Degrees of Epistemic Opacity

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Abstract The paper analyses in some depth the distinction by Paul Humphreys between ‘epistemic opacity’ —which I refer to as ‘weak epistemic opacity’ here— and ‘essential epistemic opacity’, and defends the idea that epistemic opacity in general can be made sense as coming in degrees. The idea of degrees of epistemic opacity is then exploited to show, in the context of computer simulations, the tight relation between the concept of epistemic opacity and actual scientific (modelling and simulation) practices. As a consequence, interesting questions arise in connection with the role of agents dealing with epistemically opaque processes such as computer simulations.

1 Introduction

It is a general agreement that computer simulations characteristically have in epistemic opacity one of its central features. In that context epistemic opacity is commonly understood in terms of a lack of knowledge of the full details of the (computational) process,[1] and is purportedly behind some of the issues that make computer simulations so interesting, and arguably novel, from an epistemological point of view (Humphreys, 2004, 2009; Parker, 2014; Winsberg, 2001, 2010). According to Humphreys (2004, 2009), in fact, these issues are largely a consequence of what he has termed the ‘anthropocentric predicament’, namely the problem as to “how we, as humans, can understand and evaluate computationally based scientific methods

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[1] Although epistemic opacity is usually discussed in the relevant literature in connection to knowledge some voices, e.g., Stuart and Nersessian (2019), also emphasise the fact that it also involves issues best addressed from the point of view of ‘understanding’. These are issues concerned with the difficulties epistemic opacity introduces when it comes to understand the empirical content of computational models.

that transcend our own abilities" (Humphreys, 2009, p. 617). Epistemic opacity is one such issues tightly related to the 'anthropocentric predicament'.

Roughly, the idea of epistemic opacity refers to the impossibility to check, trace or survey all the steps within a process such that we are no longer able to establish a link between the process' input and output. In the case of computer simulations this in turn has obvious implications in connection with the justification of the outputs of computer models, the knowledge they purportedly provide, as well as with their acceptance as reliable effective scientific tools. In particular, due to the fact that computer simulations involve epistemic opacity we often face difficulties when it comes to justifying the inferences made at every step of the process (at least from a standard epistemological point of view, based on the verification of the links between some premises and their corresponding conclusions).

The fast growing literature on epistemic opacity has what I see as two shortcomings. On the one hand, to my knowledge the notion of epistemic opacity is almost exclusively discussed, at least as far as its implications concern, as a 'yes-no' property of processes. Though it is true that some authors seem to be aware of the fact that some processes are more (or less) opaque than others, i.e., that epistemic opacity indeed comes in degrees, the issues at stake do not usually focus on that very fact or its implications, but just concern instead questions around the idea that epistemic opacity is a property that a process either possesses or not. Thus, issues around epistemic opacity are invariably discussed with the idea in mind that processes *are* (or are not) epistemically opaque, and little attention is paid to the implications of a process being epistemically opaque to some extent only.[2]

On the other hand, the relevant literature does not emphasise enough, in my opinion, important aspects of the strong dependence of epistemic opacity on agency. In particular, little attention has been paid to questions concerning the precise role of us humans as cognitive agents dealing with epistemically opaque processes, and its relation to the specific (scientific) modelling practices that these involve.[3] I shall attempt to overcome these shortages here.

The object of this paper is thus twofold. On the one hand, the paper aims to contribute to a better understanding of the concept of epistemic opacity, beyond the commonplace views that take it as a 'yes-no' property. The paper intends to complement this common lore by suggesting that an alternative view based on the idea that epistemic opacity comes in degrees which can be manipulated is more fruitful, especially in connection with actual modelling and simulation practices. Building on this broader analysis of the concept in the specific case of computer simulations, the paper aims at exploring, on the other hand, the relation between epistemic opacity and actual modelling and simulating practices, and more specifically concerning the role of agents (modeller scientists) in these.

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[2] Some authors do make explicit reference to 'degrees of epistemic opacity' (Durán and Formanek, 2018) or to a simulation being 'partly opaque' (Lenhard, 2019). Also, e.g., Kaminski et al. (2018), Saam (2018) and even Humphreys' original definition of the notion (Humphreys, 2004, 2009) makes room for conceiving the idea that there are degrees of epistemic opacity (see definitions 1 and 2 below and my remarks to this extent in Section 2).

[3] Some exceptions are, e.g., Durán and Formanek (2018); Newman (2015) or Kouw (2016).

Thus, starting from Paul Humphreys (2009)'s original definitions of 'epistemic opacity' —which I shall refer here as 'weak epistemic opacity' (see footnote 4)— and 'essential epistemic opacity', the paper first discusses some presuppositions, consequences and implications behind the concept of epistemic opacity itself. The paper goes on to analyse in some depth Humphreys' distinction in the context of computer simulations. I argue that, while from a qualitative point of view the notion of epistemic opacity can be identified as a fundamental characteristic common to all computer simulations, from a quantitative perspective it seems very natural to think of epistemic opacity as coming in degrees. This view sparks a number of new questions concerning epistemic opacity: if we can make sense of the idea of 'degrees of epistemic opacity' then we may ask questions such as whether such degrees may be measured and if so how exactly are they to be measured, whether models and simulations displaying epistemic opacity can be manipulated such that their opacity may be reduced at all —i.e., whether they can be transformed into less opaque models or simulations— or be even completely eliminated, what is the role of agents (scientists, modellers, etc.) and the actual scientific (simulation and modelling) practices deployed by them in this regard, etc. The paper shall attempt to answer some of these questions through the analysis of a specific example, namely the simulation of the motion of the simple pendulum. The example is introduced, in particular, as a tool to explore the limits of the concept of epistemic opacity rather than to put into question the notion as a whole.

The structure of the paper is as follows: in Section 2 the precise notion(s) of epistemic opacity to be discussed, following the original definitions in Humphreys (2009), is presented. Humphreys' definitions are discussed in some depth, revealing some of the assumptions and presuppositions in them. With these in mind the idea that epistemic opacity comes in degrees is then introduced as a more comprehensive reading of the original definitions. In Section 3 the discussion is narrowed in to the particular case of computer simulations, and goes deeper in the analysis and prospective implications of the idea that epistemic opacity comes in degrees. In Section 4 some of the consequences and implications of the discussion in the previous sections are illustrated with the help of a specific example, i.e., the simulation of the motion of a simple pendulum. The paper closes with some further remarks and open questions concerning the relation between epistemic opacity, and specifically the idea of 'degrees of epistemic opacity', and actual simulating and modelling practices.

2 Two Notions of Epistemic Opacity

As pointed out earlier, the idea of epistemic opacity is usually framed in terms of knowledge, and in the context of computer simulations it conveys, roughly, the idea that it is not possible for human cognitive agents to trace, check or verify all the steps of the process that a computer simulation involves. In the words of Wendy

Parker, "no human can examine and justify every computational step performed by the computer, because the steps are too numerous" (Parker, 2014, p. 142).

The idea is generalised beyond computer processes and human agents and made more precise in Humphreys (2004, 2009). There, two different notions of epistemic opacity are distinguished, which differ most notably in their respective logical structures, each arising from slightly different considerations concerning cognitive agents. These two notions therefore have significantly different conceptual implications, as we shall see.

Humphreys defines first what we may take as a (logically) weak notion of epistemic opacity:[4]

Definition 1 (Weak Epistemic Opacity)

> [A] process is [weakly] epistemically opaque relative to a cognitive agent X at time t just in case X does not know at t all of the epistemically relevant elements of the process. (Humphreys, 2009, p. 618)

The definition of 'weak epistemic opacity' above basically expresses a sufficiency condition, i.e., it is sufficient for the agent X to not know all of the epistemically relevant elements of a process $\mathcal{P}$ at time t for it to be epistemically opaque. Humphreys also provides a stronger notion of epistemic opacity which includes, in addition, a further necessity condition, namely 'essential epistemic opacity':

Definition 2 (Essential Epistemic Opacity)

> A process is essentially epistemically opaque to [a cognitive agent] X if and only if it is impossible, given the nature of X, for X to know all of the epistemically relevant elements of the process. (Humphreys, 2009, p. 618)

As I suggested before the two notions of epistemic opacity defined above, i.e., 'weak epistemic opacity' and 'essential epistemic opacity', carry different conceptual implications with them, which are worth considering. This is largely due to the fact that Humphreys' definitions are not the usual definitions of objects —based, e.g. in a description of its properties, features, etc.— but logical statements concerning some conditions a property, be it 'weak epistemic opacity' or 'essential epistemic opacity', needs to fulfil to be defined so. In other words, both 'weak epistemic opacity' and 'essential epistemic opacity' are *properties*, the ascription of whose (to a process $\mathcal{P}$) depends on some requirements expressed by logical statements.

A first thing to note then is that, since 'weak epistemic opacity' and 'essential epistemic opacity' are properties of processes —specifically computer simulations related processes in our case (see Section 3 to follow)—, computer algorithms, difference equations, analytical equations, theorems, etc., are not *per se* epistemically

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[4] Humphreys (2009) refers to this first notion of epistemic opacity simply as 'epistemic opacity'. In order to stress the distinction of the two notions of epistemic opacity further and highlight the fact that this first notion has in fact a logically weaker structure, I shall refer to it as 'weak epistemic opacity' in what follows. Throughout the paper I will use the expression 'epistemic opacity' in a generic way instead to refer to either 'weak epistemic opacity' or 'essential epistemic opacity' indistinctly.

opaque. It is a particular (computer) process $\mathcal{P}$, the undergoing of which may of course involve one or more of the above, that is epistemically opaque. This already brings to mind the idea that actual computer modelling and simulation specific practices may prove central and, in particular, the intuition that epistemic opacity is tightly related to such hands-on scientific practice.[5]

A second relevant feature in both definitions above is that epistemic opacity in general —i.e., whether we refer to 'weak epistemic opacity' or 'essential epistemic opacity'— is an agent-relative notion. The role of the agent, however, is different in each of the two notions. More precisely, the two definitions differ in how actual agents relate to a purportedly epistemically opaque process $\mathcal{P}$. On the one hand, we see for instance that the notion of 'weak epistemic opacity' is contingent on what we could term the '*state of knowledge*' of an agent X. This 'state of knowledge' involves, not only X's own intrinsic epistemic capacities but also the fact that, within the limits set by these, the agent can gain further knowledge about the process $\mathcal{P}$. The agent's 'state of knowledge' therefore may very well vary (improve) over time, even to a point that X comprehends the full epistemic details of process $\mathcal{P}$. As a result, then, to one same agent X a process $\mathcal{P}$ might be (weakly) epistemic opaque at time t but it might well be perfectly epistemically transparent at another time t'. The notion of 'essential epistemic opacity' on the other hand does not hinge on the 'state of knowledge' of the agent X, but just on her epistemic capacities and limitations — i.e., what Humphreys refers to as the 'nature of X'. In this sense, 'essential epistemic opacity' is nothing else than a particular case of 'weak epistemic opacity' —for the case in which it is the intrinsic nature of the agent X, which we assume does not change over time, what does not allow her to know the full epistemic details of the process $\mathcal{P}$ at any given time t.

At a first reading Humphreys' definitions may suggest that we should think of epistemic opacity (either 'weak epistemic opacity' or 'essential epistemic opacity') as a 'binary' property of a given process $\mathcal{P}$, i.e., as a 'yes-no' property. This interpretation is reinforced by the fact that Humphreys' definitions are laid out in logical terms as requirements for a process $\mathcal{P}$ to be epistemically opaque. Thus, the definitions work well when it comes to distinguishing or identifying epistemically opaque processes. In other words, a process $\mathcal{P}$ is defined to be either (weak or essential) epistemically opaque or not depending on whether it does fulfil the requirements in the relevant definition, i.e., on whether or not an agent X has full epistemic knowledge of it.

Despite the fact they are logical statements Humphreys' definitions make room, or at least allow, for further qualifications concerning the different variables involved in them i.e., cognitive agents, states of knowledge or processes, which point to the idea that epistemic opacity can be conceived beyond a 'yes-no' approach as coming in degrees. While this observation is not new,[6] I should stress once more that the literature on the subject does focus mostly on issues arising from an analysis of

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[5] I briefly address this issues in the closing remarks in Section 5.

[6] See, e.g., Durán and Formanek (2018); Kaminski et al. (2018); Lenhard (2019) or Saam (2018). Also Humphreys himself refers at some point to 'partially epistemically opaque' processes in contrast with 'fully epistemically opaque' ones (Humphreys, 2009), thus entertaining the idea that epistemic opacity comes in degrees.

epistemic opacity understood as a ‘yes-no’ property. However, thinking of epistemic opacity exclusively in binary terms may leave aside important considerations that have to do, not only with the agent’s X nature and epistemic capacities, but also for instance with her more pragmatic attitude, purpose when engaging with a concrete process $\mathcal{P}$ —such as e.g., the use of computer simulations—, or other considerations concerning the actual process itself, etc. In sum, there is nothing, really, in the definitions above that forces on us a view of epistemic opacity strictly in binary terms, and going beyond this conception is fruitful both to achieve a better understanding of the notion of epistemic opacity itself as well its implications concerning the role of cognitive agents and their methods in dealing with epistemically opaque processes.

As I have already noted above, given the definition of ‘weak epistemic opacity’, whether a process $\mathcal{P}$ is said to be weakly epistemically opaque depends on the ‘state of knowledge’ of the agent X, which typically changes over time. This in turn means that a process $\mathcal{P}$ may be found to be (weakly) epistemically opaque to an agent X having different ‘states of knowledge’ at different times t and t'. The question then arises whether the process $\mathcal{P}$ is going to be equally epistemically opaque to X at time t and at time t'. Intuitively, the answer to this question should be in the negative, leading to the idea of *degrees* of epistemic opacity, at least when it comes to the notion of ‘weak epistemic opacity’ (but see below for an extension of the argument to ‘essential epistemic opacity’).

Similarly, for one same process $\mathcal{P}$, two different agents X and X' may present different ‘states of knowledge’ at the same time t. Thus, it seems rather natural to think that, at the very same moment t, a process $\mathcal{P}$ is not equally epistemically opaque to X and X'. With this consideration in mind, we can carry the idea that epistemic opacity comes in degrees all the way to the stronger definition of ‘essential epistemic opacity’. For two cognitive agents X and X' need not have the same epistemic capacities, i.e., they each can have a different epistemic nature. The idea of degrees of epistemic opacity can be supported further by noting that even for one same agent X there are processes that may present different ‘depths’ of epistemic opacity. Put it another way, two different processes $\mathcal{P}$ and $\mathcal{P}'$ may involve different degrees of epistemic opacity for one same agent X at a given time t. Such considerations apply equally to both ‘weak epistemic opacity’ and ‘essential epistemic opacity’. An interesting issue in this context concerns whether cognitive agents might be capable of transforming a process $\mathcal{P}$ into another one $\mathcal{P}'$ such as the epistemic opacity associated to the former differs from that of the latter. We shall pursue this and related issues in the following two sections.

Once we have made sense of the idea that epistemic opacity comes in degrees, whether we refer specifically to the notion of ‘weak epistemic opacity’ or to ‘essential epistemic opacity’, we may further note that ‘essential epistemic opacity’ introduces a crucial difference, namely that there is a threshold to epistemic transparency (as opposed to opacity). This threshold is in fact a lower bound of opacity set by the ‘nature’ of the agent X involved, i.e., given her specific epistemic capacities. Thus, while ‘weak epistemic opacity’ leaves it open whether an agent X may reach at some time t a state of knowledge in which she knows ‘all of the epistemically relevant elements’ of the process $\mathcal{P}$, in the case of ‘essential epistemic opacity’ this option might not be possible at all (when the particular epistemic capacities of a cognitive agent unavoidably prevent it). This suggests that for some agents some processes are 'irreducibly' epistemically opaque.

In sum, epistemic opacity being crucially defined as an agent relative property of certain processes, a property that depends on the specific epistemic capacities of the agent involved as well as on the agent's 'state of knowledge' with respect to the epistemic relevant details of such process, can be said to admit degrees. But, also, on the other hand, it has become clear that despite the fact that there are degrees of epistemic opacity, and because the notion is heavily dependent on the actual epistemic capacities of the agent, it may not always be possible to reduce opacity such that it is eliminated completely, for given specific cases (processes).

In this context thus a whole range of new interesting questions arise. There are questions, for instance, concerning the actual meaning of the idea of degrees of epistemic opacity and how it is to be implemented; whether such degrees can be measured at all and, if so, how are they to be measured; whether the measuring will inevitably be subjective —mainly because of its strong dependence on agents— or whether it can be otherwise made objective, etc.

This paper is not concerned so much with such questions but with issues in connection with the actual role of agents and their practices in connection to specific processes (which we may regard as epistemically opaque). Thus, for instance, as hinted above, it remains open whether agents may be able to transform —e.g., through specific practices— a given process $\mathcal{P}$ into another one $\mathcal{P}'$ so that their respective epistemic opacities associated to them turn out to be also substantially different. Questions such as this are absolutely relevant in connection for instance with the use of computer simulations and their philosophical status as effective scientific tools. Thus, I shall narrow the focus of my analysis to the specific case of computer processes, i.e., computer simulation practices, designed, built, run, etc., by human agents. In this context I shall explore issues concerning the possibility that usual scientific practice may effectively reduce epistemic opacity in computer simulations.

3 Epistemic Opacity of Computer Simulations

Let us turn then to the specific case of computer simulations as potentially epistemic opaque processes. We may regard in fact computer simulations as a good benchmark to test some of the intuitions outlined above, and tackle the questions related to these. A good place to start seems to explore in more detail the issue as to whether the processes involved in computer simulations are indeed epistemically opaque or not, and if so, what kind of epistemic opacity they feature.

This question in not new, and has in fact already been answered by Humphreys himself:

> [N]o human can examine and justify every element of the computational processes that produce the output of a computer simulation or other artifacts of computational science [. . .] Many, perhaps all, of the features that are special to simulations are a result of this inability of

> human cognitive abilities to know and understand the details of the computational process. The computations involved in most simulations are so fast and so complex that no human or group of humans can in practice reproduce or understand the processes. (Humphreys, 2009, p. 618)

The quotation above thus makes clear that not only are computer simulations epistemically opaque processes but also that they are *essentially* epistemically opaque to us humans as cognitive agents. In other words, according to Humphreys the epistemic opacity displayed in the running of computer simulations is basically associated to the lack in human's ability to trace, understand and justify "every element of the computational process". By definition, this is just 'essential epistemic opacity'.

Following this line of thought a further important remark concerning the epistemic status of computer simulations in relation to humans as cognitive agents is in order, however. Namely, we must note that because of the logic structure of the definition of 'essential epistemic opacity' discussed in Section 2, if we restrict the use of computer simulations to human agents only we may very well claim that computer simulations not only are (essentially) epistemically opaque but also that they are *necessarily* so. Put it another way, computer simulations are essentially opaque to humans as cognitive agents but also it is sufficient for a cognitive agent to be a human to claim that computer simulations are epistemically opaque to her.

This conclusion is well inline with some of our conclusions in the previous section. In particular, and as far as we (human cognitive agents) are dealing with computer simulations, we seem to be able to claim safely that there is a threshold in our knowledge of the computer process which we are not able to cross given our particular (human) epistemic capacities. Therefore the process, i.e., the computer simulation, is essentially epistemically opaque. In sum, for us human agents computer simulations feature an *irreducible* epistemic opacity which in principle is not possible to eliminate.

Going back to the idea that epistemic opacity comes in degrees, however, the remarks above do not preculde the possibility that the epistemic opacity initially associated to a specific computer simulation may be reduced somehow. In fact it was also one of the conclusions of Section 2 that even in the case of 'essential epistemic opacity' we can make sense of epistemic opacity as admitting degrees.

The interesting question then —which we can now ask in the specific context of computer simulations— is whether it is possible at all to reduce epistemic opacity to some extent (or degree), even such that it can be even eliminated. In other words, is it really the case that epistemic opacity in computer simulations is absolutely irreducible (meaning non-eliminable)? More specifically, is it true for any computer simulation that it is irreducibly epistemically opaque to human cognitive agents, as Humphreys claims in the quotation above, or is it possible, as opposed to that, to make sense of *some* computer simulation as an epistemically transparent process somehow, despite our (human) cognitive and epistemic limitations? Attempting to give answers to these questions shall put scientific (modelling and simulation) practices at the centerstage. In particular, as I hinted above, actual practices (modelling and simulation practices) carried out in this case by human agents (scientists) shall prove crucial in any attempt to explain the reduction (and perhaps elimination) of epistemic opacity in computer simulations. This shall open, on the other hand, a further whole range of new interesting questions concerning the precise role of humans as cognitive agents when it comes to the use computer simulations as a scientific tool. We may ask for instance what is the precise role of agents in attempting to reduce (or eliminate) epistemic opacity.

Before going on to address such issues, however, a note is in order concerning what would mean to reduce or eliminate epistemic opacity. In order to understand reduction of epistemic opacity we shall first make clear what a fully epistemically transparent process may look like. Given that we are dealing with computer simulations, a rather straightforward way to think of transparency seems to be in opposition to what typically introduces opacity in computer simulations, namely complexity. Recall that according to Humphreys it is our inability as cognitive agents to "examine and justify every element of the computational processes" what is behind the epistemic opacity of highly complex processes such as computer simulations. As opposed to that then we may identify 'epistemically transparent' processes as those characterised by little complexity or ideally a complete lack of it. In the limiting case, a fully 'epistemically transparent' process would be that involving exclusively equations that can be solved analytically.

In order to address the questions above I shall make use of a simple, although arguably somehow artificial, example of a computer simulation, namely the simulation of the motion of a simple pendulum. I propose the example, in particular, as a tool to explore the limits of the concept of epistemic opacity and suggest new issues rather than to put into question the notion as whole. I shall attempt to show, in particular, that the wide range of methodological techniques modelling and simulation scientists typically deploy when putting computer simulations at work have an impact on epistemic opacity. This includes, for instance, as the example specifically shows, the use of expert knowledge to effectively reduce a simulations's original complexity.[7] I hope to make clear, furthermore, that the idea of degrees of epistemic opacity is crucial to that effect.

4 Reducing Epistemic Opacity in Computer Simulations

Consider a particularly simple example of a computer simulation. Namely, the simulation of the motion of a simple pendulum (see Figure 1). As is well known, the motion of a simple pendulum, in its most general case —that is, for arbitrarily large oscillation amplitudes—, is governed by the following non-linear equation:

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[7] This should not come as a surprise since the use of expert knowledge, in one sense or another, is widely regarded as necessary in many cases of computer simulation as a complexity reduction technique (see, e.g., Winsberg (2001)). And one can argue that, even if issues concerning epistemic opacity may not be explicitly present in the modeller's mind when using expert knowledge, its use has clearly as a motivation to simplify the original problem, making it more tractable and, after all, easier to grasp epistemically.

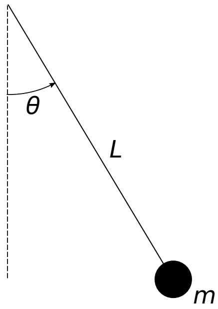

Fig. 1 An oscillating simple pendulum.

$$\frac{d^2\theta}{dt^2} + \frac{g}{L} sin\theta = 0. \tag{1}$$

The equation above, being non-linear, cannot be solved applying standard mathematical analytic methods. It needs to be solved instead by applying numerical methods, which results in a computer simulation of the motion of the pendulum. We do not need to describe in detail the specifics of the actual simulation here. It will be enough to point out that it will include, roughly, the designing of an appropriate algorithm, applying a range of numerical methods to implement it, performing the corresponding calculations, and finally plotting the calculation outputs into a sensible image that we can 'read', allowing for an interpretation of the result.[8] In Figure 2 the corresponding numerical solution to the equation of motion is plotted. The image displays constant energy orbits in phase space —i.e., velocity $d\theta/dt$ versus position (amplitudes) θ normalised values— which gives and idea of the motion of the pendulum for given energy values. This solution, as the plot shows, applies to arbitrarily large oscillation angles.

According to what we have seen so far the process that comprises the solving of equation (1) into the output in Figure 2 is to be regarded as an epistemically opaque process. But not only that. For, according to Humphreys, since we are dealing with a computer simulation, from the human agent point of view, the process is necessarily an essentially epistemically opaque one —featuring, again necessarily, an irreducible component of epistemic opacity.

As I pointed out, the above, being the solution to the general equation of motion for the simple pendulum, applies to arbitrarily large oscillation angles. For the case of small oscillations, however, the problem of the motion of the simple pendulum can be approached differently.

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[8] Note that here I am implicitly endorsing the view that computer simulations are not just number crunching processes, but rather part of a more complex 'multi-component' scientific practice. This will be a relevant point in the discussion to come.

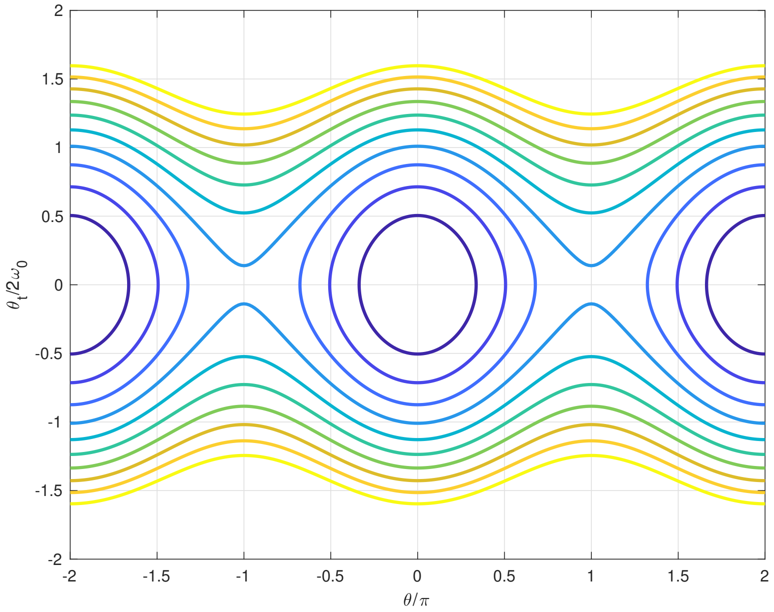

Fig. 2 Motion of a simple pendulum for arbitrarily large oscillations (constant energy contours in phase space).

To start with, it is well know that for small enough oscillating amplitudes the general equation (1) above can be simplified substantially in terms of its complexity. In particular, for small enough amplitudes, i.e., for $\theta \approx 0$, we have that[9]

$$sin\theta \approx \theta. \tag{2}$$

This in turn means that, for small amplitudes, the general equation of motion above can now be rewritten as

$$\frac{d^2\theta}{dt^2} + \frac{g}{L}\theta = 0. \tag{3}$$

This is a linear second order differential equation, which can be handled using standard mathematics and admits an analytical solution, namely

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[9] The approximation below is the result of considering the first term of Taylor expansion of the function $sin\theta$, i.e.,

$$sin\theta = \theta - \frac{\theta^3}{3!} + \frac{\theta^5}{5!} - \frac{\theta^7}{7!} + \dots$$

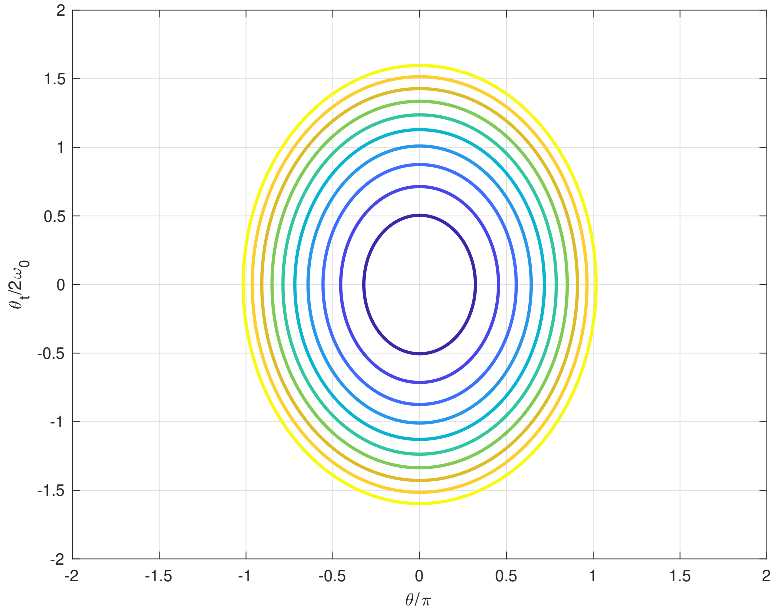

Fig. 3 Motion of a simple pendulum for small oscillations (constant energy contours in phase space).

$$\theta(t) = \theta_o \cos\left(\sqrt{\frac{g}{L}}t\right). \tag{4}$$

The solution can be plotted, as in the case of arbitrarily large amplitudes, as a phase space diagram, displaying the motion of the simple pendulum (for small amplitudes) at different energy values (see Figure 3).

In contrast to the case of the motion of the pendulum for arbitrarily large amplitudes, we may now claim that arriving at the small amplitudes solution, given it only involves standard mathematical operations (and knowledge), constitutes a fully *epistemologically transparent* process (see my remarks to this effect at the end of Section 3).

What we have just seen illustrates nicely a very commonplace typical procedure in computer simulation practice. Namely the use of expert knowledge, which is invoked at many levels and stages of a simulation, to simplify its original complexity. The use of expert knowledge varies depending on the specific field of application of a simulation, or the purposes and interests of the scientist running it. It may be aimed for instance at making the problem computer-wise simpler or more tractable, at reducing computing time and power, etc., and typically includes, among other things, the use of mathematical tricks —this is actually the case in the example of the simple pendulum above—, substituting and/or eliminating variables, a range of parametrisation techniques, the use of empirical laws, etc. These kind of procedures, as pointed out, are very commonplace in actual simulating and modelling practice in a wide variety of fields, ranging from climate science, astrophysics, or high energy physics to population genetics and econometrics.[10]

In a sense what we just saw is nothing new and, of course, the use of expert knowledge in this context is usually very well justified —be it either formally, technically, scientifically, etc.— and thus in general does not spark any controversies. However, if we focus specifically on the issue of epistemic opacity, we may now see that the use of expert knowledge, along with simplifying the original complexity of a simulation with different purposes in mind, helps reduce epistemic opacity. Even more, if the reduction of epistemic opacity by using expert knowledge is taken to the limit, we may end in a complete elimination of epistemic opacity as a result, as the example of the simple pendulum above shows. In sum, making use of expert knowledge, which is part of the standard scientific practice in modelling and simulation, may help reducing epistemic opacity and even eliminating it fully (as long as we manage to transform the problem into an analytically solvable one).[11]

This is indeed a good example of one of the ideas hinted at the end of Section 3, where we asked whether a process $\mathcal{P}$ could be 'transformed' into another one $\mathcal{P}'$ such that the later displayed a different (reduced) degree of epistemic opacity with respect to one same agent X. In this case, as we can see, an epistemically opaque process, i.e., the original computer simulation of the motion of the simple pendulum, *can be transformed*, for the case of small enough oscillation amplitudes, into a new process that seamlessly simulates the original system, i.e the motion of a simple pendulum, which according to our remarks in the previous section can be regarded as epistemically transparent. As a consequence, and going a step further, we may claim that the assumption that computer simulations are *necessarily* epistemically opaque cannot be maintained in general.

This conclusion opens a new range of questions concerning the role of agents (i.e., experts) as regards the epistemological status of tools such as computer simulations. But before we go on to discuss the possible implications of the above, we need to deal with what could be a serious objection. It can be objected, in particular, that once we have transformed our original computer simulation —of the motion of the simple pendulum for arbitrarily large oscillations in this case— into an analytically solvable problem we are not dealing with a computer simulation any more. Thus, the example above would not provide any evidence that computer simulations are not necessarily epistemically opaque, as we just concluded.

There are at least to answers one can offer to deal with the objection above. First, it needs to be stressed that the objection relies crucially on how the expression computer simulation is understood. In particular, since there are different notions

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[10] It is perhaps worth pointing out, as a side remark, that some authors attribute some of the epistemic particularities associated to computer simulations to the fact that they involve this kind of praxis. Some go as far as to claim that it is (partly) because of this that computer simulations demand a new epistemology (Winsberg, 2001, 2010).

[11] This is not to say that a full such reduction of epistemic opacity can be achieved in all cases. This is in fact the most common scenario when it comes to computer simulations of complex systems.

of computer simulation on offer, whether the objection effective or not will rest heavily on which of these views is endorsed. So, drawing for instance on a standard distinction in the literature (Winsberg, 2019; Parker, 2014) the expression 'computer simulation' can be understood either in a *narrow* sense or a *broad* sense, or else in terms of *similarity*.

We do not need to go into the distinction in great detail here and it will enough to recall that, roughly, a computer simulation is understood in a *narrow* sense as referring basically to the actual specific routines running on a computer[12] to solve numerically a very often analytically intractable or unsolvable problem, i.e., 'number-crunching'. A broader understanding of the notion of computer simulation takes into account instead, not just the actual 'number crunching' component, but the whole process of choosing a model, implementing an algorithm, calculating numerically the output of that algorithm, analysing and visualising resulting data, etc. Finally, a third notion of the term is also documented in Humphreys (2009) and Winsberg (2010, 2019) following Hartmann (1996)'s view on simulation based on the idea of similarity, either dynamical or structural, between a system and its simulation.[13]

Thus, if we consider the three possible understandings of computer simulations, we can easily see that the objection will only stand if a *narrow* sense of computer simulation is endorsed. For, since under that view computer simulations are identified exclusively as number crunching processes, analytical problems will clearly fall out of this classification. If computer simulations are understood instead in a broader sense to include, beyond the actual number crunching process, the choosing of the most convenient or effective algorithm, the application of appropriate numerical methods to implement it, any parametrisation, approximation or simplification, the actual numerical calculations, analysing and visualising resulting data, etc., one can argue that the whole process —which involves transforming the non-linear problem of the motion of the simple pendulum for arbitrarily large oscillations into our analytically solvable problem (for small enough angles), solving it, and representing the raw numerical output— may also be considered a simulation. The objection above, thus, would not stand in this case. Similarly, if computer simulations are understood as processes based in the idea of similarity[14], it can be argued that just like the simulation of the motion of the simple pendulum for arbitrarily large oscillations is indeed a simulation in virtue of the fact that there is some (dynamical) similarity with respect to the motion of the actual physical system, the simplified

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[12] It is important to distinguish between a computer routine –i.e., the code– *to be* run on a computer and the routine actually *running*. While the former does not convey barely epistemological novelty concerning the dynamical properties of the simulation, the latter does. This point is stressed and well motivated in Humphreys (2009), for instance. This stresses, once more, the importance of understanding computer simulations as actual *processes* which are actually *run*.

[13] A important point which is however incidental to our discussion here is that this distinction on how to understand computer simulation seems key when addressing the issue as to whether computer simulations involve epistemological novelty of any kind —or even demand a new epistemology. This is a hot issue in the literature with strong arguments on both sides. See, for instance, Frigg and Reiss (2009); Humphreys (2009); Winsberg (2001).

[14] This seems the view preferred by Humphreys (2009) as opposed to a narrow understanding of computer simulations endorsed by Frigg and Reiss (2009) for instance.

version of the problem still conserves that (dynamical) similarity with respect to the motion of the actual physical system, even if only for small enough oscillation angles. In that sense, therefore, we can claim that the later can also be considered a simulation.

The point can be pushed harder, however. For, it can be objected further that the above overlooks a crucial feature of the similarity view of computer simulations. Namely, that under this view the term *computer* is just as important, and that a *computer simulation* is a simulation which happens to be performed with a *computer*. With this in mind, it can be pointed out that while the case of the simulation of the motion of the simple pendulum for arbitrarily large oscillations is clearly a computer simulation —i.e., a computer is needed to solve numerically the problem—, the simplified case (for small oscillations), even if it can be still taken as a simulation, is not a computer simulation any more since no computer is involved in solving such an analytical equation. To this, one can reply by asking in turn what is really the difference between solving numerically a differential equation (such as equation (1) in the example of the motion of the simple pendulum above), and calculating the values of the relevant variables entering some well defined analytical function (e.g., equation (4)). So if, at the end of the day, what we need is to come up in either case with a numerical output, i.e., a table of numerical values, which can be turned into a plot or similar that allows for their interpretation, both processes seem rather similar, if not exactly the same, from an operational point of view. To my mind, thus, there is no difference beyond the fact that in one case the operation may require more steps, computer time or effort.

There is a further point that can be made as regards the original objection formulated above that once we reach an analytically solvable problem (with the help of expert knowledge), we are not dealing with a computer simulation anymore. The point is, in particular, that the use of expert knowledge may as well be epistemically opaque in itself. To that extent, therefore, transforming a highly complex problem which is to be solved using a computer simulation into an analytically solvable one by introducing concrete elements of expert knowledge may be seen to result, not really in the elimination of the epistemic opacity originally attributed to the computer simulation, but just in a ‘redistribution’ of it. More specifically, it can be argued that, at the end of the day, expert knowledge may just ‘absorb’ the epistemic opacity originally associated to a computer simulation rather than eliminate it. In other words, scientific practice, as exemplified for instance by the use of expert knowledge, may not quite help eliminating epistemic opacity in the context of computer simulations but just transform it, or shift it around, once the whole process is taken into consideration. This line of though would seem to reconcile our claims as a consequence of the analysis of the simulation of the simple pendulum above with Humphreys’ views that computer simulations are necessarily (essentially) epistemically opaque to human cognitive agents. The issue may be trickier than that, however, since in this new approach considerations about the role of agents and their actual practices when dealing with potentially epistemically opaque processes —beyond an agent’s epistemic capabilities or her ‘state of knowledge’ at some time *t*— become absolutely relevant. In the context of computer simulations simulations, more in particular, such considerations may have an impact for instance on the epistemic status, effectivity and reliability of computer simulations as scientific tools.

5 Closing Remarks and Open Questions

The discussion above illustrates, above all, the strong dependence between agency and epistemic opacity, or better, how is the latter understood. This dependence is so strong, in fact, that one could even go as far as to claim that whether a process proves epistemically opaque or not —or, more precisely, in what degree a process proves epistemically opaque— depends not only on the particular epistemic capabilities or limitations of an agent —the 'nature' of an agent in the words of Humphreys— and/or her epistemic 'state of knowledge' at a given moment, but also on how agents 'interact' with the process itself, i.e., on the actual scientific practice. This is what in may opinion examples such as the simulation of the motion of the simple pendulum above illustrate. The issue, as suggested above, sparks a number of new interesting questions.

For instance, a first issue we may want to tackle concerns whether epistemic opacity is merely *agent-related* or, in a stronger sense, an *agent-induced* or *agent-generated* notion. In particular, if Humphreys' definitions are taken literally one can think of epistemic opacity as simply an agent dependent notion, meaning that the agents' specific epistemic nature and/or state of knowledge are just enough to claiming whether a process is epistemically opaque or not, without further qualification. However, as we saw above, if we consider the idea of degrees of epistemic opacity we then move into new ground. For in such as case it is not the specific 'epistemic qualities' of the agent that we just need to consider but also the actual 'interactions' of the agent with the process —e.g., specific modelling and simulation practices. We have seen that the impact of such 'interactions' may result in a reduction (or, with some qualification, even an elimination) of epistemic opacity. Thus, in this view we are then moving from epistemic opacity as an agent-related notion to a more complex notion in which the agent is capable to induce/reduce epistemic opacity depending on the actual practices in play.

We may also inquire into whether there is a relation between epistemic opacity and (some) model uncertainties. It can be argued in this respect that the use of expert knowledge typically introduces model uncertainties in the actual simulations.[15] In view of this and with the discussion above in mind we can conclude that reducing epistemic opacity by means of the use of expert knowledge may entail, on the other hand, an increase of model uncertainties. If this is so, then, there would seem to be a tension between the degree of epistemic opacity which a simulation involves and the model uncertainties it contains. In this sense, optimising epistemically a model by reducing its opacity would require a careful trade-off between the amount of expert knowledge to be used and the amount of uncertainties it may introduce so

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[15] Note that this need not apply to other kinds of uncertainties, such as those originating in the actual computer calculations, which can in fact even be reduced.

that the right balance is reached. (I have in mind, in particular, cases in which the use of expert knowledge may on the one hand simplify the original problem such that it is transformed into an analytically solvable one but, on the other hand, the simplification is made at the expense of e.g., approximations, which would introduce structural model uncertainties.)

Of course, the above applies only if epistemic opacity is in fact reduced and not 'shifted around' or redistributed (being removed so to speak from the actual computer process to become associated to expert knowledge), as we argued above it could be the case. Considering such a situation would rise further questions, however, concerning modelling and simulation practice. We may want to explore, for instance, whether the epistemic opacity attributed to expert knowledge would still be of the same kind than that associated to computer simulations. The answer to this question would take us back to the issues related to the distinction between 'weak epistemic opacity' and 'essential epistemic opacity'. In particular, it would seem rather straightforward to think that epistemic opacity associated to the use of expert knowledge will be closer to the idea of 'weak epistemic opacity', since the epistemic nature of the agent does not seem to play a role in this case.[16] If this is so then, and if the answer to our question above is in the positive, i.e., if epistemic opacity associated to expert knowledge is in fact of the same kind that the epistemic opacity at the actual computer solving process level, we must then conclude that we are dealing really with 'weak epistemic opacity' throughout. As a consequence therefore the idea of 'essential epistemic opacity' would not apply to the computer process component of the simulation either. This latter claim certainly sounds daring, though, if not straightforwardly in opposition with Humphreys' intuition that it is not possible for us humans as cognitive agents to be able to follow "examine and justify every element of the computational processes that produce the output of a computer simulation" (Humphreys, 2009, p. 618).

Exploring such issues could also take us to ask further questions specifically about the epistemic status of computer simulations, especially if these are understood as a whole complex process where scientific practice —crucially characterised by the intervention of agents— is at its very centre. One can analyse in particular, for instance, whether we should favour, be inclined, or be in a better disposition to accept, e.g., as more reliable, epistemic opacity resulting from the use of expert knowledge than that associated to the actual computer process.

These are interesting issues which deserve further analysis and perhaps a full paper on their own. What it seems clear, in any case, is that regardless of the answers to such questions, we can claim confidently that scientific practice is tightly related to the notion of epistemic opacity, and further that it has an impact on how epistemic opacity is to be understood. The discussion above hopefully has made this clear

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[16] This is not to say, of course, that the epistemic nature of the agent does not set any restrictions or conditions on the actual expert knowledge that comes into play. The character of the expert knowledge, the range of possibilities of the knowledge, so to speak, does depend on the epistemic nature of the agent. However, once that range of possibilities of knowledge is set, whether this or that specific piece of expert knowledge is introduced in the building of a simulation will not depend on the nature of the agent any more.

enough. I hope to have also been successful in suggesting that thinking of epistemic opacity as coming in degrees is indeed a fruitful approach. As I argued, this view on epistemic opacity contributes to reveal important aspects of scientific practice in the context of computer simulations. In particular it helps appreciating that the use of expert knowledge in the computer modelling and simulation practice plays a crucial role in the dealing with epistemically opaque processes, helping manage, justify or attempt to reduce epistemic opacity.

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References

Durán J, Formanek N (2018) Grounds for trust: Essential epistemic opacity and computational reliabilism. Minds and Machines pp 645–666

Frigg R, Reiss J (2009) The philosophy of simulation: hot new issues or same old stew? Synthese 169:593–613

Hartmann S (1996) The world as a process: Simulation in the natural and social sciences. In: R Hegselmann UM, Troitzsch K (eds) Modelling and Simulation in the Social Sciences from the Philosophy of Science Point of View, Kluwer, Dordrecht, pp 77–100

Humphreys P (2004) Extending ourselves: Computational science, empiricism, and scientific method. Oxford University Press, New York

Humphreys P (2009) The philosophical novelty of computer simulation methods. Synthese 169:615–626

Kaminski A, Resch M, Küster U (2018) Mathematische Opazität. Über Rechtfertigung und Reproduzierbarkeit in der Computersimulation: Jahrbuch Technikphilosophie 2018, pp 253–278

Kouw M (2016) Standing on the shoulders of giants – and then looking the other way? Epistemic opacity, immersion, and modeling in hydraulic engineering. Perspectives on Science 24:206–227

Lenhard J (2019) Calculated Surprises: A Philosophy of Computer Simulation. Oxford University Press, New York

Newman J (2015) Epistemic opacity, confirmation holism and technical debt: Computer simulation in the light of empirical software engineering. In: Gadducci F, Tavosanis M (eds) History and Philosophy of Computing, Third International Conference, HaPoC 2015, Springer, Cham, pp 256–272

Parker W (2014) Computer simulation. In: Psillos S, Curd M (eds) The Routledge Companion to Philosophy of Science, 2nd Edition, Routledge, Oxford and New York, pp 135–145

Saam N (2018) Measuring epistemic opacity. Presented at *SAS'18: Epistemic Opacity in Computer Simulation and Machine Learning* conference, HLRS, Stuttgart

Stuart M, Nersessian N (2019) Peeking inside the black box: A new kind of scientific visualization. Minds and Machines 29:87–107

Winsberg E (2001) Simulations, models, and theories: Complex physical systems and their representation. Philosophy of Science 68:S442–S454

Winsberg E (2010) Science in the Age of Computer Simulation. University of Chicago Press, Chicago

Winsberg E (2019) Computer simulations in science. In: Zalta EN (ed) The Stanford Encyclopedia of Philosophy, winter 2019 edn, Metaphysics Research Lab, Stanford University

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