaterial, an ideal laboratory experiment is strictly material. Also the demonstration methods are also significantly different. The distinction between a virtual experiment and a mathematical model, on the other hand, seems to be located solely in the method of demonstration, which is experimental for the former and deductive for the latter. Morgan also shows how models of stock market prices, despite being mathematical models simulated on a computer, can also be classed as a virtual experiment on account of the input data and the observation of results (2003, 225). The boundaries between all four classes of experiment, however, seem to be unfixed and dependent on factors external to the experiment in question. For instance, if a 3-D grid of the cow bone makes use of real measurements of the cow bone as input data, then what was originally a virtual experiment becomes virtually an experiment.

The epistemological analysis, on the other hand, is a function of the degree of materiality of the class of experiment: “ontological equivalence provides epistemological power” (2005, 326), as Morgan indicates. Back inference to the world from an experimental system can be better justified when the experiment and the target system are of the same material. As Morgan explains: “the ontology matters because it affects the power of inference” (2005, 324). A computer simulation, for instance, cannot test theoretical assumptions of the represented system because it has been designed for delivering results consistent with built-in assumptions. A laboratory experiment, on the other hand, has been explicitly designed for letting the facts about the target system ‘talk’ by themselves. According to Morgan, then, it is the material substratum underlying an experiment that

is responsible for its epistemic power. Hence, the ideal laboratory experiment is epistemically more powerful than a virtually experiment; in turn, a virtually experiment is more powerful than a virtual experiment, and so on. Since computer simulations can only be conceived as hybrid experiments or as mathematical experiments, it follows that they are always less epistemically powerful than ideal laboratory experiments. To Morgan's mind, therefore, there are *degrees of materiality* that determine the *degrees of epistemic power*.

In this context, Morgan uses the terms *surprise* and *confound* to depict the epistemic states of the scientist regarding the results of a computer simulation and of a material experiment, respectively. Results of a computer simulation can only surprise the scientist because its behavior can be traced back to, and re-explained in terms of, the underlying model. A material experiment, on the other hand, can surprise as well as confound the scientist, for it can bring up new and unexpected patterns of behavior inexplicable from the point of view of current theory (2005, 325; 2003, 219). The materiality of the experiment, then, works as the epistemic guarantee that the results may be novel, as opposed to the simulation, which takes results as capable of being explained in terms of the underlying model.

This shows how Morgan's ideas regarding experiments and computer simulations bear the stamp of the materiality principle. It exhibits the same rationale, putting materiality as the predominant feature for epistemic evaluation. Despite Morgan's strong emphasis on the place that materiality has in the discovery of new phenomena, there are examples of virtual experiments whose epistemic power is clearly superior to any ideal laboratory experiment. Take as a simple example the dynamics of the micro fracture of materials. It is virtually impossible to know anything about micro fractures without the aid of computers. Indeed, only the computational efficiency of finite element methods and multi-scale strong discontinuity can tell us something about the micro fractures of materials (Linder 2012). The lesson is that understanding something about the world do not necessarily comes from material experiments, or from any degree of materiality whatsoever. Neither a field experiment nor a high-definition 3-D image would provide the understanding about the dynamics of micro fractures that can be provided by an accurate mathematical model. The conclusion is that the rationale behind the materiality argument is once more misdirecting us regarding the epistemic power of computer simulations.

Models as (Total) Mediators

The last account in my list is the one I called ‘models as (total) mediators.’ As the title suggests, this account is directly influenced by Morgan and Morrison’s *Models as Mediators* (2009). Briefly, their book is a defense of the mediating role of models in scientific practice. It considers that scientific practice is neither driven by theories, nor is purely about direct manipulation of Nature. Instead, scientific practice needs the mediation of models in order to be successful in achieving its goals. A theory, then, cannot be directly applied to the phenomenon, but only by means of the mediation of a model; similarly, in experimental practice, models render data from measurements and observations in a form that is available for scientific use. In the following, I focus on the mediating role of models in experimental practice, since the proponent of the models as (total) mediators approach is more interested in analyzing computer simulations in the light of experiments. I will thus leave the mediating role of models in the context of theory unanalyzed.

Now, according to the proponent of the models as (total) mediators account, experimental practice consists in obtaining, by manipulation of the phenomenon, data that inform us about certain properties of interest. This data, however, is in such a raw state that it is impossible to consider it reliable or representative of the properties measured or observed. Rather, for these raw data to be of any scientific use, it is necessary to further process it by filtering out noise, correcting values, implementing error-correcting techniques, and so forth. These correcting techniques are conducted by theoretical models and, as such, are responsible for rendering reliable data.

Scientific practice, then, is conceived as strongly mediated by models; and scientific knowledge is no longer obtained uniquely by our intervention into the world, but also by the conceptual mediation that the model–world relation represents. In this vein, the epistemic analysis now concerns the data filtered out, corrected, and refined by models, rather than the raw data collected by directly manipulating Nature.

Computer simulations should easily fit into this new image of scientific practice. One might think that since they are conceived as models implemented on the digital computer, then their results must be data produced by a reliable model in a straightforward sense. Unfortunately this is not what the proponent of models as (total) mediators has in mind. To them, it is correct to say that computer simulations are models running on a digital computer, and it is also correct to say that there is no intervention

into the world in the empiricist's sense.⁸ Nevertheless the data obtained by running a simulation are 'raw' in the same sense as the data collected by a scientific instrument.⁹ The reason for this is that there are material features of the target system that are being modeled into the simulation, and thus represented in the final simulated data (Morrison 2009, 53). Simulated data, then, need to be post-processed by a further theoretical model, just in the same way as raw data. In other words, simulated data must also be filtered, corrected, and refined by another set of models in order to produce data that can be reliably used in scientific practice. Ontologically speaking, then, there are no differences between data produced by a scientific instrument and data produced by a computer simulation. In addition, the proponent of this approach takes that there are no epistemic differences between these two kinds of data either.

Let me now elaborate on these points by appealing to the work of Margaret Morrison. In 2009, she published a fundamental contribution to the debate on measurement in the context of computer simulations. In that work, she claimed that certain types of computer simulations have the same epistemic status as experimental measurements precisely because both kinds of data are ontologically and epistemically comparable.

To illustrate this point, let us briefly consider her example of measuring the force g .¹⁰ In an experimental measurement, Morrison argues, a scientific instrument measures a physical property up to a certain degree of precision, although such measurement will not necessarily reflect an accurate value of that property. The difference between *precision* and *accuracy* is of paramount importance for Morrison here: whereas the former is related to the experimental practice of intervening in nature (or computing the model in the simulation), the latter is related to the mediation of models as rendering reliable data. In this context, a precise measurement consists of a set of results wherein the degree of uncertainty in the estimated value is relatively small (2009, 49); on the other hand, an accurate measurement consists of a set of results that are close to the true value of the measured physical property.¹¹

⁸ I am using the term *empiricists* in a rather loose way. Here, I refer only to the epistemic attitude of knowing the world by causally intervening or manipulating it.

⁹ In order to keep these two notions of data separate, I will continue referring to data collected by the scientific instrument as 'raw data,' while I will refer to the data obtained by running the computer simulation as 'simulated data.'

¹⁰ Morrison also discusses the more sophisticated example of spin measurement (2009, 51).

¹¹ The difference between *precision* and *accuracy* is framed by Franklin in the

The distinction between these two concepts constitutes the cornerstone of Morrison's strategy: data collected from experimental instruments only provide precise measurements of g , whereas reliable measurements must first and foremost be accurate representations of the value measured. It is in this context that Morrison considers that raw data must be post-processed in the search for accuracy (for the particular case of measuring g , Morrison proposes the ideal point pendulum as theoretical model).

From Morrison's perspective, then, the reliability of the measured data is a function of the level of accuracy, which depends on a theoretical model rather than on the scientific instrument or on the computer simulation.

The calculation generates a large amount of data which requires that they be appropriately modelled in order to render them interpretable. Only by doing that can we say that the computer experiment, like an ordinary experiment, has measured a particular quantity. In both cases models are crucial. And, just as in the pendulum example where we are interested in both the precision and accuracy, similar concerns arise for simulation where the precision of the machine and the behaviour of apparatus is related to the observed properties of the microscopic system. (2009, 53)

Computer simulations, just like scientific instruments, share the same fate of being precise but not accurate—for the latter, it is because of the physical constraints related to manipulating the real world; for the former, it is because of the fact that a computer simulation implements the physical constraints of the target system as well as the physical constraints of the machine itself (e.g., round-off errors, truncation errors, and so forth). The precision/accuracy dichotomy, then, applies to computer simulations just as it does to experimental measurement, making both practices ontologically equal at the level of precise data, and epistemically equal at the level of accurate data. The materiality argument is also present here: equal ontology determines equal epistemology. And this was precisely the intention behind Morrison's analysis: "the connection between models and measurement is what provides the basis for treating certain types of simulations outputs as epistemically on a par with experimental measurements, or indeed as measurements themselves" (2009, 36).

following example: "a measurement of the speed of light, $c = (2.000000000 \pm 0.000000001) \times 10^{10} \text{ cm/s}$ is *precise* but *inaccurate*, while a measurement $c = (3.0 \pm 0.1) \times 10^{10} \text{ cm/s}$ is more *accurate* but has a lower precision" (Franklin 1981, 367n1).

Thus interpreted, Morrison is applying a philosophy of modeling and experimentation onto a philosophy of computer simulations. This is also a consequence of following the materiality principle; that is, there is no analysis provided of computer simulations in itself, but only in the light of a more familiar philosophy. By making raw data and simulated data ontologically equal, and the post-processing a further epistemic step, Morrison is applying model techniques to computer simulations, regardless of the particularities of the latter. With this move in mind, Morrison also narrows down the class of computer simulations to those that are used as measuring devices; and in doing so, she is narrowing down the epistemic analysis to those simulations.

There is a further concern about Morrison's argument. According to it, simulated data need post-processing. The claim considers simulated data *as if* they were not model data in a straightforward sense, but rather raw data as obtained by experimentation. A computer simulation, however, consists of a series of nested models that produce a final output, and therefore the data produced by a simulation is already accurate as regards the value measured. In this vein, there is no need to postulate any further post-processing step, as Morrison does. However, let us accept for a moment the argument that simulated data needs to be post-processed. If this were the case, Morrison's argument faces another challenge. Given the fact that computer simulations produce vast amounts of data, arguing for a separate correcting process such as post-processing begs the question about a possible 'computer regress'; that is, the need for another computer model capable of processing the initial simulated data. This new computer model would fix some inaccuracies in the original data, but would also introduce new ones, since the same physical constraints apply to this new processing stage. It then seems reasonable to be concerned about a possible infinite regress of post-processing simulated data. To my mind, there are no other motivations for thinking about post-processed simulated data except for Morrison's interest in analyzing computer simulations in the light of scientific experimentation, which is an unnecessary precondition for the epistemological analysis of computer simulations.

Conclusions

I have discussed three different views of how philosophers currently understand the epistemological study of computer simulations. I have shown that all three make use of the same rationale as the guide for their argumentation. I called this rationale *the materiality principle*, and I conceptualize it as the philosophers' commitment to an ontological

account of computer simulations (and experimentation) that determines the evaluation of their epistemic power.

The aim of this paper was to show that the materiality principle is a rationale shared by many philosophers working on the epistemology of computer simulations. It was also the aim of this paper to alert us to the possible consequences of allowing the philosophical discussion to be so diverted. In this vein, I have suggested that adapting our philosophical investigations in line with the materiality principle might be placing a conceptual corset on inquiries regarding the epistemology of computer simulations. In this context, I distinguished three viewpoints that conform to this rationale, and set out the various restrictions that they place on the epistemological analysis of computer simulations.

The first two views were rejected on the grounds that they purport internal inconsistencies in the conceptualizations of experiments and computer simulations. The objection to the ‘identity of the algorithm’ is that it makes implausible claims regarding the ontology of computing machines; whereas the objection to the strong version of the ‘materiality stuff as criterion’ is that misplaces the role of computer simulations in scientific practice. I also claimed that the materiality principle is the underlying motive for these inconsistencies. On the other hand, the weak version of the ‘materiality stuff as criterion’ and the ‘models as (total) mediators’ views are, to my mind, the most promising interpretations of experimental as well as computational practice. However, as I showed, neither account directly addresses the epistemology of computer simulations. Rather, they reduce it to the epistemology of semi-material experiments (weak version of the ‘materiality stuff as criterion’), or to scientific modeling via measurement (‘models as (total) mediators’).

The conclusion is that philosophers who accept the materiality principle are less likely to recognize what is distinctive about the epistemology of computer simulations than those who do not. Of course, I am not urging the adoption of an entirely new epistemology, enlightened and guided by computer simulation, as Frigg and Reiss have proposed (2009). My conclusion is more modest, and aims to encourage certain changes in the philosophical inquiry on computer simulations. For instance, Barberousse et al. (2009) have made a central contribution to the notion of computer-simulated data, and Humphreys has followed their work by analyzing the notion of data in more detail (this volume). Nevertheless, more work needs to be done and, to my mind, it must begin by reconsidering certain classic topics in the philosophy of science through the lens of computer simulations. In this sense, a review of

traditional notions of *explanation, prediction, confirmation, evidence*, and the like might work as the starting point.

Evidently, there is a way of doing philosophy of science that is strongly grounded on empirical inquiry exemplified by experimentation. The guiding epistemic principle is that the ultimate source of knowledge is given by interaction with and manipulation of the world. However, the continuous success of computer simulations is calling these principles into question: first, there is a growing tendency towards representing rather than intervening into the world; second, computational methods are pushing humans away from the center of the epistemological enterprise (Humphreys 2009, 616). The philosophical inquiry on the epistemological power of computer simulations has thus been misguided, for some philosophers are still maintaining a false dichotomy between experiment and computer simulation while ignoring the fact that scientific practice has already transcended this division.

References

- Barberousse, A., Franceschelli, S. et al. "Computer Simulations as Experiments". *Synthese*, 169, no. 3, (2009):557–574.
- Dowe, P. *Physical Causation*. Cambridge University Press, 2000.
- Franklin, A. "What Makes a 'Good' Experiment?" *The British Journal for the Philosophy of Science*, 32, no. 4, (1981):367.
- Frigg, R. and Reiss, J. "The Philosophy of Simulation: Hot New Issues or Same Old Stew?" *Synthese*, 169, no. 3, (2009):593–613.
- Giere, R. N. "Is Computer Simulation Changing the Face of Experimentation?" *Philosophical Studies*, 143, no. 1, (2009):59–62.
- Guala, F. "Models, Simulations, and Experiments". In *Model-Based Reasoning: Science, Technology, Values*, edited by L. Magnani and N. J. Nersessian, 59–74, Kluwer, 2002.
- Hacking, I. *Representing and Intervening. Introductory Topics in the Philosophy of Natural Science*. Cambridge University Press, 1983.
- Hartmann, S. "The World as a Process: Simulations in the Natural and Social Sciences". In *Modelling and Simulation in the Social Sciences from the Philosophy of Science Point of View*, edited by R. Hegselmann et al., 77-100, Kluwer, 1996.
- Humphreys, P. W. *Extending Ourselves: Computational Science, Empiricism, and Scientific Method*. Oxford University Press, 2004.
- . "The Philosophical Novelty of Computer Simulation Methods". *Synthese*, 169, no. 3, (2009):615–626.

- . “Computational Science and Its Effects”. In *Science in the Context of Application*, edited by M. Carrier and A. Nordmann, 131-159, Springer, 2010.
- Linder, C. “A Numerical Investigation of the Exponential Electric Displacement Saturation Model in Fracturing Piezoelectric Ceramics”. *Technische Mechanik*, 32, (2012):53–69.
- Morgan, M. S. “Experiments without Material Intervention”. In *The Philosophy of Scientific Experimentation*, edited by H. Radder, 216–235. University of Pittsburgh Press, 2003.
- . “Experiments versus Models: New Phenomena, Inference and Surprise”. *Journal of Economic Methodology*, 12, no. 2, (2005):317–329.
- Morgan, M. S. and Morrison, M. (eds.). *Models as Mediators: Perspectives on Natural and Social Sciences*. Cambridge University Press, 1999.
- Morrison, M. “Models, Measurement and Computer Simulation: the Changing Face of Experimentation’. *Philosophical Studies*, 143, no. 1, (2009):33–57.
- Parker, W. S. “Does Matter Really Matter? Computer Simulations, Experiments, and Materiality”. *Synthese*, 169, no. 3, (2009):483–496.
- Tanenbaum, A. S. and Woodhull, A. S. *Operating Systems Design and Implementation 3rd ed*, Prentice-Hall, 2006.
- Winsberg, E. “A Tale of Two Methods”. *Synthese*, 169, no. 3, (2009):575–592.
- Woodward, J. *Making Things Happen*. Oxford University Press, 2003.