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The most promising way to regard thought experiment is as a species of experiment, alongside concrete experiment. Of the authors who take this view, many portray thought experiment as possessing evidential significance intrinsically. In contrast, concrete experiment is nowadays most convincingly portrayed as acquiring evidential significance in a particular area of science at a particular time in consequence of the persuasive efforts of scientists. I argue that the claim that thought experiment possesses evidential significance intrinsically is contradicted by the history of science. Thought experiment, like concrete experiment, has evidential significance only where particular assumptions—such as the Galilean doctrine of phenomena—are taken to hold; under alternative premises, in themselves equally defensible, thought experiment is evidentially inert. Copyright © 1996 Elsevier Science Ltd.

1. The Experimentalist View of Thought Experiment

It frequently occurs in science that a claim is established or discredited by a thought experiment. Since they appear to be no more than short fictional narratives, how do thought experiments come to have this power?

One answer is offered by what I shall call the 'experimentalist view' that thought experiments are experiments, albeit an extreme form of them.[1] On this view, a thought experiment, like a concrete experiment, provides evidence about the world; and a thought experiment establishes or discredits a scientific claim in the way a concrete experiment does, in the light of the evidence about the world that it provides. This view has lately been endorsed by Roy A.

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[1]Among alternatives to the experimentalist view are the view that a thought experiment is a reconceptualization of old empirical data, advanced by T. S. Kuhn, 'A Function for Thought Experiments' (1964), in T. S. Kuhn, *The Essential Tension: Selected Studies in Scientific Tradition and Change* (Chicago, IL: University of Chicago Press, 1977), pp. 240–265; the view that it is an argument of a particular sort, advanced by J. Norton, 'Thought Experiments in Einstein's Work', in T. Horowitz and G. J. Massey (eds), *Thought Experiments in Science and Philosophy* (Savage, MD: Rowman and Littlefield, 1991), pp. 129–148; and the view that it is the manipulation of a mental model, advanced by N. Miščević, 'Mental Models and Thought Experiments', *International Studies in the Philosophy of Science* **6** (1992), 215–226.

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Sorensen and, in some respects, by James R. Brown.[2] I share the belief that the experimentalist view offers the best prospect of making sense of thought experiment, though I regard it as having implications that Brown and Sorensen would not accept, as will become clear.

Since the experimentalist view assimilates thought experiment to concrete experiment, one might expect experimentalist accounts of thought experiment to parallel the most persuasive available accounts of concrete experiment. In fact, the accounts of thought experiment offered by Brown and Sorensen, as well as those of other supporters of the experimentalist view, diverge from the most persuasive present-day accounts of concrete experiment. The divergence occurs where the discussion turns to the evidential significance of thought experiment. Brown and Sorensen hold to a logicist notion of evidential significance, according to which evidential significance is an intrinsic property of thought experiment. In contrast, the most convincing accounts of concrete experiments available today hold to a historicist notion of evidential significance, according to which the evidential significance of concrete experiment is the outcome of historical and local accomplishments.

The present paper examines this divergence between accounts of thought and concrete experiment. I will suggest that the logicist notion of evidential significance is no more tenable for thought experiment than it is for concrete experiment, and will argue that our understanding of thought experiment is advanced if we adopt for thought experiment the historicist view of evidential significance that has been developed for concrete experiment. This paper will not offer a taxonomy of thought experiments. It is likely that a full account of thought experiment requires such a taxonomy: thought experiments, like concrete experiments, can take various forms and serve various purposes.[3] But, whatever forms and purposes it has, thought experiment must possess evidential significance in order to play a role in science; and it is with the nature of evidential significance that this paper is concerned.

2. Logicist and Historicist Accounts of Evidential Significance

If a particular concrete experiment is to be accepted in a science as a source of evidence, the practitioners of that science must be persuaded of its legitimacy

[2]R. A. Sorensen, *Thought Experiments* (New York: Oxford University Press, 1992), and 'Thought Experiments and the Epistemology of Laws', *Canadian Journal of Philosophy* **22** (1992), 15–44; J. R. Brown, *The Laboratory of the Mind: Thought Experiments in the Natural Sciences* (London: Routledge, 1991), and 'Why Empiricism Won't Work', in D. Hull, M. Forbes and K. Okruhlik (eds), *PSA 1992: Proceedings of the 1992 Biennial Meeting of the Philosophy of Science Association*, 2 vols (East Lansing, MI: Philosophy of Science Association, 1993), vol. 2, pp. 271–279.

[3]Taxonomies of thought experiment are offered by Brown, *The Laboratory of the Mind*, *op. cit.*, note 2, pp. 33–48, and Norton, *op. cit.*, note 1, p. 131. The claim that concrete experiments have various forms and purposes is substantiated for example by I. Hacking, *Representing and Intervening: Introductory Topics in the Philosophy of Natural Science* (Cambridge: Cambridge University Press, 1983), pp. 149–275.

on two counts. Most obviously, they must be persuaded that the particular experiment satisfies the standards of competence in experimental practice holding within that science. These standards may prescribe that an experiment should be suitably controlled for extraneous factors, that any instruments used in its performance should be properly calibrated, and so on. But more fundamentally, the practitioners must be persuaded that experiment at all yields evidence relevant to resolving controversies in the science. Unless they regard appealing to experiment as relevant to the resolution of controversies, there will be no point for them to debate whether a particular experiment has been conducted competently. I express the fact that, in a given science, experiment counts as a source of evidence relevant to establishing and discrediting claims by saying that, in that science, experiment has evidential significance.

Let us consider how our view of the evidential significance of concrete experiment has recently evolved. Until some time ago, discussion of concrete experiment was conducted on what I shall call the 'logicist premise' that the evidential significance of experiment is intrinsic to it, and not dependent on argumentative context. If this premise held, it would be self-evidently justified to resolve scientific controversies by experiment: it would follow from an intrinsic property of experiment—namely, its evidential significance—that it is valid to appeal to experiment to establish and discredit scientific claims.

The logicist premise invokes a distinction between the evidential significance of experiment and the evidential significance of a particular experiment for a particular scientific claim. Whether a given experiment is relevant to establishing and discrediting a given claim—in other words, whether a given experiment has evidential significance for a given claim—depends in part on background assumptions. For example, whether Robert A. Millikan's oil drop experiments have evidential significance for the claim that the electron has a particular charge depends on assumptions about electrons, oil drops, and Millikan's apparatus. Because of this, the evidential significance of a given experiment for a given claim is not intrinsic to the experiment: it may occur that an experiment has evidential significance for a given claim on some assumptions but not on others. This is acknowledged widely in present-day philosophy of science, including by those whom I cite as holding to the logicist premise. But our topic here is not the evidential significance of a particular experiment for a particular claim: it is the evidential significance of the practice of experiment. The logicist premise asserts that whether experiment, in this latter sense, has evidential significance does not depend on any assumptions: there are no special factors that can annul the relevance of experiment to establishing and discrediting scientific claims.

The distinction between the evidential significance of experiment and the evidential significance of a particular experiment for a particular claim is emphasized by the following observation. It is possible to discover that a particular experiment lacks evidential significance for a particular claim—for example, that Millikan's experiment has no bearing on the claim that the electron has a particular mass. But such a discovery does not undermine the belief that experiment has evidential significance: anyone holding such a belief would remain convinced that scientific claims are established and discredited by experiment, and would simply search for an alternative experiment that has evidential significance for the given claim.

Among those who have given logicist accounts of concrete experiment is Karl R. Popper.[4] On Popper's view, the evidential significance of experiment is conferred by the fact that experiment is the source of observation statements which refute possible theories. The evidential significance of experiment thus derives entirely from the logical relation between observation statements and the claims of possible theories: it is affected neither by argumentative context nor by any other factor. It follows from this that the validity of appealing to experiment to discredit and establish scientific claims is self-evident. Accordingly, Popper expects that no scientist who is sufficiently well informed and fair minded will resist testing theories by experiment. Of course, Popper acknowledges that whether a particular experiment is relevant to testing a particular claim depends on background assumptions.

In recent years, the logicist premise has come increasingly to be regarded as an inadequate foundation for the understanding of concrete experiment. The principal reason is this: while the logicist premise deems evidential significance to be intrinsic to experiment, the historical record suggests strongly that it is the outcome of historical and local accomplishments. More precisely, the historical record suggests that the evidential significance of experiment is not an intrinsic property of the practice, but rather is conferred on experiment at particular times in particular areas of science by the persuasive effort of scientists. Without this effort having been expended in a particular science, experiment in that science is evidentially inert. It follows from this that the validity of appealing to experiment in establishing and discrediting scientific claims can never properly be considered self-evident: if effort was required to establish the evidential significance of experiment, it must be that the justification of appealing to experiment was once disputed, and it cannot be ruled out that some day it will again be.

In this light, the logicist premise has two shortcomings as a foundation for an understanding of experiment. Firstly, and most directly, by treating the evidential significance of experiment as an intrinsic property of it, the logicist premise conflicts with the finding that it is the outcome of historical and local accomplishments. Secondly, the logicist premise precludes our understanding

[4]K. R. Popper, *The Logic of Scientific Discovery* (London: Hutchinson, 1959; tenth impression, revised, 1980), pp. 106–111. Popper puts forward a logicist account of thought experiment, *ibid.*, pp. 442–456.

the states of affairs that obtain in sciences where and when experiment is not attributed evidential significance. For instance, the logicist premise makes it impossible to comprehend the stages in which experiment comes to be attributed evidential significance in a science, and to make sense of the reasoning of scientists who oppose this attribution. On the logicist premise, the latter are merely insufficiently aware of the intrinsic evidential significance of experiment.

Largely on the strength of these considerations, the logicist premise has been generally replaced in studies of concrete experiment by what I shall call the 'historicist premise', that the evidential significance of experiment is conferred on it in particular areas of science at particular times by the persuasive effort of scientists.[5]

On the historicist premise, the concept of evidential significance escapes the descriptive/normative dichotomy that is imposed on it by the logicist premise. The logicist premise envisages that the statement 'Entity *E* has evidential significance in science *S*' may be given a descriptive or a normative interpretation. On the descriptive interpretation, the statement asserts that practitioners of *S* believe *E* to provide evidence relevant to establishing and discrediting claims in *S*. On this interpretation, the statement leaves open the possibility that this belief is mistaken, and that *E* in fact fails to provide such evidence. Logicists would apply a descriptive interpretation to, for example, the statement that observations of the positions of celestial bodies have evidential significance in astrology: they would understand this statement as asserting that astrologers erroneously believe such observations to provide evidence relevant to establishing and discrediting claims about human affairs. On the normative interpretation, the statement 'Entity *E* has evidential significance in science *S*' asserts that *E* truly provides evidence relevant to establishing and discrediting claims in *S*. Logicists would apply this interpretation to, for example, the statement that X-ray diffraction experiments have evidential significance in crystallography: they would read this statement as asserting that we ought to evaluate claims in crystallography by appeal to such experiments. In contrast, on the historicist premise, the statement 'Entity *E* has evidential significance in science *S*' asserts that practitioners of *S* stipulate that *E* provides evidence relevant to establishing and discrediting claims in *S*. On this interpretation, since the possession of evidential significance by *E* is the outcome of a stipulation, the statement does not allow the possibility that *E* as a matter of fact fails to provide evidence in the science—though of course it allows that practitioners of a different science may instead attribute evidential significance to entities other than *E*.

[5]What I call the 'historicist premise' for concrete experiment is set out for example by S. Shapin and S. Schaffer, *Leviathan and the Air-Pump: Hobbes, Boyle, and the Experimental Life* (Princeton, NJ: Princeton University Press, 1985), pp. 3–21.

3. The Dispute over Forms of Evidence in Early Modern Mechanics

Our choice between the logicist and the historicist premise in the discussion of concrete experiment affects particularly strongly our understanding of early modern mechanics. Logicist treatments presume that concrete experiment has intrinsic evidential significance in mechanics as in all other sciences, and that it is thus self-evident that concrete experiment is a source of knowledge about the motion of bodies. But a more careful examination of the historical record shows that concrete experiment acquired evidential significance in mechanics at a particular time and in particular circumstances, as the outcome of efforts of Galileo Galilei and others.[6]

In its Aristotelian form, mechanics was conceived primarily as a project to account for occurrences in natural circumstances, which I shall call 'natural occurrences'. This conception of the discipline shaped both the form of the claims admitted within it, and the entities regarded as apt to establish and discredit these claims. Theories in Aristotelian mechanics strove to account for the particularities of natural occurrences: for example, the Aristotelian theory of free fall attempted to explain the variety of the attributes of natural falls, by appeal to factors such as the substance, shape, and weight of individual falling bodies. Correspondingly, evidential significance in Aristotelian mechanics was vested in reports of natural occurrences, intended to record happenings with as little idealization and loss of detail as possible. For example, evidence about free fall was constituted by reports of natural falls that strove to record the myriad particular attributes of each. Aristotelian theories in many areas of mechanics, including the Aristotelian account of free fall, were quite well supported by the evidence constituted by natural occurrences.

Concern for natural occurrences was not shared universally, either in antiquity or in the Renaissance. In an alternative approach to the natural world, which may be retraced to Pythagoras and Plato, natural occurrences were of much less import than a reality conjectured to lie behind them. The 16th-century natural philosophers who depicted the world as embodying proportions and ratios, such as Simon Stevin, viewed mechanics primarily as a study of invariant forms underlying, and often not immediately apparent in, natural occurrences.

This approach to the natural world was formalized by Galileo, who came to conceive of mechanics as a project to identify and describe phenomena,

[6]Other episodes in and aspects of concrete experiment's acquisition of evidential significance in physical science in the seventeenth century are studied by Shapin and Schaffer, *op. cit.*, note 5; S. Schaffer, 'Glass Works: Newton's Prisms and the Uses of Experiment', in D. Gooding, T. Pinch and S. Schaffer (eds), *The Uses of Experiment: Studies in the Natural Sciences* (Cambridge: Cambridge University Press, 1989), pp. 67–104; and P. Dear, 'Narratives, Anecdotes, and Experiments: Turning Experience into Science in the Seventeenth Century', in P. Dear (ed.), *The Literary Structure of Scientific Argument: Historical Studies* (Philadelphia: University of Pennsylvania Press, 1991), pp. 135–163.

fundamental modes in which physical reality manifests itself. On his account, each natural occurrence is the resultant of one or more phenomena and a great number of accidents. Two natural occurrences can be recognized as occurrences of the same sort—for example, as two instances of free fall—in virtue of the fact that the same phenomenon—the phenomenon 'free fall'—partly determines them both; but they differ from one another in virtue of the distinct accidents—ensuing from properties of the individual falling bodies and of the media in which they fall—by which they are determined for the remainder. Although accidents are thus responsible for the great variety of natural occurrences, only phenomena lie within the scope of theorizing in Galilean mechanics.[7]

The Galilean conception of mechanics prescribes both the form of the claims that the discipline admits and the entities deemed relevant to assessing them. Since phenomena are taken to be much simpler and much less numerous than natural occurrences, theories about them will be concise and often mathematical, and there will be a relatively small number of them: such theories came eventually to be known as 'laws of nature'. Correspondingly, it follows from the relation in which phenomena stand to natural occurrences that reports of natural occurrences are of little significance in establishing and discrediting theories in Galilean mechanics. It is not that reports of natural occurrences are insufficiently exhaustive: on the contrary, they are excessively inclusive, since among the attributes that they record are many that derive from accidents rather than from phenomena. On these grounds, Galileo proposed that evidential significance in mechanics be withdrawn from natural occurrences, and vested in entities that, he believed, were better indicators of phenomena. One of these entities was what Galileo called 'experiment'. While in Aristotelian terminology *experimentum* was a witnessed natural occurrence, experiment in Galileo's usage is a contrived occurrence determined in its entirety by a phenomenon and to no extent by accidents. Because experiments display phenomena in accident-free form, they provide a direct test of theories in Galilean mechanics.[8]

Those who conceived of mechanics as a science of natural occurrences disputed Galileo's attribution of evidential significance to experiment: they believed—with considerable justification—that many experiments were too heavily contrived to yield knowledge about the object of their interest, natural

[7]N. Koertge, 'Galileo and the Problem of Accidents', *Journal of the History of Ideas* **38** (1977), 389–408; E. McMullin, 'Galilean Idealization', *Studies in History and Philosophy of Science* **16** (1985), 247–273.

[8]Changes in the meaning of 'experiment' in the late sixteenth century are discussed by C. B. Schmitt, 'Experience and Experiment: A Comparison of Zabarella's View with Galileo's in *De motu*', *Studies in the Renaissance* **16** (1969), 80–138. Previous studies of concrete experiment in Galileo include M. Segre, 'The Role of Experiment in Galileo's Physics', *Archive for History of Exact Sciences* **23** (1980), 227–252, and R. H. Naylor, 'Galileo's Experimental Discourse', in Gooding, Pinch and Schaffer, *op. cit.*, note 6, pp. 117–134, where also further references may be found.

occurrences. Between the proponents of mechanics in its Aristotelian and Galilean versions there thus opened a dispute about the forms of evidence that were to be admitted in the discipline. This dispute is very well illustrated in the Fourth Day of Galileo's *Discorsi*, where Salviati responds to Simplicio's concern for what actually happens in particular circumstances by arguing that natural occurrences yield little information about phenomena.[9]

Accounts of the evidential significance of concrete experiment that adhere to the logicist premise seriously misrepresent this dispute. On the assumption that experiment possesses evidential significance intrinsically, such accounts would portray Galileo as unveiling a property of experiment that his opponents refused to recognize. But it is clearly open to the practitioners of mechanics to choose whether it should be a science of phenomena, as Galileo advocated, or of natural occurrences, as his opponents intended. Therefore, neither natural occurrences nor experiments either have or lack evidential significance in mechanics intrinsically: rather, evidential significance is attributed to natural occurrences in the Aristotelian form of mechanics, and to experiments in the Galilean form. Only if the discussion of concrete experiment is conducted on the historicist premise can we do justice to the dispute between the proponents of these different forms of mechanics.

4. The Aristotelian Rejection of Thought Experiment

We now turn to the evidential significance of thought experiment. For a particular thought experiment to be accepted in a science as a source of evidence, two conditions must be satisfied, paralleling the conditions discussed earlier for the acceptance of a concrete experiment. Firstly, the practitioners must be persuaded that the thought experiment is well formulated on the standards holding in that science; these standards may for instance require the scenarios envisaged in thought experiments not to violate pertinent established laws of nature.[10] But more fundamentally, the practitioners must be persuaded that thought experimentation at all provides evidence relevant to establishing and discrediting claims in the science, i.e. that thought experiment has evidential significance there. An account of thought experiments that aspires to completeness must therefore explain how thought experiment comes to have evidential significance.

Recent discussions of this issue—even by those authors who have adopted the 'experimentalist view' that thought experiment is a species of experiment—have been conducted for the most part on the logicist premise that the evidential significance of thought experiment is intrinsic to it. The logicist premise for

[9]G. Galilei, *Two New Sciences* (1638), translated by S. Drake (Madison: University of Wisconsin Press, 1974), pp. 223–227.

[10]This requirement is stipulated for example by K. V. Wilkes, *Real People: Personal Identity Without Thought Experiments* (Oxford: Clarendon Press, 1988), pp. 15–21.

thought experiment, like that for concrete experiment, invokes the distinction between the evidential significance of a particular experiment for a particular claim and the evidential significance of experiment as a practice. Whether a given thought experiment has evidential significance for a given claim depends in part on background assumptions. Because of this, the evidential significance of a given thought experiment for a given claim is not intrinsic to the experiment: it may occur that a thought experiment has evidential significance for a given claim on some assumptions but not on others. This is acknowledged by those whom I cite as holding to the logicist premise for thought experiment. But our topic here is not the evidential significance of a particular thought experiment for a particular claim: it is the evidential significance of thought experiment as a practice. The logicist premise asserts that whether thought experiment, in this latter sense, has evidential significance does not depend on any assumptions: there are no special factors that can annul the relevance of thought experiment to establishing and discrediting scientific claims.

Among those who give logicist accounts of thought experiment are Brown and Sorensen. Brown commits himself to the view that the evidential significance of thought experiment is intrinsic to it when he claims that thought experiment yields *a priori* knowledge of the world: thought experiment would be unable to yield such knowledge if its evidential significance depended on circumstances.[11] Sorensen believes that a thought experiment that fulfils its goal is one which refutes a scientific claim by disproving modal consequences of it.[12] Thus, in a manner reminiscent of Popper's treatment of concrete experiment, Sorensen retraces the evidential significance of a thought experiment to the logical relation between its conclusion and the claims of possible theories. Since logical relations between statements are supposed to be unaffected by circumstances of any kind, Sorensen too acquires a commitment to the view that, whatever evidential significance a thought experiment has, it has intrinsically.

Their logicism about the evidential significance of thought experiment leads Brown and Sorensen to three conclusions. Firstly, they conclude that there is a number of exemplary thought experiments, to which scientists through the centuries have added, that have an intrinsic high efficacy in establishing scientific matters of fact. Secondly, they conclude that scientists of all disciplines and epochs who are sufficiently well informed and fair minded will acknowledge the evidential significance of these thought experiments. Thirdly, they conclude that there is no such event as a process in which thought experiment acquires or loses evidential significance in a science. Of course, Brown and Sorensen can and do allow that the evidential significance of a thought experiment may come only gradually to be acknowledged or

[11] Brown, *The Laboratory of the Mind*, *op. cit.*, note 2, pp. 76–98.
[12] Sorensen, *Thought Experiments*, *op. cit.*, note 2, pp. 132–166.

appreciated, but they are committed to the view that thought experiments always possess the evidential significance that comes to be recognized in them.

In contrast, I advocate a historicist account of the evidential significance of thought experiment. My account claims that thought experiment, like concrete experiment, is conferred evidential significance at particular times in particular areas of science by the persuasive effort of scientists.[13]

Let us test the logicist and the historicist accounts of thought experiment for their ability to make sense of developments in early modern mechanics. As has often been remarked, thought experiment attained prominence in mechanics with the work of Galileo.[14] Brown and Sorensen devote particular attention to a thought experiment that Galileo portrayed as discrediting Aristotle's theory of free fall and establishing his own theory.[15] Aristotle had claimed that the rate of fall of bodies depends partly on their weight, and that, in general, heavier bodies fall faster than lighter ones; in contrast, Galileo claimed that rate of fall is independent of weight. Galileo asks us to imagine dropping a compound body consisting of a cannonball joined to a musket ball. On one reading, he says, Aristotle's theory implies that the compound body falls more slowly than the cannonball alone would, since the musket ball retards the cannonball to some extent. On another reading, however, Aristotle's theory implies that the compound body falls faster than the cannonball alone would, since the compound body is heavier than the cannonball. Galileo concludes that Aristotle's theory of free fall is inconsistent. To avoid this inconsistency, a theory of free fall must entail that the compound body falls at the same rate as the cannonball alone would; and in order to entail this, the theory must claim that the rate of fall of bodies is independent of their weight.[16]

How does this thought experiment come to have evidential significance in the discussion of free fall? Holding to the logicist premise, Brown and Sorensen believe that, whatever evidential significance this thought experiment has, it has intrinsically. They view it as self-evidently establishing that the rate of fall of bodies is independent of their weight, and imply that they think that

[13]An experimentalist view of thought experiment that is compatible with the historicist premise is put forward by D. Gooding, 'What is *Experimental* About Thought Experiments?', in Hull, Forbes and Okruhlik, *op. cit.*, note 2, vol. 2, pp. 280–290; see also D. Gooding, 'Imaginary Science', *British Journal for the Philosophy of Science* **45** (1994), 1029–1045.

[14]Previous discussions of thought experiment in Galileo include L. Geymonat and A. Carugo, 'I cosiddetti "esperimenti mentali" nei *Discorsi* galileiani e i loro legami con la tecnica' (1960), in L. Geymonat, *Per Galileo: attualità del razionalismo*, edited by M. Quaranta (Verona: Bertani, 1981), pp. 79–98; A. Koyré, 'Galileo's Treatise *De motu gravium*: The Use and Abuse of Imaginary Experiment' (1960), in A. Koyré, *Metaphysics and Measurement: Essays in Scientific Revolution* (London: Chapman & Hall, 1968), pp. 44–88; and Naylor, *op. cit.*, note 8, pp. 124–127.

[15]Galilei, *Two New Sciences*, *op. cit.*, note 9, pp. 66–72.

[16]For further discussion of Aristotle's account of free fall and Galileo's interpretation of it, see B. M. Casper, 'Galileo and the Fall of Aristotle: A Case of Historical Injustice?', *American Journal of Physics* **45** (1977), 325–330.

anyone who understood the thought experiment would be compelled to reject Aristotle's theory of free fall for that of Galileo.[17]

This view misrepresents the nature and understates the depth of the disagreement between the proponents of the Galilean and Aristotelian forms of mechanics. Galilean mechanics is a science of phenomena, in which contrived occurrences can serve as evidence; Aristotelian mechanics is a science of natural occurrences, in which evidence is vested in reports of natural occurrences. Thought experiments appeared to the practitioners of Aristotelian mechanics as very dissimilar from and not reducible to reports of natural occurrences. On these grounds, they regarded thought experiment as having no relevance to establishing and discrediting claims in mechanics.[18]

The decision of Aristotelian natural philosophers to vest evidential significance in reports of natural occurrences and to withhold it from thought experiment is apparent in their reactions to the thought experiments that Galileo used against them. In a few instances, Aristotelian natural philosophers argued that Galileo's thought experiments admitted conclusions different from those that he drew: this response effectively concedes the dispute to Galileo, since it grants thought experiments relevance in establishing and discrediting claims in mechanics. For the most part, however, Aristotelian natural philosophers countered Galileo's thought experiments with reports of actual occurrences. Against his thought experiment about free fall, for example, they cited observations of actual falls of bodies of different weights, in which the heavier body reached the ground before the lighter body.[19] In the attempt to establish that we should not expect the earth's motion to have a detectable effect on the motion of objects around us, Galileo presented a thought experiment in which an object dropped from the mast of a moving ship falls precisely at the mast's foot: Aristotelian natural philosophers retorted with testimony that, in some actual occurrences of stones dropped from ships' masts, the stones had fallen not onto the deck at all, but overboard.[20] Such

[17]Brown, *The Laboratory of the Mind*, *op. cit.*, note 2, pp. 1–3 and 77–79; Sorensen, *Thought Experiments*, *op. cit.*, note 2, pp. 126–127; Sorensen, 'Thought Experiments and the Epistemology of Laws', *op. cit.*, note 2, pp. 17–18.

[18]P. King, 'Mediaeval Thought-Experiments: The Metamethodology of Mediaeval Science', in Horowitz and Massey, *op. cit.*, note 1, pp. 43–64, suggests that thought experiment was used in medieval natural philosophy; as he concedes, however, his examples can be regarded equally validly as instances of reasoning from hypothesis and analogy familiar to Aristotelian dialectic.

[19]Reports of actual falls cited against Galileo by Aristotelian natural philosophers are documented in W. R. Shea, *Galileo's Intellectual Revolution* (London: Macmillan, 1972), p. 11, note 10. For a present-day review of the evidence that the speed of fall of a body in natural circumstances depends on its weight, see G. Feinberg, 'Fall of Bodies Near the Earth', *American Journal of Physics* **33** (1965), 501–502, and C. G. Adler and B. L. Coulter, 'Aristotle: Villain or Victim?', *Physics Teacher* **13** (1975), 35–37.

[20]The moving ship thought experiments are in G. Galilei, *Dialogue Concerning the Two Chief World Systems—Ptolemaic and Copernican* (1632), translated by S. Drake (Berkeley: University of California Press, 1953), pp. 143–145; the reaction to them by Aristotelian natural philosophers is described in Shea, *op. cit.*, note 19, p. 156, and E. Grant, 'In Defense of the Earth's Centrality and Immobility: Scholastic Reaction to Copernicanism in the Seventeenth Century', *Transactions of the American Philosophical Society* **74** (1984), part 4, p. 41.

natural occurrences are what the Aristotelian form of mechanics takes as evidence.

The grounds on which the proponents of the Aristotelian form of mechanics rejected Galileo's reliance on thought experiment suggest that none of Brown's and Sorensen's three conclusions about thought experiment is tenable. Firstly, it is unjustifiable to conclude that certain thought experiments can be identified as possessing an intrinsic high efficacy in establishing or discrediting scientific claims: thought experiment has evidential significance in a science only in virtue of being attributed it on particular premises. In consequence, both Brown's view that thought experiments yield *a priori* knowledge of the world, and Sorensen's view that they refute scientific claims by disproving modal consequences of them, require qualification: thought experiments may be taken to have these powers, but only where premises are accepted that assign evidential significance to them. Secondly, it is by this stage clear that the denial of evidential significance to thought experiment by Aristotelian natural philosophers is not due to their being insufficiently well informed or fair minded: on the contrary, they differed with Galileo on principled grounds about what counts as evidence in mechanics. Thirdly, if thought experiment lacks evidential significance in Aristotelian mechanics but possesses it in Galilean mechanics, then there must be stages in which thought experiment acquires (and perhaps also stages in which it can lose) evidential significance. The logicists' supposition that such stages do not exist forecloses investigation of them, impoverishing our understanding of thought experiment. In the next section, I try to redress the balance by offering a sketch of how, in consequence of the efforts of Galileo, thought experiment acquired evidential significance in mechanics and other sciences.

Some may think that the thesis that thought experiment has intrinsic evidential significance is corroborated by the attitude of Galileo himself. In his writings, Galileo takes it for granted that the evidential significance of thought experiment is intrinsic to it: he presents his thought experiment about free fall as self-evidently establishing that the rate of fall of bodies is independent of their weight, implying that any reader of his who rejects this conclusion must have failed to understand him. But the fact that a particular claim is portrayed as indubitable by some participants in a scientific controversy cannot be taken as evidence that the claim is indeed beyond doubt. Both the victors and the losers of controversies generally present their claims as indubitable: the task of those later studying the episode is to explain how the claims of the former came eventually to be seen as indubitable and those of the latter as false.

5. Thought Experiment in the Galilean Doctrine of Phenomena

According to Galileo's account of concrete experiment, as we have seen, a phenomenon may be displayed in accident-free form in the contrived occurrence of which an experiment consists. If an experiment is successful in stripping a phenomenon of accidents, then a description of the outcome of that experiment amounts to a description of the phenomenon. For example, if a concrete experiment could be devised that presented the phenomenon of free fall in accident-free form, then a description of the occurrence of which that experiment consisted would amount to a description of the phenomenon 'free fall'.

This account of concrete experiment entails that, if an experiment is successful in presenting a phenomenon in accident-free form, all performances of that experiment will have the same outcome: if distinct performances of an experiment have different outcomes, they must have been determined partly by accidents, and the experiment must thus have failed to present the phenomenon in accident-free form. I conjecture that Galileo perceived that, for him to be able plausibly to present an experiment as displaying a phenomenon, distinct performances of the experiment—at least, those that could be regarded as having been carried out competently—had to show substantial accord with one another.

Galileo doubtless considered that, in the case of some concrete experiments that he could envisage, distinct performances indeed showed substantial accord: each of these experiments could plausibly be presented as displaying a phenomenon. In the case of some other experiments, however, distinct performances conflicted: none of these experiments could be presented as yielding the description of a phenomenon. In areas of mechanics where every feasible concrete experiment was of the latter sort, as long as Galileo vested evidential significance exclusively in concrete experiment, he had no means of establishing and discrediting claims about phenomena.

I suggest that Galileo devised thought experiment as a source of evidence about phenomena for use where all feasible concrete experiments exhibited the shortcoming that distinct performances of them conflicted. Galileo's thinking may have proceeded as follows. Experimentation is the attempt to produce an occurrence determined entirely by a phenomenon and to no extent by accidents. If a phenomenon is so subtle that no actual occurrence can be produced in which the phenomenon is displayed in accident-free form, the only occurrence in which the phenomenon may be displayed is one that is non-actual. This is what a thought experiment does: it produces a non-actual occurrence in which a phenomenon is displayed.

My suggestion that Galileo followed this line of reasoning explains why he resorted to thought experiment in the study of free fall. Distinct performances of any concrete experiment about free fall that was feasible in Galileo's time would certainly have conflicted with one another: for example, performances involving falling bodies of different weights, densities, and shapes would not have accorded on any clear-cut phenomenon of free fall. In Galileo's terms, such concrete experiments fail to display the phenomenon 'free fall' in accident-free form. Thus, to display this phenomenon, Galileo was compelled to turn to a non-actual occurrence—the one that his thought experiment presents. This non-actual occurrence allowed Galileo to establish the claim that, in the phenomenon 'free fall', the speed of falling bodies is independent of their weight.

All the other notable appeals that Galileo made to thought experiment are similarly in areas of mechanics in which distinct performances of any feasible concrete experiment would have conflicted with one another, and therefore in which it was not possible to establish and discredit claims about phenomena by means of concrete experiment. For example, the period of a simple pendulum is dependent to some extent on the amplitude of swing; and this dependence is different in different pendulums. Because of this, no feasible concrete experiment would have supported Galileo's claim that the period of a simple pendulum is independent of the amplitude of swing. Similarly, to establish that we should not expect the earth's motion to have a detectable effect on the motion of objects around us, Galileo may originally have considered arranging a concrete experiment in which an object was dropped from the mast of a moving ship: but distinct performances of such an experiment on a rolling and pitching deck would plainly have conflicted with one another. In each of these cases, Galileo appealed instead to thought experiments, in which the phenomena whose properties he sought to establish were displayed in accident-free form.[21]

The value of thought experiment as a means to display phenomena in accident-free form was apparent also to Christiaan Huygens, who followed Galileo in regarding mechanics as a science of phenomena. Huygens used thought experiment to establish his laws of impact, including the claim that in an elastic collision between two bodies of equal mass the velocities of the bodies are exchanged. In the thought experiments that Huygens put forward to establish this claim, a collision takes place on a moving boat between two bodies, whose velocities before and after the collision are measured by observers on the boat and ashore.[22] The practicalities of boats in motion ensure that, if this were performed as a concrete experiment, distinct performances of it would conflict with one another, failing to establish any simple relation between the bodies' velocities. Huygens may have reasoned that, while concrete experiment failed to display the phenomenon 'elastic collision' in accident-free form, thought experiment would succeed.

[21]The pendulum thought experiment is in Galilei, *Two New Sciences*, *op. cit.*, note 9, pp. 97–99.

[22]C. Huygens, *De motu corporum ex percussione* (1703), in *Oeuvres complètes de Christiaan Huygens*, 22 vols (The Hague: Martinus Nijhoff, 1888–1950), vol. 16 (1929), pp. 29–91, on pp. 29–49.

On the Galilean doctrine of phenomena, to attribute evidential significance to thought experiment in mechanics has considerable plausibility. If you believe that mechanics is a science of phenomena, and that a phenomenon is displayed in an accident-free occurrence, then you will regard evidential significance in mechanics to be vested in accident-free occurrences. If in the case of some phenomena no actual accident-free occurrences can be produced, but you believe that you can produce some non-actual accident-free occurrences, then you will be content to let controversies in mechanics be resolved by appeal to such occurrences.

These remarks suggest that thought experiment is attributed evidential significance by the Galilean doctrine of phenomena, and will carry evidential weight in areas of science where this doctrine is accepted. The Galilean doctrine of phenomena is endorsed in, for example, Newtonian mechanics and Darwinian evolutionary biology: and thought experiment carries evidential significance in both these forms of science. Newtonian mechanics regards natural occurrences as determined jointly by universal regularities, which resemble Galileo's phenomena, and by initial or boundary conditions, which are considered as non-lawlike and as lying outside the scope of physical theorizing, like Galileo's accidents.[23] This analysis leads Newtonian mechanics to envisage that, while a regularity may not be apparent in actual occurrences, it may be displayed in an imaginary occurrence that abstracts from the peculiarities of initial conditions. Consequently, Newtonian mechanics attributes evidential significance to thought experiment as a means to display phenomena. An example is the phenomenon 'absolute rotation'. Concrete experiment is not suited to display this phenomenon, since the objects surrounding any actual rotating body make it impossible to distinguish absolute motion from relative motion. But Newtonian mechanics allows that absolute rotation may be displayed by thought experiment: indeed, Isaac Newton believed that this phenomenon was displayed by a thought experiment that he presented, which envisaged a rotating bucket in an otherwise empty universe.[24] Darwinian evolutionary biology subscribes to the Galilean doctrine of phenomena to the extent of envisaging that phenomena exist—natural and sexual selection, in the classical formulation—that, because of the interference of accidents, cannot be discerned in actual occurrences. In virtue of this conception of the science, thought experiment bears evidential significance in Darwinian evolutionary biology as a means to display phenomena.[25]

[23]For the Newtonian account of the relation between occurrences, regularities, and initial conditions, see for example E. P. Wigner, 'Events, Laws of Nature, and Invariance Principles' (1964), in E. P. Wigner, *Symmetries and Reflections: Scientific Essays* (Bloomington: Indiana University Press, 1967), pp. 38–50, on pp. 38–42.

[24]R. Laymon, 'Newton's Bucket Experiment', *Journal of the History of Philosophy* **16** (1978), 399–413.

[25]J. G. Lennox, 'Darwinian Thought Experiments: A Function for Just-So Stories', in Horowitz and Massey, *op. cit.*, note 1, pp. 223–245.

In contrast, in areas of science where the Galilean doctrine of phenomena is rejected and no alternative rationale for thought experiment is provided, the attribution of evidential significance to thought experiment will be implausible. In particular, if you believe that science aims to describe natural occurrences rather than something resembling Galilean phenomena, you will attribute no evidential significance to thought experiment. As we have seen, this attitude was maintained by the proponents of the Aristotelian form of mechanics; and it is widely maintained today in sciences other than physics. For example, many areas of the present-day life and earth sciences conceive of their aim as compiling a detailed record of natural occurrences in the style of natural history, rather than an inventory of Galilean phenomena assumed to lie behind occurrences. Correspondingly, these sciences are not moved to attribute evidential significance to thought experiment.

Brown and Sorensen note that thought experiment appears to have special efficacy in establishing laws of nature.[26] My suggestion that thought experiment derives evidential significance in mechanics and other sciences from the Galilean doctrine of phenomena explains this fact, though on grounds which Brown and Sorensen would not accept. Only sciences that endorse the Galilean doctrine of phenomena formulate claims presented as laws of nature; and they interpret a law of nature as the description of a fundamental mode in which physical reality manifests itself—a phenomenon, in Galileo's term, or a universal regularity, in Newton's. The Galilean doctrine of phenomena portrays thought experiment as a technique for displaying phenomena or universal regularities in pure form. From these premises it follows straightforwardly that thought experiment is well suited to establish what we call laws of nature.

6. The Imperviousness of Quantum State Transitions to Thought Experiment

I have argued that thought experiment has evidential significance only historically and locally, i.e. when and where premises that attribute evidential significance to it, such as the Galilean doctrine of phenomena, are endorsed. In a further defence of this claim, I argue in this final section that there is an area of modern physics in which current theory is incompatible with the Galilean doctrine of phenomena, and in which consequently—no additional or alternative justification of thought experiment having as yet been evolved—thought experiment lacks evidential significance. This area is the study of the discontinuous transitions between quantum states that some subatomic and atomic systems undergo. Examples of these transitions are the decay events of unstable elementary particles such as free neutrons, the decay events of radioactive nuclei, and electron jumps from excited to stable energy levels in atoms.

[26]Brown, *The Laboratory of the Mind*, *op. cit.*, note 2, pp. 76–98; Sorensen, 'Thought Experiments and the Epistemology of Laws', *op. cit.*, note 2.

What distinguishes discontinuous quantum state transitions from the occurrences treated by classical mechanics is that, while classical mechanics regards the latter as deterministic, quantum mechanics regards the former as indeterministic. The statement that classical occurrences are deterministic entails that, if two classical occurrences differ from one another, there must have been some difference in the causal factors by which they were determined. This means that, while any similarity between two classical occurrences can be attributed to causal factors common to them, we will invariably be able to identify differentially acting causal factors to which to attribute any differences between them. This amounts to a guarantee that any classical occurrence can be described as determined jointly by two factors: one or more phenomena, by which similar occurrences will also be determined, and accidents, which will be peculiar to the occurrence in question. Thus, the Galilean doctrine of phenomena holds for such occurrences, and scope is opened for thought experiment to have evidential significance as a means to display phenomena in accident-free form.

In contrast, the statement that discontinuous quantum state transitions are not deterministic entails that two such occurrences may differ from one another without there being any difference in the causal factors by which they were determined. This means that for such an occurrence it is not possible to identify a phenomenon that can be said to have contributed to determine this and all similar occurrences, and accidents that can be said to be peculiar to this occurrence. For example, given a particular radioactive decay event, it is not possible to identify a regularity common to all decay events of its kind and a set of circumstances peculiar to this event (such as may explain why it took place at one time rather than another) by which this event could be said to have been jointly determined. The same holds for the spontaneous decay of an elementary particle and for an electron jump from an excited to a stable energy state.

Because of this feature of discontinuous quantum state transitions, a procedure purporting to display the phenomena that underlie occurrences will be regarded as not applicable to them. As long as the attribution of evidential significance to thought experiment depends on portraying it as such a procedure, we should expect that thought experiment will be regarded as incapable of yielding information about such occurrences—i.e. as having no evidential significance in the study of such occurrences.

I believe that this expectation is borne out in present-day quantum mechanics. There is no shortage of thought experiments serving various purposes in quantum mechanics, and among these are many thought experiments that model the effects of discontinuous quantum state transitions in given scenarios. An example of the latter is the Schrödinger's cat thought experiment, in which a radioactive decay event is envisaged to cause a particular sequence of events. But in all such thought experiments the quantum state transition features merely as a black box, as the source of a particular output. There appears to be no thought experiment that is taken to shed light on the nature of discontinuous quantum state transitions themselves, in the way in which Galileo's thought experiment is taken in classical mechanics to shed light on the nature of free fall. In view of the fact that so many other aspects of quantum theory have been analyzed in thought experiment, I do not believe that this lack is fortuitous. On the contrary, present-day quantum physicists find the very notion of a thought experiment able to elucidate the nature of discontinuous quantum state transitions elusory, as if these occurrences were impervious to thought experiment. I regard the elusory feel of the notion of a thought experiment about discontinuous quantum state transitions as further evidence that thought experiment has evidential significance only historically and locally.

Given our inability to predict the future development of science, we cannot rule out that the state of affairs in quantum mechanics will change. It may be that causal factors resembling Galilean phenomena will be discovered for discontinuous quantum state transitions; or it may be that in physics a new doctrine will become established that regards thought experiment other than as a technique for displaying a phenomenon in accident-free form. In these eventualities, thought experiment may come to have evidential significance in the study of discontinuous quantum state transitions. It should go without saying that, in either eventuality, the evidential significance of thought experiment will remain the outcome of historical and local accomplishments.

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