WHAT ARE DATA ABOUT?
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Empiricism is no longer a tenable position in the philosophy of science. As a result, it is worth examining what it was that made empiricism such an attractive position for so long and if anything valuable can be salvaged from that tradition. The debates about empiricism usually contrasted knowledge obtained from observation and experiment on the one hand with knowledge obtained from theories on the other. Because computer simulations are firmly entrenched as a third mode of pursuing scientific inquiry, one way to explore what made empiricism important is by contrasting data that is provided by experiments and observations with data that is generated by computer simulations. In doing so, my paper will indirectly address one of the original philosophical issues about computer simulations: in what ways, if at all, do computer simulations differ from scientific theories on the one hand and experiments on the other?[1] Early in the discussions, claims were made that simulations had some kind of intermediate status between theory and experiment, while also standing as sui generis methods. More recently, claims have been made that simulations can be used in place of material experiments under certain circumstances.[2] Although it is true that there are similarities between certain aspects of simulations and experiments, pointing out analogies between laboratory experiments and computer simulations, such as the ability to manipulate variables and control for confounders, does not address one of the central epistemological questions that arises once simulations are brought into the picture. This question is: Are the data produced by computer simulations different in kind and in content from experimental and observational data, and from data generated by traditional scientific or mathematical theories? If we have reasons to agree that they are different in a scientifically relevant way, that is one dimension along which simulations occupy a distinct scientific niche. Empiricists have usually treated the issue of the empirical source of data within a methodological context such as confirmation, verification, or falsification. I shall focus instead on content. One important question is this: what is it for a datum to have empirical content?[3] An answer to that question is provided in (Humphreys forthcoming); here we can make additional progress by addressing a related question: what are various kinds of data about?

1. What are Data?

In order to remain as ontological neutral as possible about data, I take a datum to be the value of a variable. The term `variable' will be used here in a way that is neutral between items such as a mathematical function that represents a property and the property itself.[4] This dual use carries with it certain dangers because the role of representations in computer simulations is crucial, but where appropriate I shall explicitly note which use is in play. The variable can be scalar and discrete valued, which covers situations in which the datum concerns a qualitative monadic property such as "is red", or it can be vector and continuous valued, capturing relational features such as "has velocity v with respect to frame F". Other possibilities can be accommodated. I shall not distinguish between atomic and non-atomic data because nothing that follows depends upon making that distinction. Finally, although the expression "data" often carries the force of something given, something fundamental, those connotations must be rejected. Data can be the result of processing, transformations, and interpretation, and we can and often do question the data.[5]

Data can be assessed on their own terms, without regard for what generated them and an important aspect of our definition is that it does not mention the origins of a datum, allowing data to originate from computational processes, from experiments, from theory, and perhaps other sources. Yet if we are to address the question of what the data are about we must solve the *inverse inference problem*. The inverse inference problem consists in making, and providing a justification for, an inference from the data to its source. In the debates between scientific realists and empiricists, the issue is usually cast as one of whether terms in scientific theories that purport to refer to unobservables genuinely refer, but it can be recast as the problem of what objects' and properties' existence can justifiably be inferred from the empirical data. In these terms, inferring the existence of Saturn's rings and their properties from what is observed through a low powered telescope is an inverse inference problem, as is inferring the existence of a virus from an electron microscope image. The converse of the inverse inference problem, the direct inference problem, is the problem of what data will be available given the existence of the source.

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[1] This issue was present almost from the inception of computer simulations. Explicit attitudes towards it can be found in Ord-Smith and Stephenson [1975], p. 3, Rohrlich [1991], Humphreys [1994].

[2] See e.g. Norton and Suppe [2001], Winsberg [2003], Parker [2009].

[3] There are other epistemological issues about simulations and experiments including 1) the a priori versus the a posteriori content of data from each, 2) the empirical versus the formal content of data from each, and 3) the relative rates of reliability as truth generators for data from each.

[4] The variable can be purely formal and hence represent nothing.

[5] The distinction between data and phenomena drawn in Bogen and Woodward [1988] and other papers is compatible with the definition of a datum given here, although their emphasis on the causal production of data perhaps indicates a narrower use of the term "data" than is considered here.

To see how addressing the inverse inference problem and assessing the content of data make a difference to how we evaluate data, consider the traditional division between empiricism and rationalism.[6] For empiricists, data that are the result of direct perceptual experience, or on a slightly more liberal agenda, data that are a result of observations by elementary equipment that include the human senses, are the most desirable and, for many, are the only source of genuine knowledge. The reasons for this desirability vary. On the one hand there is a widely shared belief that the origins of the data in the causal world make their content more desirable than the content of data whose origins are whatever produces a priori knowledge. On the other hand the empiricists' starting point was the content of the datum and not its origin, a orientation that deliberately left open the possibility that the external world might not be the source of the empirical datum and might not even exist, leading either to a lack of commitment to the existence of that data's origins, as in constructive empiricism, or to an outright denial, as in idealism.

Empiricists have granted privileged status to observational data for a number of other reasons. One was that data about directly observable entities seem to have the certainty that was lacking in data that was about unobservables. This certainty was a reason for refusing to provide a solution to the inverse inference problem and it was the intrinsic content of the data to which any certainty attached. A second reason was that data about observables was supposed to act as a theory independent basis for deciding between rival theories. On what might now seem to be rather naive grounds for taking the intrinsic content of a datum to be theory-independent, this gave privileged status to such content, and a bonus was that by avoiding making inverse inferences, no theory was needed in that capacity either. A third reason was that empirical data were taken to be the only reliable source of information about contingencies existing in our world; a priori methods were incapable of that degree of specificity. For various reasons, all of which are plausible, the first and second of these reasons no longer have the force once attributed to them and in light of the well-known arguments formulated by Quine [1951], the distinction between the a priori and the a posteriori is now seen to be a much more difficult distinction to make than was originally imagined.

It is a different issue that lies behind some of the difficulties in assessing the status of data from simulations and experiments. The issue is the extent to which inverse inference problems need to be solved in order to decide what the data are about. One set of solutions to this problem, following the empiricist tradition, attempts to attribute content to the data without taking into account their origins. This approach starts with data and avoids making inferences about their origins as far as is possible. If the content of data from simulations and from experiments is equivalent under this approach, then data from the two classes are inter-substitutable. Thus, if a simulation of independent tosses of a coin with parameter p is based on an accurate model of a sequence of tosses of a real coin with that degree of bias, the data from the simulation can replace the data from the experiment and we can ignore the origins of the data.[7] Another set of solutions suggests that the origins of data in material systems makes those data about something different than data coming from a computer simulation and so inferences that are often not easy to justify are required to use data from simulations in place of data from experiments. These are complicated issues and I can only sketch a solution here, but the overall view is that the origins and mode of production of data must be taken into account.

2. Simulations and Experiments

In recent years there has been considerable discussion about whether computer simulations can serve as a replacement for material experiments. Those who have argued for relevant similarities between simulations and experiments tend to emphasize methodological considerations.[8] Barberousse, Franceschelli and Imbert [2009] (hereafter BFI) have drawn an important distinction between two types of data, data_E and data_A. BFI define data_E as being `of empirical origin, namely produced by physical interactions with measuring or detection devices' (op. cit., p.560). It seems clear from this definition, and also from the examples used to illustrate the definition, that data_E are data produced by purely causal instruments. In contrast, data_A are about a physical system. BFI note that data_A may be produced by data_E `but also via other processes, among them analytical or numerical pen-and pencil-computed solutions of systems of equations representing the target systems, and computer simulations' (op. cit., p.560) In the present context I shall take simulations to be like traditional pencil and paper solutions in the sense that they are drawing out consequences of formal representations.[9]

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[6] What constitutes empiricism and rationalism is, and probably forever will be, a matter of scholarly dispute. I am using the terms here as surrogates for broad epistemic attitudes that I assume most philosophical readers will recognize. For the record, I subscribe to the view that although it is often a matter of historical contingencies when a particular philosophical issue is raised and becomes the subject of focused discussion, the issue itself transcends those historical contingencies.

[7] This is the position taken by Kästner and Arnold [2012] in which well-confirmed theories play a central role. See also Winsberg [2009]

[8] In this paper `simulation' refers to a digital computer simulation and `experiment' refers to a laboratory experiment. In the latter, all known relevant variables except for explicitly specified independent variables are controlled and the manipulations of the independent variables are epistemically transparent in the sense that the causal effects of the manipulations on those variables are known. The point of the experiment is then to identify the causal effects of the independent variables on the dependent variables. The situation with a single independent variable and a single dependent variable is a special case.

[9] This assertion is consistent with my position (Humphreys 1994, 2004) that the physical implementation of computer simulations places constraints on simulation methods that are not present in traditional a priori mathematics and that epistemic opacity, including the need to make inductive inferences in place of deductive inferences, is usually present. Despite some claims in the literature to the contrary, I have

The distinction drawn by BFI is important and helpful and their insistence that it is the representational aspects of computer simulations that constitute the dividing line between experiments and simulations is exactly right, but we shall need to see how the distinction plays out in the realm of causal-computational instruments (see section 3 below). The distinction also opens up some important philosophical questions. One is how to interpret data that have transformations applied to them after their origination. Suppose we grant that we can correctly specify what counts as a measurement or a detection device.[10] Then, in the case of data$_E$, consider what happens when a representation of an empirical datum has a formal transformation applied to it. Suppose that we have a square divided into two so that the left hand side is white and the right hand side is black. An imaging device (consider a digital camera for simplicity) takes a photograph of the square and forms a digital visual image that duplicates the original square. The image is unquestionably a representation of the square and the data, which are a spatial array of black and white pixels, are about that square. It is easy to perform a formal transformation on that data set so that all of the pixels on the right hand side are transformed from black to white and all of the pixels on the left hand side are transformed from white to black. What is this second image a representation of and what is it about? Exactly the same image could have been obtained by a purely causal process by using a mirror to produce the left-right inversion. So one answer to these questions is that it is a mirror image of the original square, hence a representation of it and that the data$_A$ are about the original square. Now consider the case where only the formal transformation of the right hand side from black to white is carried out. The resulting image is a completely white square. What is this a representation of and what is it about? A variety of answers is plausible. To preserve consistency with the first and second cases, it seems we should give the same answers: The purely white square is a representation of the original square and the data are about it. Yet it is such an extremely poor representation that one wonders in what sense it counts as a representation at all.

To see more clearly what is at issue, suppose that we have a digital photograph of a couple, Jack and Jill, against a white background. A computer algorithm removes the pixels representing Jack, replacing them with white pixels, leaving only a visible image of Jill. This image contains data$_E$ according to the above definition, and this is surely correct, but what is it about? Most people would say that the image, which consists of a spatial data array, is about Jill. Clear enough, although this answer deviates from the criteria we used for the black and white squares example. So now consider a parallel example in which the original photograph is of Jill alone, but an algorithm transforms white pixels into a colored array that is a representation of Jack. What is this new image about? It is a representation of Jack and Jill, and it is therefore about Jack and Jill, although it is a photograph of Jill only and so, on an origins view of data content, about Jill only.[11] The pixels that make up the image of Jill are all data$_E$ as well as data$_A$, whereas the pixels that make up the image of Jack are data$_A$ only.

We have here a familiar set of philosophical issues. data$_A$ can be about the causal sources that give rise to data$_E$. Emphasis on the causal origins of the data, typified by causal theories of reference and perception, lead to one set of answers regarding what data$_A$ are about. But what data$_A$ are about can have nothing to do with the relevant data$_E$ and the interpretation is imposed by the intentions of an interpreter of the data. We thus need to say more regarding what the data$_A$ are about. Under the causal view, for an individual datum we can plausibly say that it is about whatever gave rise to that datum regardless of the accuracy of its content. In this there is an echo of the causal theory of reference in that all of the descriptive content of a piece of referential apparatus can be wrong and yet that apparatus can successfully refer. Thus, rather than begin with the datum itself, we begin with a realist attribution of the existence of the source. The inverse inference to that source is underdetermined, but this is an additional complication that is unavoidable and I set it aside here.[12] The underlying problem here is this: when philosophers still believed in pure observations, the idea was that such things gave us direct access to what was being observed. In contrast, we required inverse inferences to know what the referents of theoretical terms were. That view about direct access seems quite naive now, but we can retain one element by highlighting the fact that there is a causal pathway connecting the observation with the entity observed. Yet we lose that causal pathway not only with simulations but also with a widely used class of imaging devices. The point here is that what data are about is a vexed and complicated issue that is intimately tied to an adequate theory of reference. BFI were right to draw our attention to this aspect of the simulations versus experiments debate. The origins of the data, whether material or not, are insufficient to determine the content of data$_A$. So let us generalize the concept of data$_E$ to data$_O$ where data$_O$ are data generated either by causal or computational sources. Here the `O' indicates that the origin of the data be included in a specification of the data.

3. Causal-Computational Instruments.

To help clarify matters, it is useful to consider a particular type of instrument, those that I shall call causal-computational instruments. Almost all discussions of scientific instruments implicitly restrict themselves to what I shall

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never endorsed the view that running simulations on material computers is itself a reason to justify substituting data from simulations for data from experiments. Numerical experiments are significantly different from material experiments.

[10] This is not at all easy and I shall not attempt to solve the problems here.

[11] Definitions of `photograph' stipulate that the image must have been formed by electromagnetic radiation (usually visible light) falling on some recording device.

[12] This is not to suggest that underdetermination problems in inverse inference methods are unimportant. Both theoretically and in practice solutions to these problems must be found.

call non-computational instruments.[13] By a non-computational instrument I mean that the instrument receives some physical process as an input, the instrument causally interacts with the input to transform it, the instrument's output is another physical process, and none of these processes or interactions is a computation.[14]All of the familiar scientific instruments discussed in the philosophical literature are of the non-computational kind: optical telescopes and microscopes, magnetometers, oscilloscopes, and so on.[15] In the last fifty years or so, a potentially different class of instruments has been developed that I shall call causal-computational instruments. These take physical processes as inputs and at some point in the operation of the instrument, they convert physical states into digital representations that undergo computational transformations before producing the instrument's output.[16] Of course, these causal-computational instruments have causal aspects not only because of their inputs but because the implementation of the computations is carried out by causal processes. Yet causal-computational instruments fall into a class intermediate between purely causal instruments and computer simulations because inferences and representations play a crucial role in their operation but, unlike pure simulations, the causal inputs to the physical device also play a central role in the interpretation of the output.

I shall take as examples of causal-computational instruments the category of medical imaging devices that includes computed tomography (CT) and positron emission tomography (PET) instruments.[17] Although the physical operation of specific types of instruments is crucial for understanding how they produce data, most of the philosophical points I make here generalize from the specific examples discussed. A generic diagram of scientific instruments is given in Figure 1.

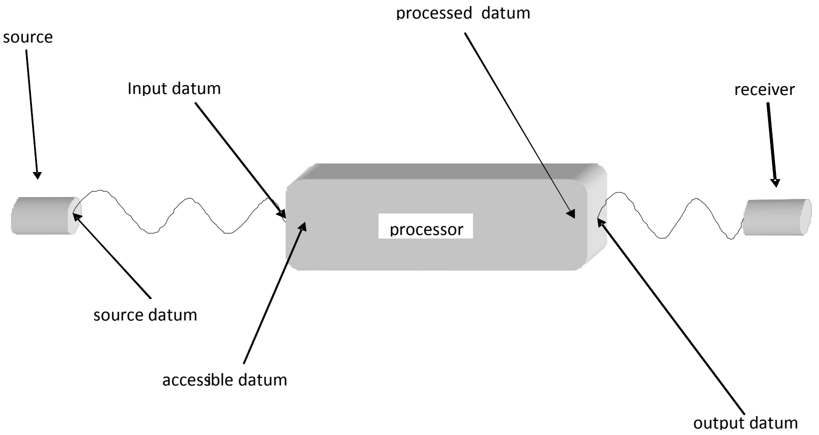

Figure1

What I have called the processor can be either a purely causal transformation device, such as a telescope lens, or a computational device. The generic case that I consider has the source as an object with a single spatially varying quantitative property represented by a continuous or discrete function $f(\mathbf{s})$ on the space $\mathbb{R}^2$ or $\mathbb{R}^3$. Values of f are the source

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[13] One of the few exceptions is Israel-Jost [2011].

[14] For our present purposes, what counts as a computation will involve only those in the class of Turing computable discrete functions. This rules out the view that all physical processes are computations and provides the basis for a principled distinction between computational and non-computational instruments.

[15] I am in this paper excluding the human perceptual system as an example of a scientific instrument because it is too difficult to disentangle interpretations of the datum from the causal processes that lead to the datum, although in a more general context there are epistemological advantages to viewing the human perceptual apparatus as simply another instrument that produces data.

[16] Many traditional instruments now use digital displays for their outputs but that does not by itself introduce a computational element into the instrument. Although the distinction is perhaps not easy to make completely clear, an instrument in which the display types are antecendently fixed does not count. Under computational theories of vision, parts of the human perceptual system may count as a computationally enhanced instrument.

[17] The principal use of PET scans is for imaging of brain tumors, epilepsy, strokes, and Alzheimer's disease. Magnetic resonance imaging (MRI) devices use different methods than do PET and CT devices.

data. For concreteness, take as the running example the situation in which f represents the intensity of X-rays in a spatial region or the spatial distribution of some radioactive biological marker, where the spatial region includes some target such as a human body. The task is then to estimate the mathematical form of f or specified values of f using the receiver data. The input data are often the result of complex physical processes within the system that must be modeled in order to infer both the general form and the specific values of f.

Both CT and PET instruments construct a two dimensional (sometimes three dimensional) image from a sequence of one dimensional projections. The construction process, which is inescapably computational, involves a set of inverse inferences from the receiver data to the source of that data. A number of different mathematical techniques are used for these inferences – here I shall discuss one of the most frequently used methods, filtered backprojection. Although such inferences run against the primary direction of causation from input to output, this does not violate the causal component of these instruments. Similar inverse inferences are made in purely causal instruments, such as refracting telescopes, to the conclusion that the image at the eyepiece is an image of the source object.

In two dimensional computerized tomography instruments, X-rays, collimated to lie in a plane, traverse the object to be imaged and impinge on detectors on the far side of the object.[18] Each detector receives a one dimensional projection of the target object along a given ray and the computational algorithms combine all the projections around a 180˚ arc to construct a two dimensional image of a cross section of the target. The energy of the X-rays is attenuated by traveling through the object and the degree of attenuation depends upon the densities of the materials through which the X-ray is traveling. Although Hounsfield's CT prototype used matrix inversion methods, these are no longer used to recover the values of attenuation coefficients because there is a relatively high level of noise in the projections and this can cause instabilities in direct inversion techniques. In addition, the large amount of data collected makes the computational load on matrix inversion methods infeasible. The choice of mathematical techniques is thus affected by both technological constraints and the fact that the physical system does not satisfy the idealizations needed for matrix inversion to be effective. Instead backprojection algorithms or iterative methods are used.

The backprojection methods that make inverse inferences from the detected intensities to the attenuation coefficients use inverse Radon transforms.[19] The basic idea is that the total attenuation along a ray is the sum of the attenuations in each pixel and the backprojection method adds back the attenuation in each voxel by performing a line integral along the direction of the ray. By taking rays in many different directions, the 2-D matrix of pixels can be reconstructed. But the bare mathematical method assumes that the physical processes are idealized in certain ways and in order to eliminate artifacts one needs to know how the image was constructed.

In order to argue for the view that the generating conditions of the data must be known, consider an argument that Ian Hacking [1983] has used in favor of entity realism. The argument goes like this for the case of microscopes. It is sometimes possible to observe the same structure with the aid of microscopes that use different, independent, physical processes, such as ordinary optical microscopes, fluorescent microscopes, interference microscopes, polarizing microscopes, and so on. Hacking argues that it would be incredible to assert that there was no common physical structure that was giving rise to these common observations from different instruments: `If the same structure can be discerned using many of these different aspects of light waves, we cannot seriously suppose that the structure is an artifact of all the different physical systems' This argument is flawed because it does not properly take into account the fact that the observed structure is deliberately engineered.[20] We can easily see this in the case of the medical imaging techniques discussed here. Consider the example of a sinogram, which is a representation of the raw data produced from a CT scan with the frame of reference attached to the detectors and which rotates around the target object. The intensity of the radiation received at a detector is plotted against the angle of rotation of the radiation source relative to a fixed baseline in the object's frame of reference. [21] To almost all readers of this essay, sinograms do not represent anything familiar. However, when inverse Radon transforms are applied to the pixels constituting the sinogram, it is transformed into something familiar, such as an image of a human skull but that familiar image has its `obvious' representational structure imposed by choices of the instrument designers. The intentional content is useful to us because of the perceptual apparatus of human observers, but for a computer, the sinogram is at least as useful a representational device and results from a coordinate transform between the two frames of reference. We could say that the sinogram and the familiar image of the skull are both in an equivalence class of representations where the equivalence relation is determined by a set of transformations on the set of individual data points. If so, what those images are about cannot be determined from the output of the instrument alone or from the intentions of the observer. Decisions about data_A require knowledge of what causal processes were involved in producing

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[18] For simplicity I take the X-rays to be parallel rather than distributed in a fan-shaped beam.

[19] I note that some of these mathematical techniques had been developed previously for use in astronomical imaging using radio telescopes.

[20] For arguments that this point also applies to traditional causal instruments, see Humphreys [2004], pp. 33-37. One difference between causal and causal-computational instruments in this regard is the relative ease with which images can be constructed in the latter instruments.

[21] For images of sinograms see Webb [2003].

the individual data and what transformations have been performed on the individual data points.

This simple example illustrates the point that images from causal-computational instruments are deliberately constructed and the `structure' that is allegedly invariant across different imaging devices is the result of deliberate engineering. There are no limitations on how the individual pixels in a data$_A$ representation generated by a causal-computational instrument can be computationally re-arranged to form an output image. This construction process does not mean that the resultant image is arbitrary. The output will be tailored to the needs of the data user, whether it is a human scientist, an automated scientist, or some other epistemic agent. Since truth is an epistemic goal for most scientific enterprises, representations of the target object that systematically misled the users of the instrument should be avoided, although other situations, such as one in which the intelligence services of a country insert rogue software into an enemy's spy satellites, would not be subject to this constraint. Further discussion of these issues is contained in the section on artifacts below.

This ability to construct the output image is also present in purely causal instruments although these are constrained by laws of nature in ways that the computational components of causal-computational instruments are not. In order to obtain useable outputs from such instruments, a great deal of deliberate engineering is required. This tends to be disguised by the fact that the physical design of the instrument produces the constructed image automatically and correction mechanisms, such as those for chromatic aberration, are physically built into the instrument. One reason Hacking's argument seems plausible is that we can appeal to optical laws such as that light travels in straight lines and is refracted and diffracted in regular ways that allow gross spatial structure to be preserved. In the case of CT images, for each datum, we can make a case that a datum j is about a cylinder of tissue lying along the ray traversed by the X-rays detected by detector j. The causal relations between the adjoining spatial parts of tissue are, in the idealized models, absent in both the data$_A$ and in the data$_E$ and this is why it is initially not obvious what the collective data$_A$ are about. Although this lack of determination of the collective representation by the local data has always been present, the ability to easily rearrange the data$_A$ in computerized instruments makes this problem much more pressing for those instruments. Similar considerations show that what, collectively, the data points in a sonogram are about is not determined by what the individual data points are about but requires knowledge of what transformations have been performed on the detector data.

4. *Artifacts*

We have seen that with all causal-computational instruments the final image is constructed and cannot be taken as a `given'. What I want to suggest is that although all data collected from these instruments requires interpretation, simply noting that such data is `theory-laden' is uninformative. What is important is that with sufficient knowledge of the causal and computational processes that generated the data, data can be corrected to eliminate, or partially eliminate, artifacts.

In CT imaging devices an artifact is a systematic discrepancy between the real attenuation values and the values inferred from the measurements taken at the CT detectors.[22] Although artifacts of an instrument are often considered as properties of the output of the instrument, in the present case the artifacts can be considered as properties of a numerical data set just as much as a feature of a graphical image. It is probably not possible to provide a sharp division between a misrepresentation and an artifact, but there is an important conceptual difference that should be maintained. There are two kinds of artifacts to consider – artifacts that are the result of causal interactions and computational artifacts that result from approximations in the numerical methods. A standard example of the former are lines present in an image due to beam hardening, which is the progressive increase in mean X-ray energies due to the total absorption of lower energy rays by tissue. This can be corrected for either by physically filtering out lower energy X-rays before the beam enters a target region or by using software correction algorithms.

An example of the second occurs in continuous helical scans. Because the plane of the beam is tilted at an angle to the target due to the helical path, when traversing an object with a non-uniform cross-section, the beam will present a slightly different set of projections at an angle of $(\theta + \pi)$ than it will at θ. This results in a distortion of the shape of the cross-section that in the case of liver scans, for example, can be mistaken for a tumor and the errors must be corrected by software.

We can now ask the question: is an image of an artifact a representation and if so, of what? To answer this question, recall the earlier point that what data$_A$ are about can result from two quite different sources – the origins of the data or from an interpretation that is independent of the origins. Taking the definition of an artifact, if we emphasize the data$_A$ as resulting from data$_O$ then the image of an artifact represents the systematic error. In contrast, if the interpretation of the data$_A$ is made without consideration of the data$_O$, the data$_A$ can be taken to represent not an error, but a non-existent entity such as a liver tumor. Similar issues arise for computational artifacts that occur in simulations of fluid dynamics.

Issues about distinguishing what is real from what is an artifact thus hinge on whether data$_A$ are interpreted with reference to data$_O$ or not. It is the ability to distinguish between artifacts and genuine features of the target system, not the existence of the `unobservable' processes used to construct the representation that is the important issue here. No operator of computed tomography instruments doubts the existence of X-rays, radioactive matter, biological cells, cancerous tissue, and so on. The issue is one of accurate representation, not of the existence of `unobservables'.

The model dependence of data might be thought to have the consequence that there is an inseparable mixture of theory

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[22] Barrett and Keat [2004]

and observation in the data. This created a serious problem for empiricists in two cases. One was when the user of the data was unaware of what the theoretical component was, a situation that can occur when a theory or paradigm is so dominant that its effects have become invisible to practitioners in the field. The second case occurs when the data user cannot separate and remove the effects of the theory or model. This can occur when we do not have a good theory of how an instrument works, as well as in the first kind of case. But when the methods used in the models are explicit and invertible, the effects of theory and modeling can be corrected. The computed tomography example is valuable because there are many models embedded in the processing of the data and we can correct for most of them. Indeed, many correction algorithms are used in modern instruments ranging from image stabilization methods in digital cameras to optical enhancement algorithms for telescopes. Similar remarks can be made about simulation artifacts, which are a problem in molecular dynamics simulations, simulations with periodic boundary conditions, fluid dynamics, and some other areas. They often result from numerical integration methods and finite size effects.

It has also been suggested that instruments have theory built into them. Whether or not this is correct for purely causal instruments, it is clearly true for causal-computational instruments in the sense that correction models based on knowledge of the physical and computational processes occurring within the instrument are frequently used.[23] Empiricists extolled the virtues of direct, theory-free access to data, and the use of models can seem to degrade our access to the world. There are identifiable dangers of using models to correct data sets, but unmediated access to an object is not always epistemically superior to access mediated by physical or mathematical intermediaries. Look at the windshield of a car on a bright day with your unaided vision. Then don a pair of polarizing sunglasses. You will be now able to see objects inside the car that were not previously visible. If you believe these objects are artifacts of the polarizers plus windshield, simply remove the sunglasses, open the car door, and use your unaided senses, including touch. The important thing is to know how the instrument works. With the computational parts we have this knowledge because we have designed them.

Could we avoid needing to know how an instrument works by accumulating inductive evidence of successful uses? Eckhart Arnold has suggested the following thought experiment.[24] Suppose a working CT scanner with a generator is washed up on the shore of an island the inhabitants of which have never seen such an instrument and know nothing of modern physics. After experimenting with placing various familiar objects into the scanner and seeing that their internal structure is reproduced accurately, they are in a position to use the scanner in similar ways to their own visual sense, the workings of which they also do not understand. This is an ingenious suggestion but the situation with respect to CT images and artifacts is not quite so straightforward. Because the inverse Radon transform that is used to obtain the value of the function f within a given pixel is constructed by backprojecting all of the rays received at detectors between 0 and π, each reconstructed point is dependent upon the whole data set. This means that artifacts produced by factors in one part of the target can produce errors in another part. Although it is possible that inductive evidence could be obtained about the appearance of such artifacts, there would need to be a sample base of objects sufficiently similar to each future object used in the instrument in order for such artifacts to be recognized in each case.

What does all of this say about simulations? Much of what I have said about imaging devices transfers, with obvious modification, to the simulation case. A decision must be made regarding whether what the data are about is determined by reference to the origins of the simulation data, which will be the (interpreted) model upon which the simulation is based if one exists, or is determined by an intentional attribution to the output from the simulation. I have argued that an informed attribution under the second method cannot be made without knowledge of the generating conditions of the output data, in which case the origins of the simulation data also play a role in this approach. It is an unfortunate fact that in the philosophy of reference an emphasis on the conventionality of object-sign relations and social accounts of meaning has distracted attention from other, more refined, ways of representing the world.[25]

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[23] Morrison [2009] has noted that instruments often require models in order to extract meaningful data.

[24] Personal communication

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