What is *Experimental* about Thought Experiments?[1]

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1. Reasoning Experimentally

A thought experiment requires neither instrumentation nor embodied actors. Nor does it appear to introduce new empirical information about the world in which it is performed (Kuhn 1962, p. 241). Nevertheless, it presents some previously un-recognized property of that world with a logical force that no real experiment can match. Thought experiments are easy to replicate—this confers an important advantage over real ones, though the real advantage is thought to be that there is no need to conduct a real experiment in place of a thought experiment. From a rationalist position such as Jim Brown's (1991, 1993) thought experiments are either mysterious or else explicable in terms of our ability to intuit natural kinds directly. Empiricists such as John Norton (1991) regard them as disguised deductive arguments whose performance—reconstituted as formal arguments—discloses in the form of premises, information we must already have.

Are thought experiments so special? My answer is a deflationary one: the thought experimental mystique is a mistake. To be sure, thought experiments are useful, powerful elegant and important. Yet there is nothing mysterious about them. Whereas most philosophical treatments make thought experiments quite different from real ones, my analysis treats them as another form of experimental reasoning (Gooding 1990, 1992b, 1992c). I shall argue that the mystique surrounding thought experiments is due to a fact that we can explain: they make replication much easier and more reliable than the material, literary and practical trappings of real experiment ever do.

Consider experimention generally. The force of any experimental test involves criticizing some set of assumptions (usually organized into one or more theories). Experiments test the practicability of doing something in just the way required by the theories in the world as represented by theory. In other words, theory is criticized through the practices that link it to those aspects of the world that it purports to be about (Gooding 1990, chap. 8, Pickering 1989, Rouse 1987). To work as an argument the experiment—whether real or in thought—involves a subtle mix of material- and mental-world manipulations. Empirical criticism is possible to the extent that a TE recovers enough of the situated, contextual knowledge that experimenters need to make experimental processes work in that world. This includes things that they learn

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or can apprehend through being embodied. No experiment can have much impact unless its narrative conveys enough experimenter's know-how to enable replication. Recognizing this framework of understanding makes the persuasiveness of TEs less puzzling than empiricists and rationalists have made out.

Thought experiments are conducted in mental laboratories but they do not thereby cease to be experiments. Our access to most experiments, most of the time, is through narratives. Empirically-informed criticism is possible because experimental narratives invoke—though they need not explicitly recreate—the situated, contextual knowledge experimenters need to make experimental processes work in the world that experiment and theory are meant to share. This experimental know-how must be made accessible to readers so that they can follow the narrative and the transformations it describes, and so become vicarious participants.

Personal participation is essential: it is what makes a thought experiment an *experiment* rather than another form of argumentation. Real experiments (hereafter, ***RE***s) are replicated in the material world, thought experiments (hereafter, ***TE***s) are replicated in thought-worlds. From a naturalistic standpoint this difference is not important. Both kinds of experimentation seek to shift the boundary between the actual and the possible. As Kuhn points out, Galileo did not evade the constraints of an actual world (say, by altering his inclined plane experiment to exclude motion of one sort or other): his TEs involve the world as his interlocutors knew it (Kuhn 1962, p. 251-53).

It might be objected that whereas participation in TEs requires only a literary form of representation, REs require far more in the way of material resources and skill. A consequence of my view is that this rather obvious difference between TEs and REs is much less significant than it appears. The difference between real- and thought- experimentation is important only if we divide the world according to traditional dualist assumptions, that is between mental and physical sorts of stuff; between *a priori* or *a posteriori* knowledge, and so on. Rationalist and empiricist agree that TEs introduce no new information about the world because each wants to explain the novelty that a TE articulates in terms of either *a priori* or *a posteriori* knowledge. Both theories of knowledge therefore emphasize differences between REs and TEs. The separation of the T-experimenter from the world and the generality of his/her conclusions are contrasted to the immersion of real experimenters in chaos and contingency, and to the limited scope of their findings.

Koyré's argument that the innovative potential of TEs in the scientific revolution proves the *a priori* nature of scientific thought turns upon this supposed separation of head from hand and of mind from world and body (Koyré 1965, 1968). Koyré argued that Galileo's invention of the thought-experimental method was the major source of innovation in modern science. I argue a different view. A TE becomes possible when a world is sufficiently well-represented that experimental procedures and their likely consequences can be described within it. So the capacity to disseminate arguments as TEs indicates the extent to which the embodied familiarity with a world developed by a few investigators, has been represented in terms that make it more widely accessible. The presence of effective TEs in a field of inquiry *indicates how well experimenters' embodied familiarity with the world is expressed by their representations of that world.*[2]

Like Nersessian (1991, 1993) I regard TEs as process-narratives to which visualization is essential. Where she has developed a mental-models account of the process, I emphasize the role of embodiment in visualization. If I am right about the importance of embodiment, it follows that—by contrast to material-world experimentation—thought-experimentation has not changed at all since the rise of modern sci-

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ence. As Hacking aptly put it in his contribution to this session, the perfected TE does not have a life of its own (Hacking 1993). To explain the efficacy of TEs in terms of what they have in common with other activities such as argumentation (Gooding 1990, 1992a) is to show *why* they do not have a life of their own.

2. Disembodiment and Sense Experience

Thought experiments allow us to avoid the chaotic world of inchoate experience. They strip that world and its observers of those properties that might complicate analysis, making a new world in which planes are frictionless, spheres become perfect and observers are made perfectly competent. This world is stipulated to be free of the unforseen and usually uncontrollable factors encountered when making new observations in REs, or when established assumptions and practices are challenged (as they are during controversies). For example, if gravitational influence is of no consequence or if magnetic influence has been eliminated, then that remains true and beyond question until the experimenter decrees otherwise.

Observers in this world are usually disembodied. This is where TEs seem to differ most from REs. Since I contend that the effectiveness of TEs is largely attributable to features that they share with REs, we must look more closely at how TEs work. We find that they require instrumentation and embodied actors. This seems to counter two important facts about observation in science. First—bodies are often an obstacle to observation. The best experimentalists have been frustrated by the constraints of being embodied. Faraday made many excursions from his lab-bench into thought, using imagination to probe parts of the world that neither hand nor instruments could reach. In his studies of electrostatic induction, for example, the problem was that to introduce a material probe into the interior of a closed sphere would introduce the possibility of induction, thus destrying the very condition to be determined (Gooding 1990, ch. 9). Joule's experimental measurement of the mechanical equivalent of heat is another striking example. Sibum's recent repetition of these experiment show (1992) that precision was compromised by the presence of observers. Isn't it just as well that TEs allow us to leave our bodies behind? I shall argue that they cannot, in fact, do so.

The second fact is an historical one. If common sense was ever important to science, it ceased to be important to the mature, experimental sciences long ago. Historians have shown how unmediated sense experience became less and less important to scientific argument (and was often subverted by it) and they have shown how observational technologies have also transformed qualitative or observational data into something quite different from the common sense of an embodied observer. The development of each scientific field has involved a shift from qualitative to quantitative representation and away from visual perception and hands-on manipulation to calibrated instruments.

Empiricist philosophies endorsed this process, invoking a distinction between secondary qualities (unreliable because of their variability and subjectivity) and primary qualities. The latter were the real and fundamental qualities disclosed by the methods of the new experimental philosophy.[3] Conventional wisdom says that demoting personal sensory experience as incompetent or ill-equipped for properly scientific observation eroded the relevance of common sense to the arguments of the natural sciences. It has, but the process is far from complete. In order to work as arguments, TE's must make a direct appeal to 'sense'—that is—to ordinary properties of objects (as perceived through ordinary, *unaided* modes of perception) and to the avoidance of paradox (as the infringement of shared assumptions about how things can or must be). This is necessary for their narratives to provide an intelligible, sensory framework for understanding the procedures and phenomena that make up any experiment. This un-

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mediated, common-sense experience is the fulcrum of thought-experimental argument. It follows that, unlike theorizing and material-world experimentation, TEs have not changed since the scientific revolution.

3. Participation and the Experiential Fulcrum

A thought experimenter goes from an actual world to worlds in which other things are possible and returns to an actual world that has been altered by the journey. Why are readers of these travelogs often compelled to see the world differently? The answer lies in the experimental narrative. The new experimental narratives pioneered by Galileo and Boyle enabled readers to make vicarious observations though their mental participation in the practices described (Shapin and Schaffer 1985). This lent credibility to the phenomena reported to be produced by those practices.[4] This literary technology liberated observers from the need to participate physically while preserving their ability to participate mentally. Facts could be disseminated to people who could be of the experimenter's world without having to be in it.

It is still the case that most people—including most scientists—encounter experiments through narratives. The narrative elements of arguments that invoke REs require the same ability to participate. To articulate assumptions so that they can be queried, the TE narrative must extend the experimenter's world to introduce unforeseen possibilities. In order that these novelties be understood, they must be constructed out of familiar elements of experience. Thus TE narratives posit a world—neither so familiar as to foreclose change nor so strange as to provide no footholds or handles on reality. TE's persuade when there is enough strangeness to disturb and enough familiarity to be accessible. As far as novelty is concerned, *familiarity breeds consent*.

An important TE strategy involves criticizing a complex of assumptions (or theory) by showing the impracticability of doing something in the way required by that theory in the world as represented or invoked by that theory. I have shown elsewhere that this is also how real experimentation works (1990, 1992a, b). To bring the impracticability of certain actions to bear in argument, the author of a TE selects just those features of a phenomenon, the environmental framework and the conceptual scheme that are *mutually* problematic. The demonstrative power of this type of TE depends on creating a situation in which most moves or manipulations are wholly transparent while certain other moves are either impracticable or, if practicable, lead to paradoxes. Examples are Faraday's electrical mites argument about the relativity of measurements of electrical charge and Einstein's 1905 argument about the relativity of simultaneity: in both cases the argument turns on creating a world in which certain procedures cannot be carried out (Gooding 1985, pp. 128-30). The force of these arguments turns not on logical contradiction, but on impracticability or on the paradoxes generated by attempts to overcome it. This sort of TE helps to articulate intuitions which, once they have been exposed, can be made into a propositionally-represented argument. Reconstruction as a deductive argument may be illuminating, but it is not necessary (as Norton's (1991) analysis seems to require). TEs involve other types of reasoning and argument and—as Hacking points out—these can be compelling without being cast into a deductive form.

To explain the force of an experiment it helps to understand it as a process to be worked through, rather than as a logical structure. I suspect that logical reconstruction is possible only when the working-through has been successfully completed. Hacking's example from Leibniz illustrates this nicely (Hacking 1993). To understand the process it is necessary to understand the world that is invoked in order for the process to be possible. That world is invoked and defined by an experimental narrative. Whether the experiment as narrated has been conducted in thought or in the material world, that

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world is constituted whenever and wherever the experiment is performed. It must be possible to construe its less familiar features through familiar ones. I now argue that to establish this familiarity presupposes knowledge of a sort that *embodied* actors have.

Consider the sort of knowledge we must have in order to be able to experiment at all. The development of a new pictorial language to describe the behaviours of electricity and magnetism drew on a variety of skills and resources, including intimate, first-hand knowledge of the behaviours of electrified and magnetized objects (Gooding 1989a, esp. pp. 208-16). The representational capability of experimental narratives is not a given: it is crafted. The authors of succinct, transparent and compelling narratives must have been intimately involved with the worlds they want to enable others to explore vicariously. As one particle physicist puts it, "Beauty comes from the dirt".[5] To be involved in this way is to reason experimentally—that is, to *find out* about some world, rather than to demonstrate facts or general truths about it. The possibility of reliable demonstration depends on *learning the world* in the way that, for example, Faraday's laboratory notes show him learning about the *minutiae* of electrostatic phenomena. The closeness of his involvement is apparent from the many procedural refinements he needed to make in order to experiment at all (Gooding 1985 and 1990, chap. 9). Experimental reasoning includes tinkering, thinking about doing, and so on. TE's also capture something of this exploratory spirit of experimentation: we do not know beforehand quite where the excursion will lead. In this respect, as Hacking notes, they work in the same way that jokes do.

4. The Ascent from Embodied Sensation

Of course, most experimental reasoning would not count as thought experimentation, even on a less strict criterion of argument than Norton's deductive reconstruction requirement. Nevertheless, the importance of this personal knowledge to both the construction and the accessibility of thought-experiments should not be underestimated. That it is so neglected has much to do with philosophers' preoccupations with objective, *im*-personal knowledge. It has little to do with the nature of science research, as distinct from science pedagogy. A TE narrative has a pedagogic role which can be accomplished without recreating all of the sensory scaffolding with which it was constructed. In this respect TEs resemble exemplary, text-book versions of REs. References to clocks and rods (and the illustrations that show how they are used) are replaced by systems of coordinates. These are replaced by equations that make transformations between them. Sense experience and practical knowledge become superfluous. Some of the enabling experience must be rediscovered by novices as they learn to reproduce the procedures that led to innovation.[6] To acquire experimental competence requires skills—disciplining the senses as well as the mind to respond as uniformly as possible in contrived situations. A TE therefore functions more like a perfected, 'black-boxed' instrument than like a competently performed RE.

It might be conceded that TE's need an experiential fulcrum as well as a logical one, yet still denied that a TE world must include embodied agents. Since TEs address our intellect through our mind's eye and not through our bodies, won't passively perceiving minds suffice? I think there is a necessary connection: what makes experimental narratives compelling *depends on* what makes them accessible to the mind's eye. This connection is far from obvious.

5. Is Seeing Sufficient?

Let us return to the narratives that enable vicarious witnessing of experiments. The main difference between TE and RE narratives is one of complexity: TE narra-

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tives are much simpler than those of REs. Simplicity is achieved by editing out all possible sources of error—all contingent or context-specific factors— bodies and all. To achieve representations and to think with and about them is to ascend from embodied personal experience. We are so used to thinking that this confers an epistemological advantage that it is difficult to see any connection—never mind a necessary connection—between having a body and the ability to reason with universals and to make judgements about similarities and differences.

TEs do address our intellect through the mind's eye. This appeal to the primacy of vision makes the experimenter's *judgement* rather than his or her embodied state crucial to understanding and accepting new knowledge. This makes the embodied state imperceptible. Recalling the problematic nature of secondary qualities and of observer effects, this would seem to be a good thing: the variability of personal sensation is a well-known source of error in real-world observation. In addition to being unreliable, perception is also ambiguous: sensations can be construed in various ways. Thus there is no guarantee that a given stimulus will produce the same percept in each observer —even when an authoritative source is active, such as the instructor in a laboratory class, or in the making of microscope observations (Gooding 1986, 1989, 1990 chap.1).

Visual perception is crucial because the ability to visualize is necessary to most if not all thought experimentation. By tacit convention, it is taken to be sufficient as well. Visualization is governed by another important convention: that all perceptual experience is unambiguous and unproblematic. There are no optical illusions in TEs. Moreover, what the eye perceives is wholly transparent to the mind. TEs deal with the problematic relationship between sensation and perception by banishing the former entirely. Visualization in a TE is guaranteed by the infallibility and transparency of perception. It is as if T-experimenters perceive the relevant properties only as primary qualities, or with the viridicality that primary qualities would be perceived, if they could be perceived directly by us instead of by our instruments.

In this way TEs create a set of perceptions which, though different from those of ordinary experience, can inspire the same confidence as common-sense perception. However, the focus on purely *visual* perception has drawn attention away from other kinds of perceptual experience on which visual perception depends. These presuppose embodiment of a sort that permits intervention in, not merely passive observation of, the world. Thought-observers are not deprived of these other sensations. They must be able to imagine feeling weightless; feeling and seeing the effect of gravity on a ball; they must see flashing lights well enough to make judgements about their simultaneity. How does an experimenter perceive that Maxwellian demons can interact with gas molecules if not through having interacted with similar (macroscopic) objects? The experimenter can 'see' directly, transparently, that (say) a collision involves a perfectly elastic recoil. Here many complex perceptual processes and theoretical judgements are distilled into one simple statement of the nature of the entities and their interactions. The experimenter *knows* that such is the case, without having to observe at all. Knowledge of a perfectly elastic recoil is not given through sensation: it combines ordinary experience of imperfectly-elastic objects with propositionally represented definitions. Behind this knowing also lies a great deal of embodied, real world experience. I contend that T-experimenters must have learned enough about a world of one kind (through vision, touch and hearing) to access other, less familiar worlds. The very possibility of participating depends on familiarity with ordinary perceptual experience of any kind. T-experimenters must be *at home in their bodies*.

Access to the implications of some thought-world requires something besides *a priori* principles and empirical intuitions. In his study of scenes from deep time in

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19th century natural history, Rudwick shows that the persuasive force of the images owes a great deal to the embodied, human viewpoint. He argues that the power of this genre depended not on its contrivance of the human viewpoint, but on the tacit concealment of its contrived status (Rudwick 1992, chap 7). Familiarity with the perceptual furniture of a TE is similarly tacit and, therefore concealed. It must remain so to preserve the cognitive efficacy of the account. Making experimenters aware of their dependence on these other kinds of experience would reintroduce particularities of practice and vagaries of competence—the very sources of error that a TE must avoid in order to achieve generality for its conclusions. The epistemic role of the tacit status of embodied competence has parallels in real experimentation, for example, in the way that Faraday made human artifice disappear from his demonstrations, so as to present their effects as self-evidently *natural* phenomena (Gooding 1985).

6. Illustrating Embodiment

I have argued that the transparency of an experimental situation depends tacitly upon experience acquired through non-visual forms of perception. This point can be illustrated, *i.e.*, what is tacit can, for a time, be made explicit. This will call for a short excursion into the history of civil engineering. Visualize the following description of Benjamin Baker's exposition of the structural principles of the proposed Forth Bridge, as performed by his staff. Baker was hired to design this bridge soon after the collapse of the Tay bridge in 1879. So his demonstration had to be as accessible and compelling as any TE.

Two men sit side by side on chairs. Each of their arms is straight, each hand holds the end of a rigid rod that runs from the base of the chair to the hand. From the tip of each of the outermost rods hangs a load of bricks or similar weights. Each of the innermost rods supports a seat, on which a third man sits. Above the three men is a diagram of the proposed structure. [7]

The man in the centre is supported, via the rods and the arms of the other two men, by the weight of the bricks. The three men illustrate how the long centre span of the bridge is supported.

How do we understand what this enactment shows? We visualize and read the structure through our personal knowledge of what it would be like to experience being in the position of each of the three men. Could we do this if we had no experience of pushes and pulls of the sort we see that they experience? Some of the knowledge needed to participate in a TE is like the knowledge needed to read the bridge diagram. Some people can read such diagrams in terms of concepts such as sheer stress, compression and tension, without reference to the situation that the men are in. Even for them, ordinary, embodied experience is invoked in addition to the specialized (tacit) knowledge needed to read the diagram. Some of this sharing depends on readers being at home in their bodies.

Einstein's argument about simultaneity judgements made by stationary and moving observers and his man-in-the-elevator illustration of the perceptual identity of gravitation and acceleration work in a similar way. In order to understand that there is a problem about simultaneity, the reader must be able to understand the properties that clocks and rods must have in order to measure the qualities they do. These concepts are transparent to readers who have been taught them. Some (such as rigidity) invoke, however tacitly, *personal* experience of the same sort shown by the men in Baker's illustration (e.g., of trying to compress or stretch a rigid object, of feeling weightless, etc.)

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Baker's demonstration is not a TE. Nevertheless there is a set of procedures through which we can trace the stresses and strains illustrated to work out whether, if they balance, the man in the centre would be supported by the weight of the bricks. The men stand for the context of embodied human experience on which our ability to read the diagram depends. The schematic diagram is analogous to a TE. It works like an experimental narrative from which complexity has been removed. The diagram in the picture is a schematized representation of something, but it can be a schema only for those who already know how to read it. For everyone else the whole picture provides the context through which potential bridge-users understand what the the diagram represents. Even so, the picture exposes only what is essential to understanding the whole. We may be aware that we read the diagram through the men's experience, but we are are not necessarily aware that we grasp the men's experience through our own.

The need to draw attention to the relationship between the bridge diagram and the men in the picture illustrates how embodiment, complexity and contingency are edited out of TE narratives. It is not only technicians that are invisible (Shapin 1989) but the embodied experimenters as well. Hacking (1993) agrees that "just as pictures of real life experiments usually omit the experimenters, we too often forget that it is the bodily feel of the experiment that convinces us". Like Sorensen (1991) and like Mach (1905), I believe that this explains the "intuitive grasp" of natural kinds and of universals that Koyré and Brown place beyond material-world expanation. Brown (1991, 1993) argues that T-experimenters access the worlds presented in TE narratives by apprehending or intuiting natural kinds. I think that 'direct intuition' is no substitute for the real thing—especially when many studies of science now show what makes thought experimentation possible and persuasive.

7. Iconoclasm about Icons

Hacking likens TEs to jokes. The most ubiquitous—such as Stevin's inclined plane—he likens to icons. We do not find the impact of a jokes or icons mysterious; we do not invoke Platonic intuitions or hidden deductive structures to explain their effect on us. But we do find jokes difficult to explain to those who don't yet have the common- (i.e. shared) sense of our culture (such as young children and adults from different cultures). To understand how TEs work it is important to show what has been going on behind the scenes; to analyse the transition from pre-TE science to science which depends upon TEs for the articulation and dissemination of new laws and concepts. This returns us to the historical process I mentioned in section 2. For four centuries the sciences have moved away from personal observation into realms in which the entities posited are beyond ordinary modes of perception. In some cases these strange worlds are accessible *only* through thought experimentation whose purpose is, in part, to strip away common-sense notions such as object-hood, causality, or the unidirectionality of time.[8] Scenarios operationalize relativity or complementarity in order to argue the irrelevance of commonsense criteria of object-hood such as identity (defined in terms of persisting spatial location). This brings us full circle. These TEs still rely on visualization and on modes of apprehending procedures that depend on embodiment. They enable us to locate our interaction with the constituents of a simulated world through our *ordinary, shared* perceptual and judgemental capacities. In order to appeal to the mind's eye, they return us to something pretty close to common-sense perception.

This is why TEs require so little preparation to perform and yet can quickly provide new insight about how things must be in some world. Truths about that reality are not apprehended *a priori* by some mysterious process. Nor do TE's somehow capture (only) our correct empirical intuitions. Rather, TEs disclose possibilities and necessities we had not realized because they begin in worlds made to be far more sta-

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ble than—and use experimenters made to be far more competent than any RE ever enjoys. But the disembodiment enabled by a TE is no less carefully crafted than the disembodied perception enabled by X-ray machines, electron microscopes, mass spectrometers, cloud-chambers or even stop-watches. In each case a complex alliance of skill, education and technology enables reliable perception. This makes the observational process so transparent that we seem to apprehend a bit of reality directly. The appearance of directness is an illusion.

Notes

[1]This is a shortened version of papers presented to the session on "Instrumentation and Experiment" at the joint *BSHS-HSS-CSHPS* meeting, Toronto (July 1992); to the *BSPS* annual conference at the University of Durham (September 1992) and to the session on "Thought Experimentation: the Theoretician's Laboratory" at the Thirteenth Biennial Meeting of the *PSA*, Chicago (October 1992). I have benefited from commentaries by Alfred Nordmann (at Toronto) and Ian Hacking (at Chicago), and from discussion with participants at these meetings. The support of a Special Project Grant from the Joint Research Councils Cognitive Science/HCI Initiative and of the British Academy (for travel to Chicago) is gratefully acknowledged.

[2]I owe this fomulation to Alfred Nordmann who points out that it would explain why a scientist such as Priestley apparently did not use thought experiments.

[3]This trend was not unopposed: Babbage, for example, attacked the move from common (i.e., unaided) sense (1830, p. 168). For a trenchant critique of the objectivist stance in epistemology see Johnson (1987).

[4]Nersessian (1991) argues that the claim that vicarious witnessing lent authority to knowledge claims needs further—cognitive—explanation.

[5]A. Martin, "Particle Physics: the standard model and beyond", *BSPS* Annual Conference, University of Durham, September 1992.

[6]Nersessian (1991) points out how, in training, tacit knowledge must be recovered, learned, and then made tacit once more.

[7]This word picture is drawn from an illustration reproduced in Baxendall 1985, p. 21.

[8]Similarly, Locke's migrating soul, Putnam's brains in a vat and Searle's chinese room attempt critiques of notions of (respectively) personal identity, embodiment and the relationship between understanding and competence.

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