CHAPTER
T W O

Why Thought Experiments do not Transcend Empiricism

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2.1 Introduction

The epistemological problem of thought experiments The essential element in experimentation is the natural world. We learn about the natural world by watching what it does in some contrived circumstance. Just imagining what the world might do if we were to manipulate it in this way or that would seem futile, since it omits this essential element. Yet the literature of science frequently leads us to just such imaginary experiments, conducted purely in the mind, and with considerable apparent profit. These are "thought experiments." We imagine a physicist trapped in a box in remote space, that the box is accelerated by some outside agent, and, from tracing what we imagine the physicist would see in the box, we arrive at one of the fundamental physical principles that Einstein used to construct his general theory of relativity. If this can be taken at face value, thought experiments perform epistemic magic. They allow us to use pure thought to find out about the world. Or at least this is dubious magic for an empiricist who believes that we can only find out about the world from our experience of the world.

Can thought experiments perform this magic? My concern in this chapter is restricted to this one question, which we can label the epistemological problem of thought experiments in the sciences:

> Thought experiments are supposed to give us knowledge of the natural world. From where does this knowledge come?

I shall also restrict myself to thought experiments as they are used in the sciences, although I expect that my analysis and conclusions can be used in other contexts. My concern is *not* directly with the many other interesting facets of thought experiments: their effective exploitation of mental models and imagery, their power as

rhetorical devices; their entanglement with prior conceptual systems; their similarity to real experiments; and so on. More precisely, I am concerned with these facets only insofar as they bear directly on the epistemological problem.

This chapter My goal in this chapter is to state and defend an account of thought experiments as ordinary argumentation that is disguised in a vivid pictorial or narrative form. This account will allow me to show that empiricism has nothing to fear from thought experiments. They perform no epistemic magic. Insofar as they tell us about the world, I shall urge that thought experiments draw upon what we already know of it, either explicitly or tacitly; they then transform that knowledge by disguised argumentation. They can do nothing more epistemically than can argumentation. I will defend my account of thought experiments in section 2.3 by urging that the epistemic reach of thought experiments turns out to coincide with that of argumentation, and that this coincidence is best explained by the simple view that thought experiments just are arguments. Thought experiments can err – a fact to be displayed by the thought experiment – anti thought experiment pairs of section 2.2. Nonetheless thought experiments can be used reliably and, I will urge in section 2.4, this is only possible if they are governed by some very generalized logic. I will suggest on evolutionary considerations that their logics are most likely the familiar logics of induction and deduction, recovering the view that thought experiment is argumentation. Finally, in section 2.5 I will defend this argument-based epistemology of thought experiments against competing accounts. I will suggest that these other accounts can offer a viable epistemology only insofar as they already incorporate the notion that thought experimentation is governed by a logic, possibly of very generalized form.

2.2 Thought Experiment – Anti Thought Experiment Pairs

A test for any epistemology of thought experiments How are we to know that we have a viable epistemology of thought experiments? I propose a simple test. It is presented here as a gentle warm-up exercise that the reader is asked to bear in mind as the chapter unfolds and various epistemologies are visited.

We can have cases in which one thought experiment supports a result and another thought experiment supports the negation of the same result. These I will call "thought experiment – anti thought experiment pairs." An epistemology of thought experiments must give us some account of why at least one of these fails. It is not enough for us to know by other means that one or other fails. We must be able to explain what went wrong in the failed thought experiment itself. Consider the analogous situation with real experimentation. We may be convinced that the result reported by some experiment is incorrect; it may contradict firmly held theory, for example. If we are to retain confidence in experimentation, we must – at least in principle – be able to explain how the experiment could produce a spurious result.[1]

1 So, when D. C. Miller repeated the famous Michelson–Morley experiment in 1921 and reported evidence of the motion of the earth through the ether, Einstein suggested that the result could be due to tiny thermal gradients in the equipment. See Pais (1982, pp. 113–14).

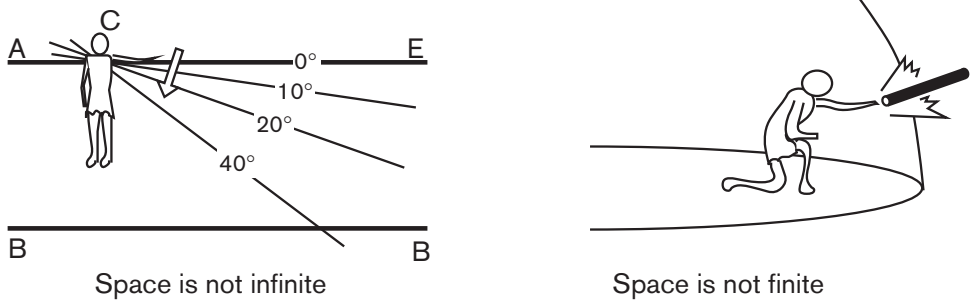

Figure 2.1 Is the world spatially finite?

In the following, I present three thought experiment – anti thought experiment pairs that are unified by the theme of rotation.[2]

2.2.1 Is the world spatially finite?

Aristotle argued, in *On the Heavens*, Book 1, Ch. 5, 272[a]8–21, that the universe cannot be infinite, since an infinite universe cannot rotate uniformly, as he believed our universe does. In such an infinite universe, he imagined a line ACE, infinite in the direction of E, rotating with the world about the center C and asked when it would cut another infinite line BB. We can make his analysis more thought experimental by imagining that ACE is the ray indicated by a pointing hand that turns with the universe (in the clockwise direction in figure 2.1). At the 0 degrees position shown, ACE is parallel to BB. Prior to attaining that position, ACE does not cut BB; afterwards, it does. But when does it *first* cut BB? It is not at the 40 degrees position, since it has already cut BB at the 20 degrees position; and it was not at the 20 degrees position, since it had already cut BB at the 10 degrees position; and so on, indefinitely. No position greater than 0 degrees is the first, but ACE has not cut BB at 0 degrees. So ACE never cuts BB, which is impossible. (It is interesting that the thought experiment does not seem to depend on the rotation of the universe; all it requires is rotation of a pointer.)

The corresponding anti thought experiment is ancient, most famous, and due to the Pythagorean Archytas. If the universe is finite and I go to the edge: ". . . could I stretch my hand or my stick outside, or not? That I should not stretch it out would be absurd, but if I do stretch it out, what is outside will be either body or place . . ." (Simplicus, *Phys*. 467, 26–32, as quoted in Sorabji, 1988, p. 125).

2 A fourth pair that retains the theme of rotation is the thought experiment of Newton's bucket that favors absolute space. Mach's anti thought experiment imagines the bucket walls to be made several leagues thick; it is usually interpreted as blocking Newton's claim. See Norton (1996, pp. 347–9) and Mach (1893, p. 284). See also Norton (forthcoming) for another thought experiment – anti thought experiment pair and for criticism of alternative epistemologies.

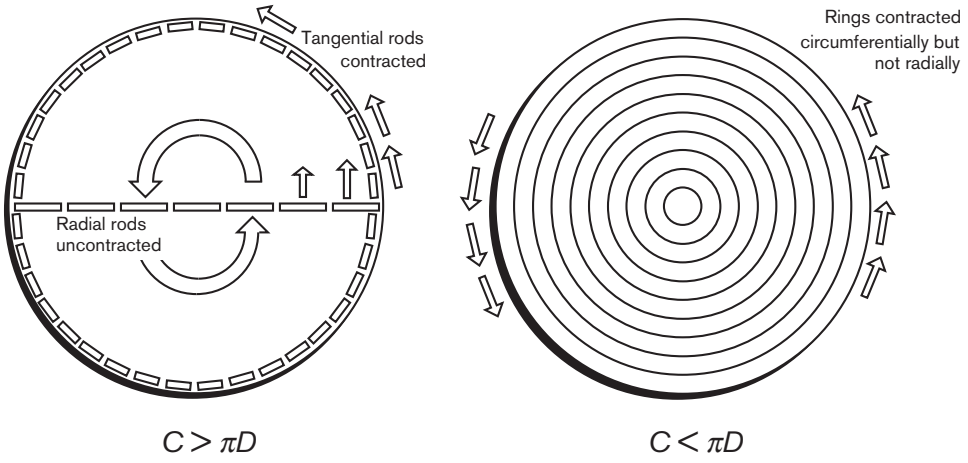

Figure 2.2 What is the geometry of space for a rotating observer?

2.2.2 What is the geometry of space for a rotating observer?

At a decisive moment in the course of his discovery of the general theory of relativity, sometime in 1912, Einstein realized that the geometry of space for an accelerated observer may be non-Euclidean. He showed this for the case of a uniformly rotating observer in special relativity by means of a thought experiment concerning a rigidly rotating disk (see Stachel, 1980). Einstein imagined that the geometry of the surface of the disk is investigated by the usual method of laying down measuring rods. If the disk's diameter is D, what will we measure for its circumference C? Will it be the Euclidean $C = \pi D$? The lengths of measuring rods laid radially are not affected by the Lorentz contraction of special relativity, since their motion is perpendicular to their length. But rods laid tangentially along the circumference move in the direction of their length and will be contracted. Thus *more* rods will be needed to cover the circumference than according to Euclidean expectations. That is, we will measure a non-Euclidean $C > \pi D$ (see figure 2.2).

While Einstein's thought experiment gives a non-Euclidean geometry with $C > \pi D$, an anti thought experiment gives the opposite result of a geometry with $C < \pi D$. The alternative was proposed, for example, by Joseph Petzold in a letter to Einstein dated July 26, 1919 (see Stachel, 1980, p. 52). It is, in effect, that the rotating disk be conceived as concentric, nestled, rotating rings. The rings are uncontracted radially, so the diameter of the disk is unaffected. But the rings are contracted in the circumferential direction, the direction of motion due to the rotation, so their length is *less* that the corresponding Euclidean length. That is, the lengths on the disk conform to $C < \pi D$.

Another anti thought experiment, investigated by Ehrenfest in 1910 and Varicak in 1911, gives the Euclidean result $C = \pi D$. The positions of distance markers on the rotating disk are transferred at some instant to superimposed but nonrotating tracing paper and the geometric figures on the disk reconstructed. The result, Varicak urged,

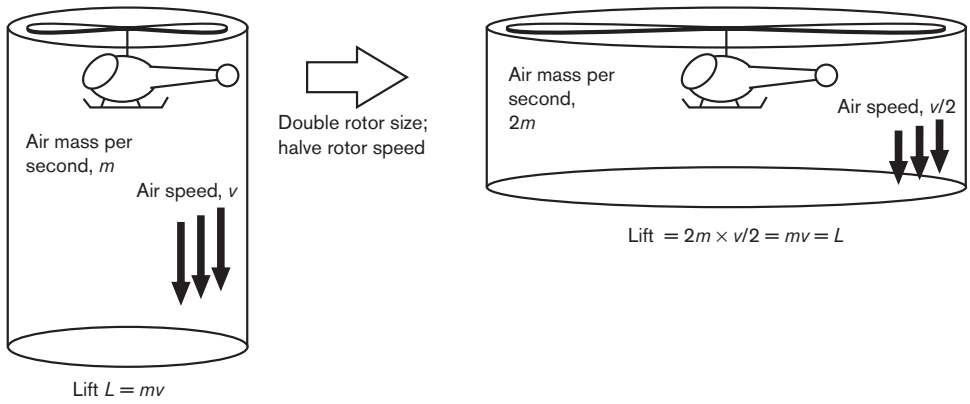

Figure 2.3 The effect of increased size and reduced speed on a helicopter rotor.

would be recovery of Euclidean figures, because the surface of nonrotating tracing paper conforms to Euclidean geometry (see Klein et al., 1993, pp. 478–80).

2.2.3 What is the lift of an infinite rotor at rest?

Imagine a helicopter rotor. When it rotates, it generates lift as a reaction force that results from the momentum imparted to the current of air that it directs downward. If the rotor moves a mass m of air in one second at speed v, then the lift L generated is just mv. What would happen if we were to double the radius of the rotor? To answer, let us assume that it is part of the design of rotors of varying size that the speed of the air currents they generate is proportional to the rotational speed of the rotor. (This can be achieved by flattening the rotor blades more, further from the center.) Since the area swept by the rotor has increased by a factor of $2^2 = 4$, if we leave the rotational speed of the rotor fixed, in one second the rotor will move a mass $4m$ of air at speed v. So the lift will have increased by a factor of 4, to $4mv$. To keep the lift constant at $L = mv$ we should now also reduce the rotational speed of the rotor by a factor of 2. That halves the speed of the air to $v/2$ and also halves the mass moved from $4m$ to $2m$. The lift is now $(2m)(v/2) = mv = L$, which is the original lift.[3]

In short, the lift stays constant at L as we double the rotor size and halve its speed. Repeat this process endlessly in thought, indefinitely doubling the rotor size and halving the rotational speed. In the limit of infinitely many doublings, we have a rotor of infinite size that is not rotating but still generates the original lift L.

The obvious anti thought experiment yields no lift for an infinitely large rotor at rest. A finitely sized rotor that does not turn generates no lift. This is true if we double its size. In the limit of infinitely many doublings, we have an infinitely large rotor that does not rotate and generates no lift.

3 The (minimum) power required to sustain the lift is just the kinetic energy of the air moved per unit time; that is, $P = mv^2/2$. So in this process the power is halved to $(2m)(v/2)^2/2 = mv^2/(2 \times 2) = P/2$. Thus, in the limit of the infinite rotor, no power is needed to sustain the lift L. "That must be how angels work. Wide wing spans." – Jeremy Butterfield.

The challenge It is hard to resist the puzzle of determining which (if either) of the members of a pair gives the correct result and what is wrong with the other one. That sort of exercise is part of the fun of thought experiments. But it is not my principal concern here. My concern is to ask how different epistemologies diagnose the existence of the competing pairs; how they explain why one succeeds and the other fails; and how the epistemologies can do this while still preserving the reliability of thought experiments as instruments of inquiry.

2.3 Thought Experiments are Arguments

Why arguments? My account of thought experiments is based on the presumption that pure thought cannot conjure up knowledge, aside, perhaps, from logical truths. All pure thought can do is transform what we already know. This is the case with thought experiments: they can only transform existing knowledge. If thought experiments are to produce knowledge, then we must require that the transformations that they effect preserve whatever truth is in our existing knowledge; or that there is at least a strong likelihood of its preservation. The only way I know of effecting this transformation is through argumentation; the first case is deductive and the second inductive.

Thus I arrive at the core thesis of my account:

(1) Thought experiments are arguments.

which forms the basis of my earlier account of thought experiments (Norton, 1991, 1996).[4] To put it another way, if thought experiments are capable of producing knowledge, it is only because they are disguised, picturesque arguments. That does not assure us that all thought experiments do produce knowledge. They can fail to in just the same way that arguments can fail; that is, either may proceed from false premises or employ fallacious reasoning.

How experience enters a thought experiment Thought experiments need not produce knowledge of the natural world. There are, for example, thought experiments in pure mathematics (for examples, see Brown, 1993b, pp. 275–6) and these, I have argued, are merely picturesque arguments (see Norton, 1996, pp. 351–3). However, the thought experiments that interest me here are those of the natural sciences that do yield contingent knowledge of the natural world. According to empiricism, they can only do so if knowledge of the natural world is supplied to the thought experiment; that is, if this

4 In my original account (Norton, 1991), I required that:

Thought experiments are arguments which:
(i) posit hypothetical or counterfactual states of affairs, and
(ii) invoke particulars irrelevant to the generality of the conclusion.

where (i) and (ii) are conditions necessary for an argument to be a thought experiment, but not sufficient. The analysis of Norton (1991) was intended in part to investigate the ramifications of the existence of these necessary conditions.

knowledge comprises a portion of the premises upon which the argument proceeds. It may enter as explicitly held knowledge of the world. We assert on the authority of an empirical theory, special relativity, that a moving rod shrinks in the direction of its motion. Or it may enter as tacit knowledge. We just know that the space of our experience never runs out; we have never seen a boundary in space beyond which we could not pass, unless there was already something past the boundary to obstruct us.

I do not seek here to argue for empiricism; the debate between empiricism and other epistemologies is as ancient as philosophy itself and not likely to be advanced fundamentally here. However, empiricism is overwhelmingly the predominant epistemology in philosophy of science, so that an account that accommodates thought experiments to empiricism in a simple and straightforward manner ought to be accepted as the default, as opposed to some more extravagant account. I claim this default status for the view advocated here.

Two forms of the thesis The thesis that thought experiments are arguments requires some elucidation. Is the claim merely that thought experiments can do no more than argumentation when it comes to justifying claims? Or is it, in addition, that the actual execution of a thought experiment is just the execution of an argument? Following Norton (1996, p. 354), I intend the stronger version and urge both:

(1a) *(Context of justification)*[5] All thought experiments can be reconstructed as arguments based on tacit or explicit assumptions. Belief in the outcome–conclusion of the thought experiment is justified only insofar as the reconstructed argument can justify the conclusion.

(1b) *(Context of discovery)* The actual conduct of a thought experiment consists of the execution of an argument, although this may not be obvious, since the argument may appear only in abbreviated form and with suppressed premises.

Justifying (1a) As indicated above, the first thesis (1a) derives from the assumption that pure thought cannot conjure up new knowledge. There is a second and more practical justification. As far as I know, all thought experiments can in fact be reconstructed as arguments, and I have little hope of finding one that cannot. Indeed, this expectation supplies a quite stringent test of thesis (1a). It can be defeated merely by finding a thought experiment that cannot be reconstructed as an argument. Norton (1991, 1996) contain many examples of reconstruction of typical thought experiments from various different areas of the physical sciences, including those have been offered as opaque to such reconstruction. The ease of their reconstruction suggests that a counterexample will not be found. The reconstructions are generally rather straightforward and often differ little from the original narrative of the thought experiment. Einstein's rotating disk thought experiment is a typical example. It can be reconstructed in summary as follows:

(D1) In Euclidean geometry, the measured circumference of a disk is π times its diameter. (Premise)

5 Given condition (ii) above, that thought experiment arguments invoke particulars irrelevant to the generality of the conclusion, thesis (1a) entails that thought experiments may be eliminated from our discourse without loss of demonstrative power, although the actual arguments that replace them may well be harder to follow. This is the "elimination thesis" (Norton, 1991, p. 131).

(D2) The geometry of a nonrotating disk is Euclidean. (Premise)
(D3) The motion of a radial element on a rotating disk is perpendicular to its length, so that (according to special relativity) the length is unaltered. (Premise)
(D4) The motion of a circumferential element on a rotating disk is along its length, so that (according to special relativity) the length is contracted. (Premise)
(D5) Therefore the measured circumference of a rotating disk is more than π times the measured diameter. (From D2, D3, D4)
(D6) Therefore the geometry of a rotating disk is not Euclidean. (From D1, D5)

Justifying (1b) The situation with the second thesis (1b) is not so straightforward. It is both a thesis in the philosophy of thought experiments and also a thesis in empirical psychology. Perhaps prudence should instruct us to assert only (1a) and remain agnostic on (1b), awaiting the verdict of empirical work in psychology. Indeed, (1a) with agnosticism on (1b) already amounts to a strongly empiricist restriction on what thought experiments can teach us. However, it seems to me that this contracted account is unnecessarily timid. There are several indications that favor (1b).

In spite of their exotic reputation, thought experiments convince us by quite prosaic means. They come to us as words on paper. We read them and, as we do, we trace through the steps to complete the thought experiment. They convince us without exotic experiences of biblical moment or rapturous states of mind. At this level of description, thought experimenting does not differ from the reading of the broader literature in persuasive writing. A long tradition in informal logic maintains that this activity is merely argumentation and that most of us have some natural facility in it. The text prompts us to carry out arguments tacitly and it is urged that reconstructing the arguments explicitly is a powerful diagnostic tool. I merely propose in (1b) that matters are no different in thought experimenting. Parsimony suggests that we make this simplest of accounts our default assumption.

Thesis (1a) supplies a stronger reason for accepting (1b). Whatever the activity of thought experimenting may be, if we accept (1a), we believe that the reach of thought experimenting coincides exactly with the reach of argumentation. If thought experimentation opens up some other channel to knowledge, how curious that it should impersonate argumentation so perfectly! How are we to explain this coincidence, if not by the simple assumption that thought experimenting merely is disguised argumentation? Analogously, we would accord no special powers to a clairvoyant whose prognostications coincided precisely with what could be read from our high school graduation year book. We would strongly suspect a quite prosaic source for the clairvoyant's knowledge.

Thought experiment – anti thought experiment pairs This account of the nature of thought experiments can readily accommodate the existence of these pairs. We can have two arguments whose conclusions contradict. It then follows that at least one of the arguments is not sound; it has a false premise or a fallacious inference. The diagnosis is the same for a pair of thought experiments that produce contradictory outcomes. The argument of at least one of them has a false premise or fallacious step, and we resolve the problem by finding it. Thus the existence of these pairs presents no special obstacle to the reliability of thought experiments. If they fail, they do so for an identifiable reason, although finding the false premise or fallacy may not be

easy. Thought experiments have the same transparency and reliability as ordinary argumentation.

2.4 The Reliability Thesis

There is a further justification for the epistemology of thought experiments advocated here and it is independent of empiricism. It is summarized as follows:

(2) *Reliability thesis.* If thought experiments can be used reliably epistemically, then they must be arguments (construed very broadly) that justify their outcomes or are reconstructible as such arguments.

The thesis will be explained and justified below. To preclude confusion, I stress here that this thesis invokes a notion of argumentation that is far more general than the one usually invoked in logic texts, so the claim is weaker than it may first appear. In addition, however, I will suggest below that the efforts of logicians to codify new inferential practices ensures that the presently familiar logics of deduction and induction will in practice suffice as the logic of present, reliable thought experiments.

Reliability Thought experiments are commonly taken to be more than just generators of interesting hypotheses. Thought experimentation is also taken to be a reliable mode of inquiry. I take this to mean that we can have good reason to believe the outcome of at least some thought experiments; that is, there is a way of using thought experiments so that we do have grounds for believing their outcomes.

We would feel licensed to believe in the reliability of thought experiments if their conclusions were inerrant, or at least almost always so. Take an oracle as an analogy. We might not know how the oracle works, but we would have good grounds for believing its reliability if it has a very strong history of successful predictions. The complication with thought experiments is that we have no such history. Thought experiments have proven far too malleable. Proponents of virtually all scientific theories, from the profound to the profoundly false, have had little trouble calling up thought experiments that speak in their favor. The existence of thought experiment – anti thought experiment pairs displays the problem vividly. The situation is more to akin to a plethora of oracles wildly generating predictions indiscriminately and willing to foresee whatever touches our fancy. So why do at least some of us believe that thought experiments can be used reliably? Is there a mark of reliability for the trustworthy thought experiments? Such a mark is possible, but it will require a small detour to find it.

The most general notion of a logic It is easy to think of logic as some fixed domain of inquiry, so that when we seek to reconstruct a thought experiment as an argument, we must rely on a fixed codification of logic that is already in the logic literature. This view underestimates the ingenuity of logicians and the fertility of logic. In recent centuries, the history of logic is a history of growth. Deductive logic has grown from the simple syllogistic logic of Aristotle through to many variant forms of predicate

logic and symbolic logic. Inductive logic has grown from the much maligned enumerative induction to a bewildering abundance that spans from elaborations of enumerative induction to accounts that draw on the resources of the mathematical theory of probability. Sometimes the growth is driven merely by the recognition that this or that extension of an existing logic is possible. On other occasions it is driven by the recognition that there are uncodified argument forms in use. Over the past one or two centuries, as science has become considerably more complicated, so have the inductive maneuvers of scientists. This has been a stimulus for the growth of the inductive logic and confirmation theory that seeks to systematize their methods of inference.

How far can this extension of logic go? We have gone too far if we say that we have a new logic, but all we do is to supply a list of valid inferences, without any apparent connections between the inferences on the list. For the extension to count as a logic, there must be some systematic, identifiable feature of the allowed inferences so that we can distinguish the valid from the invalid. In the new logic, a valid argument will have two parts: the identifiable feature and the aspects peculiar to the particular inference at hand. This is just the familiar distinction between the form and content of an argument; that is, the distinction between a schema and the propositions, terms, and the like inserted into its slots. To count as a logic in this most general sense, the specification of the admissible forms must admit some systematization; for practical reasons, we would hope that they are tractable and communicable.

As far as I can see, this systematizable distinction of form and content is all we need to say that we have a logic in the most general sense. One might be tempted to impose further restrictions. But naturally arising restrictions seem to me to be too restrictive. We might demand that the content must be finite sentences formed from a finite alphabet of symbols, as in traditional symbolic logics. But that would exclude Bayesian confirmation theory, currently the most popular form of inductive logic, for its content may include real-valued functions of continua (probability densities) that represent belief states. Or, in keeping with the notion that logics are truth-preserving and not truth-creating, we might demand that the arguments be supplied with premises that are independently known to be true. But that would contradict a standard practice in deductive logic of using tautologies as premises, where tautologies are sentences that the logic itself assures us are true in the sense of being assertable. Or we might want to insist that the argument forms licensed not be too indiscriminate; they should not end up licensing contradictions, for example. But specifying what counts as "too indiscriminate" might be difficult. Indeed, standard inductive argumentation can end up licensing contradictions. (Consider enumerative induction on the white swans of Europe and then on the black swans of Australia.) So, rather than denying the honorific term of "logic" to such indiscriminate systems, we should think of the indiscriminate logics merely as less useful and eschew them, much as we might ignore a logic, at the other extreme, that is so discriminating as to license nothing.

The mark We now seek the mark that identifies successful thought experiments, that is, those that succeed in justifying their outcomes. Without it, we have no way of determining whether some new thought experiment will succeed in justifying its result; and no way to check that a claim of successful justification is properly made.

The mark cannot be something external to the thought experiment; that is, something about the person who authors the thought experiment or about the context in which it is proposed. A thought experiment is quite portable and moves wherever its written account goes. Independently of its history, we read the account of the experiment; recreate it in our minds; and decide its success or failure. So the mark must lie within the thought experiment itself.

What can this internal mark be? It cannot reside in the brute fact that this *one* thought experiment succeeds; or in the brute fact of the success of some disparate collection of thought experiments. Exactly because they are *brute* facts, they would have to be supplied externally – a separate certificate of truth that must be carried with the thought experiments to assure the reader of their success. The internal mark must be some identifiable property of a successful thought experiment shared with others, or some identifiable relationship between the successful thought experiments. The mark cannot embrace everything in the thought experiment. Some elements can be freely changed. Einstein's celebrated elevator may be wood or steel or brass. So a successful thought experiment has a structural property shared by other successful thought experiments and freely variable content. But that demand is just that thought experiments be governed by the very general notion of a logic introduced above, by schemas into which we can insert freely variable content. The mark is just that the thought experiment either uses an argument form licensed by a logic or can be reconstructed as one.

The mark designates which thought experiments succeed in justifying their results. So we should not expect the associated logic to be a wildly arbitrary codification of admissible arguments. If we are to recognize the logic as delimiting the successful thought experiments, there must be something in the logic that evidently confers the power of a thought experiment to justify its conclusion. For example, deductive logics are characterized by their preservation of truth and inductive logics by the preservation of its likelihood, so that a thought experiment using these logics will have a justified outcome if it proceeds from true premises. In addition, we should expect the schemas of this logic not to be very complicated, so that they can be used tacitly by those who have the knack of using thought experiments reliably.

In sum, we expect thought experiments to be governed by a simple logic that licenses the ability of a thought experiment to justify its outcome.

Will the familiar logics suffice? An evolutionary argument The reliability of thought experiments leads us to conclude that thought experimentation is governed by a generalized logic. However, it does not prescribe the nature of the logic beyond the expectations that it underwrite justification and be sufficiently tractable for use. In principle, the logic may be of a very exotic type. We shall see below that some accounts portray thought experiments as manipulating mental models. Perhaps they are accompanied by their own exotic logic. That eventuality would be quite in accord with my view of thought experiments as arguments. Indeed, it would be a nice extension of it.

However, I think there are some reasons to believe that no new, exotic logic is called for. In outlining the general notion of logic above, I recalled the evolutionary character of the logic literature in recent times. New inferential practices create new niches and new logics evolve to fill them. Now, the activity of thought experiment-

ing in science was identified and discussed prominently a century ago by Mach (1906) and thought experiments have been used in science actively for many centuries more. So logicians and philosophers interested in science have had ample opportunity to identify any new logic that may be introduced by thought experimentation in science. So my presumption is that any such logic has *already* been identified, insofar as it would be of use in the generation and justification of scientific results. I do not expect thought experiments to require logics not already in the standard repertoire. This is, of course, not a decisive argument. Perhaps the logicians have just been lazy or blind. It does suggest, however, that it will prove difficult to extract a new logic from thought experiments of relevance to their scientific outcomes – else it would already have been done!

The case against the likelihood of a new logic is strengthened by our failure to identify a thought experiment in science that cannot be reconstructed as an argument using the familiar corpus of deductive and inductive logics. My own view is that thought experiments justify by means already employed more generally in science, which makes it even more likely that their implicit logic has already been investigated and codified.

Independence from empiricism We have inferred from the reliability of thought experiments to the outcome that they are arguments or reconstructible as arguments. This inference does not require the presumption of empiricism. Assume for a moment that thought experiments do somehow tap into a nonempirical source of knowledge. Since they can err but, we believe, can still be used reliably, the above analysis can be repeated to recover the same outcome.

2.5 Alternative Accounts of Thought Experiments

Challenges So far, I have tried to show that the notion of thought experiments as picturesque, disguised arguments allows us to develop a simple empiricist epistemology for thought experiments in the natural sciences. As I indicated in the introduction, my concern here is narrowly with the epistemic problem of thought experiments. I have no illusions that portraying thought experiments as picturesque arguments says everything that can be said about them. I do claim, however, that it does supply a complete epistemology in the sense that all there is to learn about a thought experiment's epistemic power can be recovered from considering it as an argument.

There are other accounts of thought experiments and I will try to list the more important ones below. Some clearly contradict the view developed here. Others may be compatible with it, typically assimilated as a refinement of the argument view. My concern in this section is to defend my epistemology of thought experiments. So I will take issue with these accounts only insofar as they contradict that epistemology.

A generic defense In formulating responses to these alternatives, it has become apparent to me that these responses are drawn from a short list of generic responses, which is suggested by my view and which seems flexible enough to accommodate all challenges. Insofar as the alternatives differ from my view, they proffer some extra

factor – let us call it "factor X" – that thought experiments are supposed to manifest but arguments cannot. It is then concluded that:

- thought experiments cannot be arguments, for arguments lack this factor X; or
- the factor X confers some additional epistemic power on thought experiments, so that the account of thought experiments as picturesque arguments cannot offer a complete epistemology.

If thought experiments are picturesque arguments and this view supports a viable epistemology, then the objection must fail. It may fail in one of four ways:

(3a) *Denial*. Thought experiments do not manifest the supposed factor X; or
(3b) *Incorporation*. Arguments can also manifest the factor X; or
(3c) *Epistemic Irrelevance*. The factor X is irrelevant to the epistemic power of a thought experiments; or
(3d) *Unreliability*. A thought experiment cannot employ the epistemic channel proposed by factor X reliably. (Thus, if factor X is essential to thought experiments, they are unreliable epistemically.)

From this list, either responses (3a) or (3b) must succeed to defeat the objection that the factor X shows that thought experiments are not arguments. Any of (3a)–(3d) must succeed to defeat the objection that factor X shows a deficiency in my epistemology of thought experiments. It is quite natural to conjoin (3b) and (3c) for a factor X that can be manifested by particular arguments, while at the same time adding that factor is irrelevant to the epistemic power of the argument. Or we may well want to deny that factor X exists (3a), while also urging that even if it were somehow essential to thought experiments, it would defeat their reliability (3d).

2.5.1 Platonism

Brown (1991, 1993a,b, and this volume) has advanced a radical epistemology of thought experiments. He maintains that the laws of nature reside in a Platonic world and that the right sort of thought experiments allows us to grasp those laws directly. While his epistemology differs in the extreme from mine, I am very sympathetic to one aspect of his project. If you decide to eschew the simple empiricist view that I advocate, then no half measures can suffice. You are committed to explaining how we can gain knowledge of the world without relevant experience of the world. Only a quite radical, alternative epistemology will suffice. Brown has not flinched from advocating such an epistemology. However, as I explained in Norton (1993, 1996), I do not believe that Brown's alternative succeeds.

My criticism, augmented with ideas developed above, follows. Brown's factor X is that thought experiments allow us to grasp directly the Platonic world of laws. Several of the responses (3) are applicable.

(3a) Denial. I do not believe that there is a world inhabited by Platonic laws. Since the debate over such worlds extends well beyond our concerns here, I will restrict

myself to noting that nothing in the phenomena of thought experiments requires such Platonic worlds and the associated Platonic perception. I have tried to show elsewhere (Norton, 1996) that Brown's favorite examples of Platonic thoughts experiments can be accommodated quite comfortably in my view. And, as I suggested above, if an austere empiricist epistemology of thought experiments succeeds, it should be accepted as the default.

Let us set aside doubts about the Platonic worlds. Even if we accept the existence of such worlds, it is a serious problem for Brown's account that we have no systematic understanding of how Platonic perception works and when it works. The difficulties arising from this opacity can be expressed in two ways:

(3b) Incorporation. Might it simply be that argumentation is *the* way of accessing the Platonic world? Then Brown's account of thought experiments would be annexed by the argument view and his account would persist only as a commitment to a superfluous ontology.
(3d) Unreliability. When a thought experiment depends upon Platonic perception, if the perception is more than mere argumentation, we have no way of knowing internal to the thought experiment that the perception was successful and that misperception did not occur. The epistemology of Platonic perceptions provides no means of adjudicating the competing claims of thought experiment – anti thought experiment pairs.

Brown (1991, pp. 65–6) tries to deflect these concerns over the opacity of Platonic perception by drawing an analogy with ordinary perceptions. The latter are accepted even though the full process from vision to belief formation is still poorly understood. I also accept Brown's (1993a) rejoinder to me that ordinary perceptions were credible well before we had the elaborate modern accounts of perception, such as vision as the reception of photons in the retina, and so on. The crucial disanalogy, however, between the two forms of perception pertains to reliability. With ordinary perception, even rudimentary experiences quickly give us abundant indicators of when ordinary perceptions will succeed or fail. Sight fails if we cover our eyes, but only depth perception suffers if we cover just one eye; sight, sound, and smell are enhanced by proximity and weakened by distance; sight is compromised by weak light, but smell is enhanced by favorable breezes – and so on, in innumerable variations. With Platonic perception, we have nothing whatever comparable to tell us when we perceive or misperceive.

The "disproof" of the continuum hypothesis Brown has conceived an ingenious candidate for a Platonic thought experiment in his chapter in this volume (see chapter 1). While I do not agree that the example succeeds, we do agree that the crucial phase is the establishment of what Brown (forthcoming) calls the Freiling Symmetry Axiom (FSA). It asserts that for every function f that maps real numbers onto countable sets of real numbers, we can always find a pair of reals x,y such that y is not in $f(x)$ and x is not in $f(y)$. It turns out to be equivalent to the negation of the continuum hypothesis.

Brown attributes a recognition of the truth of FSA to Platonic perception. Insofar as it works at all, I just find it to be the result of prosaic argumentation of an informal kind – just the sort of thing I say arises commonly in thought experiments. The recognition depends on seeing that there is a zero probability of picking a number at random from a measure zero set. We infer that result from reasoning by analogy with dart throws. On a real dartboard, there is only a small probability of hitting the thin wires. The probability drops to zero for infinitely thin wires, the analog of a measure zero set.

Brown also urges that there is no precise, formal mathematical argument that corresponds to this thought experiment. I would not be troubled if he were right, since I have always urged that thought experiments may be informal arguments. However, Brown has misstated the relevant mathematics. FSA cannot be derived as a theorem of Zermelo–Frankel set theory with the axiom of choice, where we understand such a theorem to be a result that can be derived without additional premises. However, it certainly could be derived if suitable, additional premises were allowed. Given the liberal amount of vague additional material introduced in the discussion of dart throws, I don't see how to rule out that such premises are not already at hand.

Finally, although it is again immaterial to the issues that separate us, I believe that our dart-throwing intuitions do not allow us to arrive at FSA after all, whether by argument or Platonic intuition, and the entire disproof is mistaken (see Norton, forthcoming).

2.5.2 Constructivism

Kuhn (1964) and Gendler (1998) have described how thought experiments can serve the function of revealing problems in and allowing reform of a scientist's system of concepts. As Kuhn (1964, p. 252) suggests, these thought experiments teach scientists about their mental apparatus instead; so they avoid the problem of teaching us about the world without drawing on new information from the world. For example, Kuhn recalls thought experiments due to Galileo that force Aristotelians to distinguish the concepts of average and instantaneous speed. Gendler also analyses a celebrated thought experiment of Galileo's that forces Aristotelians to see the incompatibility of assuming that heavier masses fall faster, but conjoined masses fall at an intermediate speed. The escape is the recognition that all bodies fall alike.

This constructivist view is interesting and important. From the epistemological point of view, I have two reactions. First, whatever its merits may be, the view cannot supply a complete epistemology of thought experiments in science. There are many thought experiments in science that do not yield a reform of the scientist's conceptual systems. Thought experiments may merely demonstrate results within a theory. (Mach (1893, p. 269) uses one to show that his definition of equality of mass must be transitive, else energy conservation will be violated.) This yields the response *(3a) Denial* insofar as not all thought experiments manifest this factor X.

Secondly, Gendler (1998, sections 3.1 and 3.2) has urged that mere argumentation cannot reconfigure conceptual schemes, the factor X of the objection. As far as I can tell, however, the constructivist reconfiguring is fully compatible with the view that

thought experiments are arguments.[6] So my response is *(3b) Incorporation*. I base this on the well known power of argumentation to produce the reform of conceptual schemes. A celebrated and quite profound example is supplied by Russell's paradox of naïve set theory. A basic principle of naïve set theory is that any property defines a set – those entities that manifest the property. Russell revealed the untenability of this conception in a celebrated *reductio ad absurdum*. If the principle holds, then the set of all sets that do not have themselves as a member is a legitimate set. But it has contradictory properties. It follows quickly that this set must both be a member and not be a member of itself. The *reductio* is complete; the principle must be rejected; and our conceptual system is profoundly changed.

Now there are complications in this change. Any *reductio* argument ends in a contradiction. In principle, any of the premises of the argument – tacit or explicit – may be taken to have been refuted. In each case we arrive at a different consistent subset of beliefs. Analogously, for any given set of premises we may derive arbitrarily many conclusions; pure logic alone cannot tell us which we should derive. Just as the format of the premises may suggest that we draw one conclusion rather than another, so the rhetorical formulation of a thought experiment may direct us to one result rather than another. Contrary to Gendler, I do not see any special epistemic power in this fact. Is the proposal that the format of the thought experiment somehow directs us to the true consistent subset of beliefs in a way that transcends the reach of argument?[7] How does it accrue this power?

The alternative account offered by Gendler (1998, pp. 414–15) is that the reconfiguration is arrived at by "a sort of *constructive participation* on the part of the reader"; "the person conducting the experiment asks herself 'What would I say/judge/expect were I to encounter circumstances XYZ?' and then *finds out* the apparent answer" (her emphasis). My concern is the reliability of this procedure. Insofar as it involves anything more than argumentation, why should the results of such introspection be credible? Gendler mentions Mach's idea of stores of tacit experiential knowledge. Even if we tap into these, they must be converted into the final result. If the conversion is not through argumentation, then how is it truth-preserving? How can constructive participation allow us to adjudicate thought experiment – anti thought experiment pairs? In short, if the reconfiguration is not effected by argumentation, my response is *(3d) Unreliability*.

2.5.3 Visualization and simulation

Thought experiments seem to tap into an uncanny ability of the mind to simulate the real world. As we engage in the thought experiment, we watch an experiment unfold not with our real senses but with our mind's eye in the laboratory of pure thought.[8]

6 Boorsboom et al. (2002) similarly underestimate argumentation when they claim that a particular thought experiment in probability theory cannot be reconstructed as an argument, since it is not a derivation within a theory but creates a conceptual framework for a theory.

7 This seems to be the import of Gendler's (1998, section 2.4) reflection that the Galilean thought experimenter ignores many logically admissible escapes from the *reductio* contradiction.

8 Gooding (1992, p. 285) writes: "Visual perception is crucial because the ability to visualize is necessary to most if not all thought experimentation."

Should we look to this power to underwrite the epistemic prowess of thought experiments, our elusive factor X? I think not. This prowess cannot be sustained *solely* by the mind's power of visualization or, more generally, simulation. If that were all that counts, I could readily concoct a spurious thought experiment in which the conservation of energy is violated. In my laboratory of thought I connect the shaft of an (elaborately imagined) rapidly turning electric motor to an (elaborately imagined) generator; and then I direct the electric current generated through wiring back to the motor; and I note that in my mental simulation there is surplus electrical power, as revealed by the positive reading on a (shiny brass) wattmeter. Examples such as this show that any epistemic power attributed to the mind's ability to visualize or simulate must at best be subsidiary.[9] An account that tries to explicate this subsidiary epistemic power must face the problem that the mind can visualize or simulate quite spuriously; it must explain how such visualization can be epistemically potent in one case and not in another (such as in the case of thought experiment – anti thought experiment pairs) and how we are to adjudicate.

My view is that it is merely rhetorical window dressing that, for psychological reasons, may well ease acceptance of the result. In many cases, this superfluity is easy to see, since the elements visualized can be supplied in many ways that will not affect the outcome. When Galileo's Salviati imagined a large stone and a small one dropped from a tall tower, he could equally have imagined a cannon ball and a musket ball, or a brick and pebble. All that matters is that one is heavier than the other and neither experiences much air resistance. The epistemic power of the thought experiment comes from what is common to the many formulations – the argument. The variable details, visualized so powerfully, are epistemically neutral; changing them does not change the outcome. In sum, my response to much of the talk of visualization and simulation is to dismiss it as irrelevant epistemically – *(3c) Epistemic Irrelevance*.

2.5.4 Mental models

There is an exception to this last response. In a most promising approach, Nersessian (1993) and Palmieri (2003) call on the literature on mental modeling in cognitive science to explicate mental simulations in thought experiments. This literature accounts for the relevant cognition through the formation of mental models that guide our cognition. An extremely simple example – a further simplified version of Johnson-Laird (1989, p. 472) – is drawn from two assertions:

> The fork is to the left of the plate.
> The knife is to the right of the plate.

They allow formation of the mental model

Fork Plate Knife

9 Arthur (1999, p. 228) endorses a subsidiary epistemic power in visualization when he concludes "... I do not think thought experiments are simply reducible to arguments without epistemic loss ... Thought experiments go beyond arguments in providing an easily visualizable – or ... graspable – imaginative reconstruction of the phenomenon at issue."

This mental model in turn licenses further assertions, such as

The plate is to the right of the fork.
The fork is to the left of the knife.

If these mental models can somehow be grounded properly in experience, then why should they not produce knowledge of the world if they are used in thought experiments? For me, the real question is how they can do this *reliably*. Here's how. These models are built from templates into which we slot particulars. In the above example, the template is

Object 1 Object 2 Object 3

and we substitute fork/plate/knife for object 1/object 2/object 3. If this template correctly reflects the nature of space, then the resulting model can be used reliably. But now we see immediately that this reliability is purchased exactly by incorporating just the sort of generalized logic discussed above in the context of section 2.4 ("The Reliability Thesis"). The templates are just the schema of a generalized logic. Thus my response is *(3b) Incorporation*. Use of this mental model literature implements exactly the sort of generalized logic that I had in mind. Knowledge of the world enters the thought experiment in the factual templates that ground the physical scenarios imagined.[10]

In principle, mental models may function this way in thought experiments. However, the case is yet to be made. That mental modeling might be a good account of ordinary cognition does not entail that it is a good account of thought experiments, a highly contrived activity within science with a deceptively simple name. What tempers my optimism is that I know of no example of a thought experiment in science that depends essentially on such mental modeling; or at least all the good candidates I have seen are indistinguishable from argumentation concerning pictures and schemes, much as proofs in Euclidean geometry are just arguments about certain figures. And there are many cases in which the core of the thought experiment is an explicit mathematical derivation in a physical theory and that is *unambiguously* an argument. (An example is Bohr's version of Einstein's clock-in-the-box thought experiment: its essential content is the computation of a relativistic correction to the timing of a process – see Bishop (1999).)

What of the remaining cases in which the decision is unclear? Mental modeling and traditional argumentation can be very close and thus hard to distinguish. Cognitive theorists allow that the supposed mental models of thought experiments can be reconstructed as arguments. The reverse may also be possible: the explicit argumentation of thought experiments can be simulated by mental models. Which is it? When they are close, I favor argumentation, since thought experimentation is a far more highly refined activity than simple cognition about the placing of knives and

10 That templates in logic can also be contingent is actually quite familiar. It is a contingent fact that "If something is human, then it is mortal." That fact licenses inferences as well. From "Socrates is human." we are licensed by it to infer to "Socrates is mortal."

forks on a table. It must be unambiguously communicable in a few words, and its outcome objectively verifiable – conditions that suggest a need for something more secure, such as argumentation. Or perhaps the evolutionary processes described above in section 2.4 ("The Reliability Thesis") have already culled out from the generalized logic of mental models those logics that might explicitly serve science.

I leave the matter to those with expertise in cognitive science, since either way I believe that characterization of thought experimenting as argumentation survives, if the activity is to be reliable. However, the scope of the program is limited by the presence of explicit argumentation (as derivations within theories) at the heart of many thought experiments.

2.5.5 Experimentalism

Thought experiments are so named since they mimic real experiments, the ultimate epistemic channel to the world, at least in the empiricists' view. Might thought experiments attain some epistemic power from their mimicking of this ultimate ideal? Experimentalism answers that they do. This mimicry is the factor X. My principal response is *(3c) Epistemic Irrelevance*. The reason is simple and obvious. Mimicking an experiment is just not the same thing as doing an experiment; one doesn't learn about the world by the mere fact of feigning contact with it. Here, I set aside whether *(3b) Incorporation* is also an appropriate response, since I do not want to decide what it takes for a thought experiment to be experiment-like in the way that (purportedly) gains it epistemic powers. Certainly, if all that is required to be experiment-like is that the thought experiment describe an imaginary experiment and even trace its execution, then that can be done by an argument.

There are two general accounts of how thought experiments gain epistemic powers from their experiment-like character. Sorensen (1992, p. 205) defines a thought experiment as ". . . an experiment . . . that purports to achieve its aim without the benefit of execution." They have the power "to justify beliefs in the same fashion as unexecuted experiments" (p. 213). And this last power derives from the fact that ordinary experiments persuade (justify?) in two ways: first, by "injection of fresh information about the world"; and, secondly, by ". . . armchair inquiry: by reminder, transformation, delegation, rearrangement, and cleansing" (p. 251). Thought experiments avail themselves of the second mode only. Insofar as the second is merely a synonym for argumentation, perhaps from tacit knowledge, then obviously Sorensen's view would accord, in the end, with the argument view. But Sorensen apparently does not accept that thought experiments are arguments.[11] Recalling the discussion of section 2.4 ("The

11 More precisely, he refuses to reply with "direct denial" (p. 214) and proceeds instead with a rather transparent evasion of the question. He offers a "parity thesis": "thought experiments are arguments if and only if experiments are arguments" and urges that, if we believe that thought experiments are arguments, we must take the burden of proving that real experiments are arguments. What makes the evasion curious is that there seems no strong reason to accept the parity thesis. It is not even clear what it asserts. Does "[real] experiments are arguments" mean that they are *entirely* arguments, a claim that is obviously false? Or does it mean that real experiments contain *some* argumentation, a claim that would be easily sustained if we allow that the notion of experiment includes even some minimal interpretation of the raw data read by the experimenter?

Reliability Thesis") above, this invites the response of *(3d) Unreliability*, unless Sorensen can offer another reliable, truth-preserving way of transforming or rearranging what we are reminded of.

The second account accords epistemic power to a thought experiment through their realizing some idealized limit of actual or possible experiments (for such an account and for examples, see Laymon, 1991). The immediate problem with this account is that it cannot provide a complete epistemology, since many thought experiments are not idealized limiting cases.[12] Insofar as not all thought experiments manifest this factor X, the response is *(3a) Denial*. In those cases in which the factor X is present, the obvious response is *(3c) Epistemic Irrelevance*. Unless we are simply inferring the results from the properties assumed of the ideal limit, why should our imagining of this limit have any epistemic power? I will not pursue this line since Laymon (1991) seems to agree, insofar as he analyses thought experiments as tacit argumentation.

2.5.6 Other views

The survey above omits a number of views.[13] Most prominent of these is that of Mach (1906). He accounts for thought experiments as the manipulation of instinctively gained raw experience by a few simple schemes, such as variations of the conditions that determine the result. For example, he considers (p. 138) the distance above the earth of a falling stone. If that distance is increased in thought to the height of the moon, we would still expect the stone to fall in some diminished degree, suggesting that the moon, which is composed of many stones, also falls toward the earth. The difficulty with Mach's view is that it is readily assimilated to nearly all viewpoints. I see his raw experience as supplying premises for the arguments that implement the manipulations. Nersessian (1993, p. 292) sees much in common between Mach's and her view. Gendler (1998, p. 415) calls on Mach for help in one stage of her account. Sorensen (1991) finds an evolutionary epistemology in Mach. So I am not sure how to categorize it.

Bishop (1999) has proposed a most ingenious demonstration of why thought experiments cannot be arguments. He reflects on Einstein's celebrated clock-in-the-box thought experiment, which was conducted in a classical spacetime. Bohr replicated it in a relativistic spacetime and recovered a different outcome. It is the one thought experiment, Bishop urges, but it must be reconstructed as two arguments; so thought exper-

12 For example, a thought experiment quickly establishes that the time reversibility of physical law is not directly expressed in the phenomena. The phenomena manifest a decided unidirectionality in time. To see this, we need only imagine that we locate a familiar process in a device capable of reversing its time order. If the device is large enough to host a banquet, we would find elegantly dressed diners regurgitating the content of their stomachs, chewing it back to pristine morsels and modestly conveying them back to their plates with their forks – a process compatible with the physical laws but otherwise never seen. The thought experiment does not employ a continuous approach to some ideal limit, such as the gradual elimination of friction. Indeed, the thought experiment is more effective the more we avoid idealization; that is, the more realistic we make the processes subject to time reversal.

13 See also Kühne (2001), which includes an account of Oersted's views on thought experimentation. I also pass over McAllister's (1996) claim that thought experimentation is evidentially inert unless one accepts a Galilean doctrine of phenomena, since the view does not supply an alternative epistemology but explores the foundations of all epistemologies of thought experiments. For criticism of his view, see Norton (forthcoming).

iments cannot be arguments. In my view, the difficulty is that Einstein and Bohr *do* have two different, but similar, thought experiments; and they correspond to two different, but similar, arguments. We can convert the two thought experiments into one by ignoring the different spacetimes of each. The different spacetime settings are then responsible for the different outcomes. If that is admissible, then the same stratagem works for the arguments. Ignoring premises pertaining to the spacetime setting, the two arguments proceed from the same experimental premises. They arrive at different results only because of the differences in the premises pertaining to spacetime setting.

Finally, I also correct a persistent confusion concerning my view. Some (e.g., Gooding, 1993, p. 283; Hacking, 1993, p. 303) report that I demand that the argument in a thought experiment must be *deductive*; others suggest that the argument must be *symbolic* (or so I have seen reported in a manuscript version of a paper); and others (Boorsboom et al., 2002) that the arguments must be derivations within some definite theory. A brief review of what I have written will show that none of these restrictions are a part of my view, which allows inductive and informal argumentation and premises from outside any fixed theory.[14]

2.6 Conclusion

I have defended my view that thought experiments in science are merely picturesque arguments. Their epistemic reach can always be replicated by an argument and this is best explained by their merely being arguments. I have also urged that thought experiments can only be used reliably if they are governed by some sort of logic, even if of a very general kind, and proposed that the natural evolution of the literature in deductive and inductive logic would extract and codify the implicit logic of thought experiments. So thought experiments are arguments, but not because thought experimenters have sought to confine themselves to the modes in the existing literature on argumentation; it is because the literature on argumentation has adapted itself to thought experiments.

This argument view provides a natural home for an empiricist account of thought experiments. Insofar as a thought experiment provides novel information about the world, that information was introduced as experientially based premises in the arguments. The argument view may not be the only view that can support an empiricist epistemology. I have surveyed other accounts above, and at least constructivism, mental modeling, and experimentalism may support an empiricist epistemology. However, I have also urged that these accounts are merely variants of the argument view, insofar as they are viable, and that fact may already account for their hospitality to empiricism.[15]

14 Häggqvist (1996, pp. 89–91) criticizes me precisely because he finds me too lenient in admitting inductive inference into the treatment of thought experiments as arguments.

15 What is my resolution of the thought experiment – anti thought experiment pairs? In the case of the rotating disk, the anti thought experiment fails. A rigid ring cannot be set into rotation preserving rigidity; it would shatter exactly because of the Lorentz contraction. In the case of the infinite rotor, the assumption that is false is that the limit of infinitely many doublings (of the moving rotor) produces a physically admissible system. An air current is required for lift and that is absent in the limit. Sometimes limits can yield nonsense.

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