(Submitted -- under review)

ABSTRACTING MATTER

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I want to weigh in on a discussion that has been going on in recent work on the question of how models, experiments, and simulations are to be differentiated from each other. I will not be addressing that question directly, though. Instead, I will be focusing on a point of contact between these discussions and some philosophical work on the topic of physical similarity and physically similar systems: the question of the role of matter in simulations, models, and experiments.

In some recent papers and talks Mary Morgan (2003, 2005), Rom Harre (2003), Francesco Guala (2002), Eric Winsberg (forthcoming), Uskali Maki (1992) Wendy Parker (2008) and Margaret Morrison (2009), among others, have proffered views on whether --- and how --- matter is involved in simulations, in experiments, and in the use of models. They are not the first to do so, of course: Nancy Cartwright and Herbert Simon, whose views are brought up occasionally in these discussions, had things to say on the topic as well, and Ian Hacking is often part of the background when the discussion turns to experimentation. I'll review some points in the discussion I find of special interest first, then organize the issues in the discussion in a manner that shows how some work by philosophers on physical models and physical similarity can help out. I will conclude, in fact, that one of the most problematic issues that arises in the discussion -- the question of which similarities are relevant similarities -- has an answer, and a more precise one than many of the discussants might have thought possible.

Review of Past Discussions on the Question

In his paper "Models, Simulations, and Experiments," Francesco Guala refers to Herbert Simon's formulation of a distinction between simulations and experiments. In speaking of simulations, Simon was thinking of (or at least including) analogue simulations, wherein the correspondence between two physical situations is established in virtue of their both being instantiations of the same formal equation. (The two physical situations can be said to satisfy the same formal equation only if one takes the terms in the equation to refer to different things accordingly, of course.) Simon gave the example of a researcher studying light waves via a simulation consisting of water waves. Guala, following Simon, says that in such a case the similarity is abstract and formal. The basis of the distinction they draw is thus a distinction based upon the nature of the similarity, or the similarity relation, not a distinction based upon the nature of the objects or the processes being used to perform the simulation.

In Guala's words:

> "The terms appearing in the equation describing the target and the model-systems are to be interpreted differently in the two cases: the forces are different in nature, and so are the two media in which waves travel. The similarity between the theoretical model of the light waves and the ripple-tank model holds at a very abstract level only. The two systems are made of different "stuff": water waves are not light waves. Because of the formal similarity, though, the behavior of light waves can be simulated in a ripple tank. Both light waves and water waves obey the same non-structural law, despite their being made of different "stuff." This is due to different reasons in each case: different underlying processes produce similar behavior at an abstract level of analysis. (Guala, 2002; pp. 66 - 67)

I think it is clear what Simon and Guala are trying to capture here; even though the simulation is a simulation using a *material* system to simulate a *material* system, the relationship is established in terms of each of them being a model (or instantiation) of a *mathematical* equation. This is why they describe the similarity as "abstract and formal." Guala contrasts such a simulation with an experiment, speaking specificially from the standpoint of economics:

> Experimental systems are reliable if they are made of the same "stuff" as real world economies. No process of abstraction from material processes is needed in order to draw the correspondence from the laboratory to the outside world. One may abstract from 'negligible' causal factors, but not from the basic processes at work. The similarity is not merely *formal*, but holds at the *material* level as well. (Guala 2002; p. 70)

Thus Guala thinks that an important distinction -- the distinction between *formal* similarity and *material* similarity --- turns on whether abstracting from material processes is necessary. As the terminology used to discuss materiality and abstraction is not uniform, let me say a few words now about how I will be using the terms in this paper before going further. The term "abstract", when used as a verb, is meant in the sense of "to draw off or apart." I'll use the term "material" loosely to designate one side of a distinction, drawn pragmatically: material versus nonmaterial. Likewise, "nonmaterial" can be considered the complement of "material", i.e., whatever is not material. It's not my intention here to make a metaphysical claim[1]; this is just a note about terminology in the interest of achieving an understanding with the reader about how these terms are used in this paper. Figure 1 contains examples that may be helpful in this regard.

Mary Morgan, too, sees significant distinctions turning on whether the same material processes are at work, though she often puts the point in terms of the value of using the same material or "stuff", and discusses the distinction in the context of models and experiments. In her paper "Experiments without Material Intervention," she discusses mathematical models, contrasting them with experiments. She locates mathematical models at one end of a scale she uses to indicate degree of materiality. Mathematical models are at the end designated "mathematical"; other positions on the scale are designated "material", "pseudo-material", "semimaterial", and "nonmaterial." As indicated above, I want to use terms that make contact with the existing discussion yet still keep my terminology as simple as possible, and so use the

[1] . The distinction can be used for processes as well as things: for some purposes, it might make sense to talk of material processes (e.g., a neurological process, a sorting process, a mechanical or electronic process) versus nonmaterial ones (e.g., an algorithm).

term "nonmaterial" simply to indicate the complement of "material." Hence, for me, unlike Morgan, nonmaterial includes mathematical entities and so includes mathematical models.

Morgan notes the following difference between "pen-and-paper experiments with mathematical objects compared to the experiments with material processes or objects":

> "In the laboratory case, we use the experimental results to argue (or perhaps infer) from this process and results to the same kind of material process and results in other (possibly) nonlaboratory setups. In the mathematical model experiments also, we use the results to argue, or infer, to other systems we think have similar characteristics to those of the model, but in this case those systems might be mathematical or material." (Morgan 2003; p. 221)

In discussing model organisms -- such as animal models used in a laboratory study, Morgan discusses another distinction grounded in the difference between whether or not one uses the same material (or "stuff") in the laboratory as occurs in what the laboratory model or experiment is about: the distinction between *representative of* and *representative for*. A model organism is *representative of* others of its own species, and can be a *representative for* some other species. She draws on the example of model organism in "Experiments versus Models: New Phenomena, Inference, and Surprise":

> "My notion of experiments as capturing or reproducing the world is well matched in Harre's label of domesticated versions of natural systems, for the important point for both of us is that these are made of *the same stuff* as the real world. His domesticated model systems match my laboratory worlds, they are of the same materials as the world, yet 'simpler, more regular, and more manipulable' ([Harre] 2003: 27) than those in the wild. (Morgan 2005; 322)

Here Morgan appeals not only to the same material processes being at work, but to the experimental model being made "of the same materials" as things in the real world. She is talking about natural systems, but it remains unclear how specifically "the same" is to be taken. Her remarks in other places about the same material processes being at work indicate that perhaps what matters on her view is the identity of the material processes at work, not the identity or similarity of the materials per se. This reading of her intent is in line with the importance she places on another contrast in that same paper:

> Here [when talking of experiments] 'representing' needs to be replaced by 'replicating', in the sense of 'reproducing' or 'capturing' some aspect of the world in the same kinds of materials and forms as those of the real economic world. In other words, the construction of an experiment recreates a part of the real world inside the artificial environment of the laboratory. In contrast, the construction of a model creates an 'artificial' world – artificial because made out of mathematics, diagrams, or alternative physical domain materials (i.e., not those of the economics domain). As it will turn out, this matter of their materials – the artificial world vs. the real one of people and economic decisions – is an important element in the comparison of the status of a model compared to that of an experiment. (Morgan 2005; 320)

Wendy Parker (Parker 2008) examined Morgan's claims about the importance of things being "made of the same stuff." She is critical of Morgan's appeal to the laboratory experiment being of the same material as the target system; she writes:

> The focus on materiality is somewhat misplaced because what is ultimately of interest when it comes to justifying inferences about target systems is not *materiality*, but *relevant similarity*. [. . .]
>
> The relevant similarities might be formal similarities, material similarities or some

> combination of the two, depending on the type of experiment and the target question at hand. But, crucially, having experimental and target systems made of the same materials does *not* guarantee that all of the relevant similarities obtain. (Parker 2008; 493)

I think the point about relevant similarities is right, but to be fair to Morgan, Morgan's point in talking about the experimental setup or object and the target system being of "the same stuff" or 'the same material" could be taken in a more generic sense. The notion of being made from the same material is somewhat imprecise anyway. Consider a material such as steel or cotton: is "the same material" to refer to the same grade of steel or cotton, to steel or cotton from the very same batch in the same manufacturing facility, to steel or cotton of the very same age and exposed to the very same stresses over its life history, etc.? Any notion of the same material would have to involve spelling out the characteristics of the material in some way, whether in terms of its origin and the manufacturing process used or by some other means of specification. Thus a charitable interpretation of Morgan might be to take her point to be that the world and the experimental model are in some general sense made of the same stuff. Perhaps the idea is that the experimental model and the world are made of stuff that responds to the same sort of conditions and the same sorts of changes in the same way. Then, the significance of both being made of the same stuff to the question Morgan is concerned with might be that both are subject to gravity, to the laws of geometry, to principles such as the least work principle and the conservation of momentum, or that both respond to certain changes (dampness and humidity, or sunlight, or stress, or shocks of various sorts) in the same sort of way.

Relevant similarities

Parker is certainly right that the crucial thing in making inferences from experimental models turns on whether the relevant similarities obtain. I doubt few would disagree, once this is pointed out; admonishing someone to pay attention to all and only the similarities that are relevant, however, is akin to telling someone to do the *right* thing. One is still left with the problem of determining which similarities are relevant and which are not.

Several different examples of physical similarity are given in my paper "Models of Machines and Models of Phenomena" (Sterrett 2006) The first example in that paper illustrated how subtle some relevant similarities can be: an exact, same size replica of an airplane, no matter how historically accurate the replication (in the example given there, the builders even used historically accurate tools to construct it), might not behave as the original did. In fact, it definitely won't do so, if the atmospheric conditions in which it is attempting to fly are significantly different from those that existed on the original occasion that the pilots were attempting to replicate. This general point --- the importance of probing into whether the similarities one has taken such great care to establish include all the relevant similarities --- is easily forgotten in discussing what can be predicted from a model. The question of how to identify which similarities are relevant is often considered merely a practical, and not a foundational or philosophical matter. On the contrary, it is a fundamental question concerning scientific inference.

Model organisms are excellent contexts in which to see that this point arises when defining or characterizing a system: how much of the organism's environment is relevant to its behavior? There are (at least) three different kinds of important relations: (i) the relations between features of the environment to each other, (ii) the relations between features of the organism to each other, and (iii) the relations of features of the organism and features of the environment. Relationships of all three kinds are potentially relevant; thus the need for a certain kind of holism when making comparisons of similarity. How a system ought to be characterized is generally not entirely a matter of choice or convention. It depends upon the behavior of interest, i.e., which behavior one wishes to draw inferences about may put some constraints on what counts as a system for the purposes of making inferences about that kind of behavior, and may rule out others as insufficiently inclusive.

I deliberately avoided using an example in which the relevant similarities that need to be attended to arise solely due to using a model that is of a different size than the target system. I did so by using an example of a same-size replica, and I did so in order to focus attention on the importance of being appropriately holistic (e.g., of including the environment and the relations associated with including it) in defining the system *whenever* we speak of model systems and target systems. Examples in which there is a change of size illustrate that crucial point, too, however: the fact that a geometrically similar model of a different size does not mimic the behavior of the larger target situation shows that preservation of the relevant similarities includes more than preservation of all the geometric similarities. A good illustration of this latter point is that when model-makers make a model of an archery bow smaller than the full size bow whose bending behavior it is to mimic, they must make the model bow out of a different material. The material has to have a different value for the coefficient of elasticity in order for the relevant dimensionless parameter to be the same in the model and the full size bow. So not only does using the same material not guarantee that the relevant similarities obtain, but using the same material may even be contraindicated. We are still left asking, what *does* guarantee that two systems are similar in the relevant respects, then?

Though she did not proffer an answer, Parker did hint at what relevant similarity might be based upon by way of an example; in the course of making her argument that using the same material does not ensure that the relevant similarities needed to validate an inference to a prediction about the target system will obtain, she made a brief mention of dimensionless parameters:

> . . . traditional laboratory experiments undertaken to learn about fluid phenomena, like the weather, provide prime examples of how experiments on same-stuff models can fail to be relevantly similar to target systems. *In such experiments, it is often critical to ensure that various dimensionless parameters of the fluid flow are quite similar in the experimental and target systems. For instance, it may be essential to ensure that the ratio of quantities that defines the Reynolds number of the flow is not too different in corresponding regions of the experimental and target systems*. But because some of these parameter values depend on things other than just which fluid is being used—e.g. on such things

> as the depth of the fluid and the size, shape, roughness and movement of any container holding it—the relevant similarities can fail to obtain . . . even when the experimental and target systems are made of the "same stuff." (Parker 2008; pp. 123 - 124) [emphasis added]

Eric Winsberg has tried to sort out some of these issues, too, in his "A Tale of Two Methods." The two methods referred to in the title of his paper are the two different methods used by two physicists generating numerical and graphical results. One physicist uses a laboratory setup containing a fluid, the other uses a digital computer and an algorithm based on the Navier-Stokes equations that is designed to simulate fluid flow.

Winsberg then asks the reader to consider the case of a physicist who uses an *analog* simulation rather than a computer simulation. He explains what the analog and computer simulation have in common in terms of relevant similarities. In both cases, he says, what is needed are "reliable principles for building an abstract model of both the object and the target, and an argument -- based in part on those principles -- that the object of the investigation has been configured in such a way that the two models of these systems will have relevant similarities." (Winsberg forthcoming, pg. 26 of preprint) The emphasis on the systems having relevant similarities is surely correct, but, again, there is still the problem of how to determine what counts as a relevant similarity. Winsberg appeals to "reliable principles for building" models. But there is an important question that needs to be asked here: are the principles for building the kind of abstract models needed to make the argument for external validity in the case of a *computer* simulation the same as the principles that are needed to build the kind of abstract models needed to make the argument for the external validity in the case of an *analog* simulation? If they are not, then Winsberg's unified explanation, though not wrong, would gloss over a distinction that is important to the question of the role that matter (material properties, material processes) plays in establishing the external validity of the simulation. It is this latter question that is my interest here. Winsberg's conclusion, though perhaps answering the question in which he was interested, leaves us in the same position regarding the role of matter that we were left with at the end of Parker's paper: how to identify and determine relevant similarities between two material things.

Relevant Similarities, Dimensionless Parameters, and Physically Similar Systems

Here is where the work I have done on physical similarity and physically similar systems has something substantive to contribute to the discussion. I pointed out that Parker's remark about the importance of a certain dimensionless parameter, the Reynolds Number, hinted at a formal way of identifying relevant similarities. I would rephrase Parker's point, though. Rather than saying that it is critical to ensure "that various dimensionless parameters of the fluid flow are quite similar" in the two systems, I would point out that it is possible to say something more precise than that, namely: *the similarity of two systems with respect to a certain behavior of interest is established by showing identity of the numerical value of the relevant dimensionless parameters between the two systems*. That is, for fluid behaviors that are determined by the Reynolds Number (a dimensionless number that takes on different values depending on the relation between a bunch of different quantities that includes the geometry of the flow configuration, fluid density, fluid viscosity and flow velocity), we can say quite confidently that similarity with respect to those behaviors (e.g., onset of turbulent flow) is established by showing that the Reynolds numbers of the two systems are equal. Thus, if turbulence is an important kind of behavior, we would try to keep the Reynolds number in the model system close in numerical value to the value that the Reynolds number has in the target system. Parker's point was that doing this is more important than using the same material. As I've pointed out above, the truth is even more extreme: a *different* fluid can sometimes be used in an experimental model than the fluid in the target system, as when water is used to obtain experimental information on fluid flows for use in oil pipelines. Sometimes using a different material is even *required*.

Often more than one dimensionless parameter is required to establish the similarity of two systems, and establishing similarity of behavior between the experimental system and the target system is a matter of the values of *each* of the dimensionless parameters having *the same numerical value* in the model system as in the target system. The values of the *quantities* that form the dimensionless ratios (e.g., flow, viscosity, linear dimensions) need *not* be the same in the target system as in the experimental system in order for the two systems to be physically similar, as it's the value of the dimensionless parameters, not the value of measurable quantities, that determines similarity. The dimensionless parameters that are relevant might express a relationship of any of the three kinds I have mentioned above: i.e., a relation between two or more quantities in the environment, between two or more quantities in the organism or model, or between quantities in the organism or model and quantities in the environment. Of course, in experimental practice, one can rarely ensure that all the values of the relevant dimensionless parameters are *exactly* the same, and one settles for making informed tradeoffs and doing the best one can.

The methodological point, however, is that *it is identity of the relevant dimensionless parameters that establishes similarity of two systems with respect to a certain behavior* (e.g., kinematic behavior, dynamic behavior, the existence of shock waves, the existence of turbulence, the existence of a coherent stream in a greater fluid mass, and so on). Thus the question of which similarities are relevant has been shifted to the question of which (or which sets of) dimensionless parameters are needed to establish that two systems are physically similar.

<u>Physical Similarity</u>

The general notion of physically similar systems was given a formal logical treatment in 1914 (Buckingham 1914), though it had been used in practice for particular kinds of physical similarity (heat, structural mechanics, fluid dynamics, physical chemistry) before that. I discussed the method with respect to the philosophical questions of the sources of information and and the validity of drawing inferences using it in two papers, the first of which was entitled: "Physical Models and Fundamental Laws: Using One Piece of the World to Tell About Another." (Sterrett 2002) In "Models of Machines and Models of Phenomena" (Sterrett 2006) I argued that all inferences from laboratory experiments in physics are really implicitly appealing to physical similarity in some way.[2]

As I indicated earlier, the way to establish that two systems are physically similar is by showing that the values of a set of dimensionless parameters that characterize the system have the same value in the two systems. To illustrate the point, here's a very simple example: suppose you want to examine behavior in the wake of a projectile as it goes through the sonic phase, i.e., breaks the sound barrier. What do you want to copy in your laboratory tests? Not the speed. Breaking the sound barrier is a matter of the Mach number being equal to 1.0; the Mach number is the ratio of the speed of the projectile to the speed of sound in the surrounding air (which depends on the temperature and pressure of the air.) So if the temperature in your laboratory is different than the target situation, then the speed at which Mach number equals one could be different in the laboratory than in the target situation. If the fluid you are using is different than that in the target situation, then the speed of sound in the fluid used in the laboratory could differ from the speed of sound in the fluid used in the target situation. Again, you would want to ensure that the Mach number (the *ratio* of the velocity of the projectile to the velocity of the speed of sound in the surrounding fluid) was the same in the two situations. Thus, in such an experiment, we can be quite precise about how to establish similarity, whether the material used is the same or not.

The next question is obviously: how are the dimensionless parameters obtained? There are several ways, and some require more information than others.[3] One way is to obtain them directly by manipulating an equation governing or describing the behavior of the system: first to put it into the form that is known as "a complete physical equation" if it is not already in such a

[2] A more extended discussion of the method, in the form of a critical-historical account of its development and articulation, can be found in Chapters 6 and 7 of Sterrett's *Wittgenstein Flies A Kite: A Story of Models of Wings and Models of the World* (Sterrett 2005). A handbook article "Similarity and Dimensional Analysis" delves even more deeply into the foundations of the method and includes a brief discussion of its relation to some issues of metaphysics and ontology. (Sterrett, forthcoming, 2009)

[3] See Sterrett (2006) for a discussion of all three ways of finding relevant dimensionless parameters.

form, then to put it into nondimensional form. This method, which is probably the best known to scientists, requires having a governing equation, although one need not know how to solve it for the variables of interest. This is the approach that Helmholtz took; he showed that even though solutions to the equations for hydrodynamics were not obtainable by the methods then available, that one could still make inferences from situations that one was able to observe to imagined or unobserved situations. He put the governing differential equations in nondimensional form. From these, he was able to identify the relevant dimensionless parameters. This is sometimes called the inspectional method.

However, as explained in (Sterrett 2005) and (Sterrett 2006) this is not the only way to identify a set of dimensionless parameters that characterizes a system. Such a set of dimensionless parameters can be obtained with *less* information about the system. The fact that the amount of information required is less than that needed to predict the behavior of the system is extremely significant: as we shall see, it bears on points that Morgan and Winsberg are especially concerned with.

What *is* essential is to know which quantities q1, q2, . . . qn the behavior of interest depends upon. The set of q's might not be a unique set; knowing one such set suffices. (Some sets are much more convenient than others in practice.) Using something called the method of dimensions, or dimensional analysis, a (nonunique) set of dimensionless parameters that characterizes the system can then be obtained. That is, from the knowledge that (i) if the values of all the (dimensioned) quantities q1, q2, . . . qn are determined, then the behavior of interest of that system is determined, we can use dimensional analysis to identify at least one non-unique set consisting of m dimensionless parameters p1, p2, . . . pm such that (ii) If the values of the dimensionless parameters p1, p2, . . . pm are determined, then the behavior of interest of that system is determined. This provides a means of establishing the physical similarity of two different physical systems. [4]

[4] Peter Kroes has also discussed similarity of physical systems (Kroes 1989).

This is all very formal and logical; what we now wish to ask is what it tells us about how the material, or stuff used in a model or laboratory experiment is involved in drawing inferences from the model or experiment. The way that the material figures in the analysis is through the material properties, if any, that are involved: some of the physical quantities q might have to do with the material making up a system, e.g., elasticity, heat capacity, or viscosity. Yet these are properties that are not specific to any one material, for two different materials can have the same elasticity, or the same heat capacity, or the same viscosity. You might say that these properties are abstracted from the material. If *all* the q's on which the behavior of interest depends are the same in one system as the other, then it necessarily follows that the two systems are similar.[5] That's a degenerate case of similarity. The more general question regarding similarity is, what if some of the quantities q are not the same between the two systems: then, which similarities are relevant and which are not? We know the answer by now: by making sure that all the dimensionless parameters p1, p2, . . . pm on which the system behavior depends have the same numerical value in the one system as the other, one ensures that all the relevant similarities hold. Thus, with only partial information about each of the two situations (i.e., with information that is not enough to predict the behavior of either), we can predict *that the behavior of the two situations will be the same*, even though we cannot predict the behavior of either situation. To put this point about the method in the terminology Mary Morgan used in Morgan (2005): using the method of physical similarity, we can be confident that a model is informative about a target situation with respect to a certain behavior, but *surprised* at how it behaves, because we are not able to predict what will happen.

How widely applicable is this method ---- i.e., just what does "physical similarity" cover? It is a general term covering a variety of kinds of similarity: the research question you ask will indicate which kind of behavior you are interested in and, in turn, the kind of similarity relevant to that

[5] It's important for the point made here that all the q's are the same. In the example of an exact replica of a plane given above and in Sterrett (2006), the q's are not necessarily all the same if the atmospheric conditions are not the same, so that case was *not* such a degenerate case of similarity.

behavior. Similarity of two systems is both *objective* and *relative*. Similarity is *objective* in that, once the behavior of interest is specified, the conditions for similarity are determined (by some combination of scientific theory and experimental or empirical knowledge). Similarity of two systems is *relative*, though, in that the kind of similarity that is relevant when using a model system to inquire about a target system depends on the behavior one is interested in. Whether a model system is similar to a target system is not a yes or no question; one may be interested in kinematic similarity (i.e., similar motions in proportional times), dynamic similarity (similarity of forces), or similarity with respect to heat flow, or electrical behavior. This relativity of similarity provides an answer to a skeptical point raised by Winsberg in his analysis. Winsberg wrote: "I am puzzled by the idea of two concrete entities having objective formal similarities. Give me any two sufficiently complex entities and I can think of ways in which they are formally identical, let alone similar." (Winsberg, , p. 18 of preprint) The point, we can now see, is not whether there are *some* ways in which the two are similar or not. Using the method of physical similarity as described above, we would first ask what kind of behavior (thermal, dynamic, kinetic, electrical, bending, buckling, existence of turbulence, existence of a coherent colder stream in a warmer fluid, etc.) one is interested in. Then, we could, after some work in properly identifying the system, determine which dimensionless parameters are relevant.[6] The indeterminancy Winsberg imagines to exist then disappears.

Thus the issue of relevant similarities does depend on one's aims, in a sense, but it is not a matter of whether or not a certain intention or aim *exists*, but rather a matter of properly clarifying what one's aims are with respect to the inferences one wishes to have a basis for making, and then proceeding according to the method of physically similar systems. What is important in an experiment or model is relevant similarity of two systems; the correct thing to say about materials and matter here is that *sometimes* the *properties* of a material are relevant: e.g., its elasticity, its heat capacity, the frictional coefficient for its surface, etc. Yet the way these material properties

[6] How this is actually carried out is described in some papers on physical similarity (Sterrett 2002, 2006). The example Buckingham used in his "On Physically Similar Systems" (Buckingham 1914) is also recounted in (Sterrett 2005)

figure in establishing physical similarity is the same way that other quantities do so, too: via their role in the dimensionless parameters used to establish the relevant kind of physical similarity. Given that Guala and Simon placed such significance on *the same material processes*, in drawing the distinction between simulation and experiment, where does this leave us, then?

The main point I have been leading up to may be clear by now: Guala and Simon's discussion overlooked a very important kind of case: a simulation in which the similarity is established by the method of physical similarity, rather than by means of an equation that each of the two systems instantiates. Guala and Simon cited abstraction from matter as the key to the distinction between experiments and simulations; in experiments, they said, the same material is used and the similarity holds at a deep, material level. In simulations, they said, the similarity is merely formal. What would they say about a case in which similarity is established using a set of dimensionless parameters in which material properties such as elasticity and viscosity were among the quantities occurring in some of the dimensionless parameters? The similarity is in some sense formal, yet the abstraction is not one that has totally dispensed with matter, since some material properties are involved in the formalization of the similarity. Thus, in using the method of physical similarity, the similarity between the two systems might be said to hold at a material level. Yet the two systems might be made of different materials.

Winsberg analyzed the notion of aiming for relevant similarities between two concrete entities (Winsberg forthcoming, 2009) thus: "[researchers] have a way in mind of modeling their target, and they have a way in mind of modeling their object, and what they [are] hoping is that on that way of thinking about the two entities, formal similarities will exist between those two models." (p. 19) He then dismisses the approach of looking for an "objective relationship [that] actually exists between the object of an investigation and its target, nor even on what objective relationship is being aimed for. We should focus instead on epistemological features --- on how researchers justify their beliefs that the object can stand in for the target." He goes on to give an account of "principles for model building"[7] in terms of the beliefs that the physicists who build the models have in their principles and methods. It should be clear what the method of physical similarity has to offer here: the account of models having formal similarities is on the right track, but one is able to do more than hope. One can be precise about how the similarity must be established; having established physical similarity in terms of the relevant dimensionless parameters, inferences between the two physically similar systems are warranted by them as well.

Models and Materials

We are now ready to address the role of the material in model-based reasoning in general terms. To focus on that question, I will examine the nature of the similarity relationships involved in different kinds of model-based reasoning, and I am going to do so in terms of the materiality of the two things being related.

There are four cases in all, examples of which are shown in Figure 1 (cases 2. and 3. are flip sides of each other):

1. Nonmaterial things having Nonmaterial models
2. Nonmaterial things used to describe Material things
3. Material things used to model Nonmaterial things
4. Material things used to model Material things

[7] I take Winsberg's move in saying that "it is too strong to say we need to have a model of the target system's behaviors. What one needs, I urge, are reliable principles for building models of those behaviors" (Winsberg forthcoming, 2009, p. 26), in its general lines, to be in sympathy with the move I made in Sterrett (2002), in which the point is made that though it may not be true that laws describe the behavior of physical models, that is no problem, because it is true that laws (such as general conservation laws) can tell us *how to construct* models so that the model behaves like what it is to be a model of. I take the importance Winsberg places on background knowledge of scientists to be in sympathy with the move in Sterrett (2006), in which I discussed what sources of information are drawn upon in using the method, including background and experiential knowledge. So it seems that there are some basic points of agreement between Winsberg and me, in spite of some differences.

In case 1 the similarity is established without the involvement of matter. In cases 2. and 3., the similarity is established on the basis of having appropriate formalizations of the behavior of the material things. That leaves us with case 4.

Are there any cases of 4. that do not presume being able to carry out the kind of modelling in one of cases 1., 2., and 3.? We now know that the answer is yes. In the physical sciences, the method of physical similarity tells one how to construct a laboratory situation or a physical model such that the laboratory situation or physical model will behave in ways that are relevantly similar to the target situation. In cases where one has only partial information, this is truly different from having a nonmaterial mediated relation. Why? Because there is some part in saying how things will go, in how the model will behave, that is not yet formalized. That is, although the relevant similarities (the dimensionless parameters, which are ratios) are all formalizable, the values of the individual quantities are not in general determinable from the characterization of a physical system in terms of dimensionless parameters (just as the value of any particular linear measurement of a geometrical object is not determined by its shape). In contrast, in the case of the two instantiations of the wave equation cited by Guala and Simon, the wave equation allows one to determine how the model behaves, and it is the equation that forms the basis for claiming similarity between the model and what it is a model of. Using physical similarity requires only knowledge as to which factors affect the behavior of interest. Since this is what you would need to know to set up a laboratory experiment anyway, requiring knowledge of this kind and amount is not an unreasonable demand in the physical sciences. Thus we must admit that it is not unreasonable to expect there will be instances of case 4. in which one does not have the information required to establish the kind of similarity used in cases 1., 2. or 3., at least in physics, yet one can use a model experimentally to draw inferences to other cases.

It is not clear how much the method of physical similarity allows us to say about social and economic behavior at this point. Thus, I think Morgan has a valid point about the assurance sometimes gained in using things of the same material, especially when it comes to human behavior. Two examples drawn from empirical literature are (i) simulating control room situations to train power plant operators, and (ii) using actual payoffs versus using hypothetical payoffs in experimental economics.

In training power plant operators, the goal is to is ensure that the operator is qualified to operate a specific power plant. The training simulator is thus built for training someone to operate a specific power plant. A complete, full scale mockup of the control room in which the operator will be working is built for training purposes. It is exactly like the actual control room: every material object, down to the lighting fixtures, the color of the paint, the brand and color of the carpet, and so on, is exactly replicated. This example illustrates Morgan's point that sometimes one does rely on the same material being used in two different situations, in order to obtain the same behavior. The thought is that unless you know what is going to affect the behavior, the best you can do in the absence of being able to quantify it is to try and keep the laboratory situation as close as possible in terms of causal mechanisms. You don't want to isolate those causal effects, since you need to account for their presence and all their interactions. So, you use the same "stuff" inasmuch as you can.

The other example is that, in economics laboratory experiments, it is sometimes found that you get different results if you use hypothetical incentives instead of real ones. But not always. That you do not always get different results is a sobering finding, if you think about its implications: you might be going along with experiments in which the hypothetical incentives give the same results as real ones, and gain a false sense of security as a result. Here, too, Morgan has a point about the assurance one finds in using the "same stuff", for these are situations in which the causal effects are not based on established principles and cannot be quantified in terms of properties that can be abstracted, in the way that material properties such as density, viscosity, or elasticity can be abstracted in physics. One can also take the spirit behind her point to be that, were the causal effects of the material known and expressible as material properties, that one would want to be sure to include in one's analysis any quantities associated with material properties that the behavior of interest depended upon. This is of course what is done when using the method of physical similarity.

Putting these points more generally, then, and referring to the cases in Figure 1., we can see that in cases 1., 2., and 3., the role of matter in drawing inferences, even model-based inferences, is minimal. This is not to say there is no role for matter, but that the role of matter is limited to whatever role it has in performing calculations and carrying out formal algorithms. This is true even for the model-based reasoning in cases 2 and 3, since a sufficient characterization of the material behavior is already needed as a precondition for the modeling. The same is true for any cases that can be decomposed into a combination of these three cases, even ones that are inferences from one physical system to another. Were it required that all cases of drawing an inference from one physical situation to another be so decomposable, then we could conclude that physical models are not indispensable and that mathematical models suffice for making physical inferences. Then similarity between physical situations could always be underwritten by a mathematical equation or some other formal means.

Here is where the philosophical question -- the question about whether form can be abstracted from matter, and in what way -- finds an answer, at least in the physical sciences in their current state of maturity. The method of physical similarity shows us that there are inferences we make that fall under case 4. that are *not* always so decomposable. Using the method of physical similarity doesn't require that one already be able to decompose or analyze the similarity relation in a manner such that its behavior can be modeled by something nonmaterial. Or, rather, the nonmaterial characterization is in terms of ratios, and so must be supplemented with an actual experiment, even if only a model experiment. Finding out the value of the quantity sought for using this method cannot be done without using physical materials. There are many problems in the physical sciences where model experiments are indispensable. I have found that many philosophers of science find this point surprising.

<u>Conclusion</u>

If asked to put this point in philosophy of science in terms of the language of form and matter, then, we might say that sometimes the behavior of a physical system can be described by a mathematical or formal means such that predicting its behavior[8] is a matter of calculation, proof, or computer simulation using an algorithm. In such cases, one has been able to formalize everything about the material involved in making the prediction. This is what many philosophers of science would say physical theory is for, in fact.

There are, however, cases in the physical sciences in which we can carry out an inference that predicts a system's behavior (with respect to a particular behavior of interest) even if our current state of knowledge permits it to be formalized only up to its characterization in terms of a set of dimensionless parameters. These kinds of cases of scientific reasoning are significantly different: the system behavior of interest can be predicted by the use of an experimental model and the method of physical similarity, even though prediction might not be possible (using available information) by any equation, computer simulation, or proof. In such cases, even if we have abstracted some material properties, we have not dispensed with the need for a material model. [END of paper]

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[8] with respect to a particular behavior of interest.

Figure 1 -- "Abstracting Matter"

1. "Nonmaterial" things that have "Nonmaterial" things as a model/interpretation

ex: Axioms of geometry have models consisting of sets of natural numbers

ex: Algebraic equations have models that are geometrical shapes

ex: Equation of current in circuit is a model/interpretation of equation for harmonic oscillator

2. "Nonmaterial" things used to describe Material things

[some might put this as: the material thing is a model of the Nonmaterial thing]

ex: Mathematical object or structure used to describe something

(shape of a mountain, or growth of a population)

ex: Fractal conceived of as a pattern used to model growth of leaf

ex: Equations used to model something

(current in a circuit, flow in a fluid network, flow through porous media)

3. Material thing modelling "Nonmaterial" thing

ex: Soap Bubble films modelling solutions to mathematical equation

ex: Graphics displays/printouts of fractals model abstract shape

ex: Irving Fisher's machine if used to model equations for flow of money

ex: Electrical circuit used to model equation describing flow in circuit

4. Material thing modelling Material thing

ex: Electrical circuit used to model fluid circuit

ex: Phillips machine used to model actual economic behavior

ex: Laboratory tests of people playing econ games

ex: Mississippi River Basin Model used to model Mississippi River Basin

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