In the Theoretician's Laboratory: Thought Experimenting as Mental Modeling[1]

Nancy J. Nersessian

Princeton University

1. Introduction

After a long period of neglect there has been a recent wave of interest in thought experiments in science, in mathematics, and in philosophy (See, e.g., Horowitz & Massey, 1991). I will restrict my analysis to thought experiments as they function in science, although I believe the account has implications for thought experiments, generally. The two most influential views on the topic in philosophy and history of science in this century represent the extremes of empiricism and rationalism. Pierre Duhem dismissed all thought experiments as bogus precisely because they are "not only not realized but incapable of being realized" (Duhem 1914, p.202). That is, either they can be turned into real experiments - and, thus the "thought" dimension is inconsequential—or they are to be dismissed because they are not "experimental" at all. Alexandre Koyré (1939, 1968), on the other hand, argued that the idealizing function of thought experiments is essential to scientific thinking. Idealization is required for the "mathematization" of nature and this can only be carried out in the mind, not in the laboratory. Thus, Koyré concluded thought experiment supplants real-world experimentation and demonstrates the synthetic *a priori* nature of scientific knowledge.

Historians have argued against Koyré mainly on the basis of evidence that Galileo actually performed many of what he presented as thought experiments. This does not, however, undermine the point that extrapolation to the limit and other forms of abstraction can only be carried out in thought. Philosophers of science, under the influence of logical positivism, have found Duhem's view most sympathetic and, until quite recently, it has been the predominant position. Thought experiments, while perhaps of psychological value, make no significant contribution to scientific reasoning. This stance is based on a limited conception of what constitutes "reasoning". "Reasoning" is customarily taken to comprise applying formal rules of inference to systems of propositions. However, a fuller account needs to extend the notion of reasoning to include the types of non-algorithmic inferences employed in a "reasoned change of view" (Harman 1986, Nersessian 1988, 1992). Thought experimenting is a principal means through which scientists change their conceptual structures. I propose that thought experimenting is a form of "simulative model-based reasoning". That is, thought experimenters reason by manipulating mental models of the situation

PSA 1992, Volume 2, pp. 291-301

depicted in the thought experimental narrative. As I have discussed elsewhere (1991a, 1991b, 1992), the narrative form of presentation plays a central role in communicating a thought experiment within a community of scientists. Although my hypothesis derives from examining the role of thought-experimental narratives in theoretical reasoning practices, it is reinforced by David Gooding's presentation in this volume, which derives from examining their role in experimental practices.

Briefly, my hypothesis is that what distinguishes thought experiments from logical arguments and other forms of propositional reasoning is that reasoning by means of a thought experiment involves constructing and making inferences from a mental simulation. This is what makes a thought experiment *both* "thought" and "experimental". The original thought experiment is the construction of a dynamical model in the mind by the scientist who imagines a sequence of events and processes and infers outcomes. She then constructs a narrative to describe the setting and sequence in order to communicate the experiment to others, i.e., to get them to construct and run the corresponding simulation and presumably obtain the same outcomes. Although language is used to construct that simulation, the operations thought experimenters perform in executing the experiment are not on linguistic representations, but are on the model the narrative has enabled them to construct. While thought experimenting is a truly creative part of scientific practice, the basic ability to construct and execute a thought experiment is not exceptional. The practice is highly refined extension of a common form of reasoning. It is rooted in our abilities to anticipate, imagine, visualize, and re-experience from memory. That is, it belongs to a species of thinking by means of which we grasp alternatives, make predictions, and draw conclusions about potential real-world situations we are not participating in at that time.

Curiously, the most comprehensive view of the nature and function of thought experiments—that of Ernst Mach—has had little influence in philosophy and history of science. Mach (1898, 1905) held that thought experiments are on a continuum with real-world experiments and saw them as providing empirical data with epistemological status comparable to that of real-world experiments. His argument for why the outcomes of thought experiments have empirical import rested on sensationalist psychology and evolutionary theory. In contemporary parlance, Mach's approach was "naturalistic". He sought to provide the psychological and biological basis for the epistemic status of the outcomes of thought experiments as empirical knowledge. While the specific psychological and biological theories he relied on are outmoded, his naturalistic approach to an explanation of why and how thought experiments work has much in common with the one taken here (See also, Sorrenson 1992).

I have been arguing for some time now that if we treat conceptual change not as something inherent in languages or ideas, but as something accomplished by human agents, then how human cognitive capacities and limitations facilitate and constrain the practices scientists employ in conceptual innovation and change become pertinent to philosophical analysis. From the perspective of methodological practices of scientists, thought experimenting has proven highly effective in numerous instances of conceptual change. One of my concerns in developing an account of conceptual change in science is to develop what Ronald Giere (1992) has called "the cognitive foundations" for such model-based reasoning, which, on my analysis, includes the use of analogical and visual models as well as thought experiments. Providing this foundation will establish that these heuristics are not ancillary, dispensable aids to thinking—while the "real" reasoning takes place by deductive or inductive arguments—but are reasoning methods essential to the practice of science. Recent work in cognitive psychology is pertinent for developing a framework in which to analyze the practice of thought experimenting. Examining the literature on mental modeling during narrative comprehension led to my initial proposals that the narrative form of presentation plays a significant role in the process of thought experimenting and that in one of its functions the real-world experimental narrative plays a similar role (1991a; 1991b).

2. "Mental Modeling" in Narrative Comprehension

In comprehending a thought-experimental narrative we make use of cognitive structures and operations in common use that have been investigated in some detail by cognitive psychologists. Reading, comprehending, and thinking about stories would seem to epitomize thinking with language. Yet, there is a significant body of cognitive research that supports the hypothesis that the inferences subjects make are derived from constructing and manipulating a mental model of the situation depicted by the narrative, rather than by applying rules of inference to a system of propositions representing the content of the text.

The contemporary notion that mental modeling plays a significant role in human reasoning was formulated, initially, by Kenneth Craik in 1943. Craik proposed that people reason, in general, by carrying out thought experiments on internal models. Since it was the heyday of behaviorist psychology when he proposed it, nothing much was done to further the hypothesis. The development of a cognitive psychology in the 1960s created a more hospitable environment for its articulation and exploration. Though not uncontroversial, the centrality of mental modeling to cognition is a hypothesis under investigation by many domains. The main impetus for the resurgence of the hypothesis is experimental results that demonstrate the effect of semantic information on reasoning (See, Johnson-Laird 1983, for an extensive discussion). Mental modeling has been investigated in a wide range of phenomena from thinking about causality in physical systems (See, e.g., deKleer & Brown 1983) to reasoning with representations of domain knowledge (See, e.g., Gentner & Stevens 1983) to analogical reasoning (See, e.g. Gentner & Gentner 1983) to deductive inferencing (See, e.g., Johnson-Laird 1983) to comprehending narratives (references below). Because the potential range of application is so extensive, some have argued that the hypothesis of mental models can provide a unifying framework for the study of cognition (Gilhooly 1986). I, too, find the hypothesis attractive because it provides the possibility of furnishing a unified analysis of the widespread modeling practices implicated in conceptual change.

There are several distinct theoretical accounts of mental models that tend to be conflated in the literature. The most significant distinction for our purposes is between those investigations that treat mental models as structures stored in long term memory and then called upon in reasoning and those that treat them as temporary structures constructed in working memory for a specific reasoning task. I am concerned with the latter in this analysis, where the mental model is constructed from the thought experimental narrative and used in reasoning. Since Philip Johnson-Laird's account is the best articulated of those analyses that focus on the temporary reasoning structure, it will inform my discussion. In general terms, a mental model is a structural analog of a real-world or imaginary situation, event, or process that the mind constructs to reason with. What it means for a mental model to be a structural analog is that it embodies a representation of the spatial and temporal relations among and the causal structure connecting the events and entities depicted.

Further, although it is a matter of some debate what *format* a mental model takes and what are the *generative processes* in the brain for creating and operating on mental models, these issues do not have to be resolved before we can make progress on an account of thought experimenting. The essential points are that a mental model is non-propositional in form and the mental mechanisms are assumed to be such that they can satisfy the model-building and simulative constraints necessary for the activity of mental modeling. I cannot go deeply into the "format" issue here, but to ally possible objections to the "image-like" nature of such models, I want to stress that most researchers would concur in the view that mental modeling, even if it does make use of the mechanisms of the visual cortex, is not like constructing a picture in the mind. That great thought experimenters, such as Bohr, have claimed not to be able to visualize well does not undermine my claim that thought experimenting is mental modeling. Mental modeling does not require introspective access to an image in the "mind's eye". It only requires the ability to reason by means of an analog model. The relationship between a mental model and what has been called "mental imagery" is something that still needs to be worked out.

Advocates of mental modeling argue that the original capacity developed as a way of simulating possible ways of maneuvering within the physical environment. It would be highly adaptive to possess the ability to anticipate the environment and possible outcomes of actions, so it likely that many organisms have the capacity for mental modeling. It is also likely that humans have the possibility of creating models from both perception and description. Additionally, there is mounting evidence from neuropsychology that the perceptual system plays a significant role in imaginative reasoning (See, e.g., Farah 1988). Again, this makes sense from an evolutionary perspective. The visual cortex is one of the oldest and most highly developed regions of the brain. As Roger Shephard, a psychologist who has done extensive research on visual cognition, has put it, perceptual mechanisms "have, through evolutionary eons, deeply internalized an intuitive wisdom about the way things transform in the world. Because this wisdom is embodied in a perceptual system that antedates, by far, the emergence of language and mathematics, imagination is more akin to visualizing than to talking or to calculating to oneself" (1988, p.180). The point is that contrary to the picture philosophers have constructed of the inferior status of visual modes of thinking, the visual cortex is a more highly evolved portion of the brain (Wimsatt 1990). Although the original ability to envision by mental modeling may have developed as a way of simulating possible courses of action in the world, it is highly plausible that, as human brains have developed, this ability has been "bent to the service of creative thought" (Shephard 1988, p.180).

In the domain of research into narrative comprehension the mental models hypothesis is that in understanding the meaning of a narrative, the linguistic expressions assist the reader/listener in constructing a mental model and in reasoning about the situation depicted by the narrative through this model. Johnson-Laird in psycholinguistics and others in formal semantics, linguistics and AI have proposed a theory of "discourse models" for narratives. The central idea is that "discourse models make explicit the structure not of sentences but of situations as we perceive or imagine them" (Johnson-Laird 1989, p.471). The principal tenets of the theory are: (1) the referent of a discourse is the situation the discourse describes; (2) the meaning of a discourse, i.e. the set of all possible situations it could describe, comprises both the linguistic representation and the mental mechanisms for constructing and running mental models; and (3) if a discourse has at least one model that can be embedded in a model of the world it is judged to be true (p.475).

As a form of mental model, a discourse model embodies a representation of the spatial, temporal, and causal relationships among the events and entities of the narrative. In constructing and updating a model, the reader calls upon a combination of pre-existing conceptual and real-world knowledge and employs the tacit and recursive inferencing mechanisms of her cognitive apparatus to integrate this with the information contained in the narrative. A number of experiments have been conducted to in-

vestigate the hypothesis that in understanding a narrative readers spontaneously construct mental models to represent and reason about the situations depicted by the text (Franklin & Tversky 1990; Johnson-Laird 1983; Mani & Johnson-Laird 1982; McNamara & Sternberg 1983; Morrow *et al.* 1989; Perrig & Kintsch 1985). Although no instructions are given to imagine or picture the situations, when queried about how they had made inferences in response to the experimenter's questioning, most subjects report it was by means of "seeing" or "being in the situation" depicted. That is, the reader sees herself as an "observer". Whether the view of the situation is "spatial", i.e., a global perspective, or "perspectival", i.e., from a specific point of view, is currently under investigation.

Some of the experimental evidence for the hypothesis of mental modeling during narrative comprehension comes from chronometric studies which claim to show that model-based reasoning is faster than reasoning with propositions. A situation that is represented by a mental model should allow the reasoner to generate conclusions without having to carry out the extensive operations needed to process the same amount of background information to make inferences from an argument in propositional form. The situational constraints are built into the model, making many consequences implicit in it that would require considerable inferential work in propositional form. For example, moving an object changes, immediately, its spatial relationships to all the other objects. The reasoner would grasp this simply by means of the changes in the model and not need to make additional inferences. Further, reasoning through a model should restrict the scope of the conclusions drawn. For example, moving an object in specified manner both limits and makes immediately evident the consequences of that move to those directly relevant to the situation depicted by the narrative. Thus other support comes from demonstrations that inferences subjects make are much more difficult or not made at all when they are required to reason with the situation reformulated propositionally.

3. Characteristics of Thought Experiments

Specific features of thought experiments have led me to propose that thought-experimental narratives function in much the same way as other narratives. It is not possible within the confines of this paper to present specific thought experiments. There is great variety among them and it would be a difficult task to construct a list of all their salient features. Nor need any one thought experiment exemplify all possible features. James Brown's taxonomy of thought experiments provides a useful classificatory schema (Brown 1991; See also, Anapolitanos 1991). The features I list are ones that are pertinent to understanding them as a species of simulative model-based reasoning and cut across these categories.

Feature 1: By the time a thought experiment is public it is presented in the form of a narrative. Occasionally, presentations of thought experiments also include some form of visual illustration, so my use of the term "narrative" is to be taken as broad enough to encompass these. The narrative has the character of a simulation. It calls upon the reader/listener to imagine a dynamic scene: one that unfolds in time and follows a specific causal sequence.

Feature 2: The reader is invited to follow through a sequence of events or processes *as one would in the real world.* That is, even if the situation may seem bizarre or fantastic, such as being in a chest in outer space, there is nothing bizarre in the unfolding. Objects behave as they would in the real world in the presence or absence of gravity. The assumption is that if the experiment could be performed, the chain of events would unfold according to the way things usually take place in the world.

Feature 3: By the time a thought experiment is communicated it is in a polished form. That is, we are not shown the tinkering that went into setting it up and refining it. The reader/listener rarely, if ever, gets a glimpse of failed thought experiments or avenues explored in constructing the one presented to them. When conveyed, a thought experiment is as packaged and polished as a real-world experiment is when it is published. This does not mean that it cannot fail (See, Janis 1991). Nor does it mean that it will be effective in establishing agreement on the part of the reader. The reader may execute it incorrectly or lack the competence to perform it at all. It may take some time to grasp the consequences of a subtle experiment and its interpretation. Further, the significance of a thought experiment is sometimes a matter of prolonged debate within the community.

Feature 4: The thought-experimental narrative depicts abstractions. For example, certain features of objects that would be present in a real-world experiment are not included, such as the color of rocks and the physical characteristics of observers. That is, there has been a prior selection of the pertinent dimensions on which to focus that evidently derives from experience in the world. From experience we believe, e.g., that the color of a rock does not effect its rate of fall. Such information is customarily excluded from real-world experimental narratives as well. This facilitates the reader's recognition of the situation as *prototypical*, i.e. as representing a class of experimental situations.

It is true that, as John Norton (1991) has pointed out, extremely colorful narratives may include highly specific details. Rather than being "irrelevant", as he maintains, though, these details usually serve to reinforce crucial aspects of the experiment. For example, in one version of the chest, or "elevator", experiment, Einstein depicts the physicist as being drugged and then waking up in a box. This colorful detail serves to reinforce the point that the observer could not have known before entering the chest if he were falling in outer space or sitting in a gravitational field. It also reinforces the condition that the observer cannot know whether or not there are gravitational sources around.

Feature 5: A thought experiment is usually so compelling that even in those cases where it is possible to carry it out, the reader feels no need to do so. The constructed situation, itself, is apprehended as pertinent to the real world in several ways. It can reveal something in our experience that we did not see the import of before, such as that the measurable current in a stationary and in a moving conductor cannot support the distinction made in the theoretical explanation of them as different phenomena. It can generate new data from the limiting case, for example, that in no medium lead and wood would fall at the same speed. It can make us see the empirical consequences of something in our existing conceptions, such as that the attributes called "gravitational mass" and "inertial mass" are the same property of bodies.

4. Thought Experimenting as Mental Modeling

We can only speculate about what goes on in the mind of the scientist who devises the original thought experiment. Scientists have rarely been asked to discuss the details of how they formulated these experiments. However, reports of thought experiments are presented, customarily, in the form of narratives. Because the thought-experimental narratives are what we have access to and because they are a central form of effecting conceptual change within a scientific community, I propose to examine how the narratives function. From that analysis we can infer that the original experiment involves a similar form of reasoning. To explicate the notion that thought experimenting is simulative model-based reasoning, we need to determine: (1) how a narrative facilitates the construction of a model of an experimental situation in thought and (2) how one can reach conceptual and empirical conclusions by mentally simulating the experimental processes.

According to the mental models hypothesis discussed above, the function of the narrative form of presentation of a thought experiment (Feature 1) is to guide the reader in constructing a structural analog of the situation described by it and to make inferences through simulating the events and processes depicted in it. So, as with other forms of discourse models, the operations carried out in executing the thought experiment are performed not on propositions but on the constructed model. Unlike the fictional narrative, however, the context of the scientific thought experiment makes the intention clear to the reader that the situation is one that is to represent a potential real-world situation (Feature 2). That thought experiment is presented in a polished form (Feature 3) should make it an effective means of getting comparable mental models among the members of a community of scientists. The narrative has already made significant abstractions (Feature 4), which aids in focusing attention on the salient dimensions of the model and in recognizing the situation as prototypical. Thus, the experimental consequences go beyond the specific situation of the thought experiment.

While some kinds of mental modeling may employ static representations, those derived from thought-experimental narratives are inherently dynamic. The situations undergo development. The narrative delimits which are the specific transitions that govern what takes place. In constructing and conducting the experiment, we use inferencing mechanisms, existing representations, and scientific and general world knowledge to make realistic transformations from one possible physical state to the next. Much of what we employ in these transformations is tacit. Thus, expertise and learning play a crucial role in the practice; as does what Gooding calls "embodiment" (1990, 1992). The constructed situation inherits empirical force by being abstracted from both our experiences and activities in, and our knowledge, conceptualizations, and assumptions of, the world (Features 5). In this way, the data that derive from thought experimenting have empirical consequences and at the same time pinpoint the locus of the needed representational change. This understanding forms the basis of problem-solving efforts to construct an empirically adequate conceptualization.

While I agree with Norton (1991) that thought experiments can often be reconstructed as arguments, the modeling function cannot be supplanted by an argument. As Norton acknowledges, the argument can be constructed only after the fact. That is, on my account, the argument is not evident until after the thought experiment has been constructed and executed. Exhibiting the soundness of a thought experiment by reconstructing it as an argument can perform an important rhetorical function. However, real-world experimental outcomes can be recast in argument form as well, but no one would argue that the experiment can be replaced by the argument. In similar fashion, we need to differentiate between the reasoning that is done with the thought experiment and that which is done with the reconstruction of it. On my view, thought experimenting is a complex form of reasoning that integrates various forms of information—propositions, models, and equations—into dynamic mental models. By linking the conceptual and the experiential dimensions of human cognitive processing, thought experimenting demonstrates the undesirable real-world consequences of a representation, thereby compelling representational change.

4. Concluding Remarks

In concluding I want to raise some issues that will require further analysis in light of the interpretation of thought experimenting as simulative model-based reasoning.

4.1 Thought Experimenting and Idealization

Idealization is a significant dimension of thought experimenting, but focusing on this one dimension has led to misconstruals of its nature and function. Thought-world models are abstractions but idealization is only one form of abstraction (Nersessian, in press). Limiting case analysis is a form of idealization employed frequently in thought experimenting. In this species of thought experimenting, the simulation consists in abstracting specific physical dimensions to create an idealized representation. Isolating the physical system in thought allows us to manipulate variables beyond what is physically possible and this creates data we did not possess before.

Idealization is not, however, the most salient dimension of the reasoning done with thought experiments. It is more significant that the thought experiment is understood to represent a *prototypical* occurrence of a situation. This is what gives the outcomes their generality and contributes to the impact of the experiment. Although the thought experimenter constructs a single model, its significance for a whole class of phenomena and situations is grasped in its execution. The thought-experimental model has aspects that are generic and others that are highly specific. For example, in Galileo's thought experiments with falling bodies any objects will do. The color and shape of the objects are not significant. The specific weights are also not salient, but that one object weighs more than the other needs to be specified. Most importantly, in thought experimenting the causal sequences are usually highly specific.

4.2 Thought Experiments and Real-world Experiments

Reformulating both kinds of experiments in argument form can help in persuading others and in justifying conclusions about the experimental outcomes. But, the modeling function of a thought experiment cannot be eliminated in favor of an argument, any more than the real-world experiment can be replaced by an argument.

Further, there is a significant connection between the two types of experimental narrative (Nersessian 1991b). Recently, sociologists of science have pointed out that early experimental narratives, i.e. those that helped *to establish* the practice of communicating experimental results, were much more richly detailed than is now customary (Dear 1985, Shapin 1984). In discussing Boyle's "literary technology", Steven Shapin (1984) claims that the style of the experimental narrative reflects the circumstances that Boyle was attempting to gain authority for his results by creating a way of "witnessing" an experiment while not being present. To achieve this purpose, "virtual" witnessing needed to create an "impression of verisimilitude", which Shapin interprets as conveying authority and compelling assent. From the mental models perspective developed here, that the narratives functioned to assist his readers in constructing their own mental simulation, thereby creating an understanding of what they did not actually witness themselves, is a significant factor in why Boyle's narratives were effective as rhetorical devices.

In contrast, Larry Holmes (1990) has pointed out that the experimental narratives produced by the members of the *Académie des Sciences* during the same historical period are much more succinct and quite similar to the modern experimental narrative. He argues that this stems, in part, from the practice of French Academicians of carrying out communal investigations, so authority was not in question. We have seen that tacit and explicit community knowledge and practices figure significantly in the mental modeling process. Thus, where there is a highly developed community of experimental practitioners, a more succinct experimental narrative will be effective. Knowledge of procedures and apparatus can be presumed and are part of what the community of readers will interpolate into their mental models of the experiment.

4.3 Thought Experimenting and Conceptual Change

In his influential 1964 essay, Thomas Kuhn characterized thought experimenting as "one of the essential analytical tools which are deployed during crises and which then help to promote basic conceptual reform" (Kuhn 1977, p.263). The historical record does indeed show the preponderance of thought experiments in periods of conceptual change in science. But, to understand why requires a fundamental revision in how we conceive of conceptual change, which I can only sketch here. The basic ingredients of that revision are to represent a concept by a system of constraints for generating the members of a class of models and to view a conceptual structure as an agglomeration of such constraint systems (Nersessian, in process). Thought experimenting plays a crucial role in conceptual change by showing that existing systems of constraints cannot be integrated into consistent models of the physical world. This process involves integrating constraints derived from existing conceptual structures, mathematical representations, and the world. The thought experiment pinpoints the locus of the needed conceptual reform, often providing the basis from which to construct a new representation. Thought experimenting may facilitate recognizing the undesirable consequences of our conceptualizations in much the way that experimenting by computer simulation exposes undesirable consequences of the constraints of a scientific representation. By creating a simulative model that attempts to integrate specific systems of constraints, thought experimenting enables the scientist to grasp essential points of conflict and infer their consequences more readily than would reasoning through the logical consequences of a representation. Once the initial experimenter understands the implications of a thought experiment, she can guide others in the community to see them as well by crafting a description of the experiment into a narrative.

Notes

[1] I acknowledge and appreciate the support of NSF Scholars Awards DIR 8821422 and DIR 9111779 in conducting the research discussed here.

References

Anapolitanos, D.A. (1991), "Thought Experiments and Conceivability Conditions." in Horowitz & Massey, pp. 87-98.

Brown, J.R. (1991), *The Laboratory of the Mind*. London: Routledge.

Craik, K. (1943), *The Nature of Explanation*. Cambridge: Cambridge University Press.

Dear, P. (1985), "*Totis in verba*: Rhetoric in the Early Royal Society." *Isis* 76: 145-161.

De Kleer, J. and Brown, J.S. (1983), "Assumptions and Ambiguities in Mechanistic Mental Models." in Gentner & Stevens, pp. 155-190.

Duhem, P. (1914), *The Aim and Structure of Physical Theory*. (Trans.) P. Wiener. Princeton: Princeton University Press, 1954.

Farah, M.J. (1988), "Is Visual Imagery Really Visual? Overlooked Evidence from Neuropsychology." *Psychological Review* 95: 307-317.

Franklin, N. and Tversky, B. (1990), "Searching Imagined Environments." *Journal of Experimental Psychology* 119: 63-76.

Gentener, D. and Gentner, D.R. (1983), "Flowing Waters or Teaming Crowds: Mental Models of Electricity." in Gentner & Stevens, pp. 99-130.

Gentner, D. and Stevens, A.L. (1983), *Mental Models*. Hillsdale: Lawrence Erlbaum.

Giere, R. (1992), "Concepts, Categories, and Scientific Theories." unpublished manuscript.

Gilhooly, K.J. (1986), "Mental Modelling: A Framework for the Study of Thinking." in *Thinking: Progress in Research and Teaching, (eds.) J. Bishop, J. Lochhead, and D. Perkins. Hillsdale, NJ: Lawrence Erlbaum, pp. 19-32.*

Gooding, D. (1990), *Experiment and the Making of Meaning*. Dordrecht: Kluwer Academic Publishers.

________. (1992), "The Procedural Turn; or Why do Thought Experiments Work?" in *Cognitive Models of Science*, (ed.) R. Giere. *Minnesota Studies in the Philosophy of Science 15*. Minneapolis: U. of Minnesota Press, pp. 45-76.

Harman, G. (1986), *Change in View*. Cambridge: MIT Press.

Holmes, F.L. (1990), "Argument and Narrative in Scientific Writing." in *The Paper Laboratory*, (ed.) P. Dear. Philadelphia: University of Pennsylvania Press, pp. 164-181.

Horowitz, T. and Massey, G.J. (1991), *Thought Experiments in Science and Philosophy*. Savage, MD.: Rowman and Littlefield.

Janis, A. (1991), "Can Thought Experiments Fail?" in Horowitz & Massey, pp. 113-118.

Johnson-Laird, P.N. (1983), *Mental Models*. Cambridge: Harvard University Press.

__________. (1989), "Mental Models." in *Foundations of Cognitive Science*, (ed.) M. Posner. Cambridge: MIT Press., pp. 469-500.

Koyré, A. (1939), *Galileo Studies*. Atlantic Highlands: Humanities Press, 1979.

_____. (1968), *Metaphysics and Measurement*. Cambridge: Harvard University Press.

Kuhn, T.S. (1964), "A Function for Thought Experiments." in *The Essential Tension: Selected Studies in Scientific Tradition and Change*. Chicago: University of Chicago Press, 1977, pp. 240-265.

Mach, E. (1898), "On Mental Adaptation." in *Popular Scientific Lectures*, fifth edition, (trans.) T. McCormack. LaSalle, Il.: Open Court, 1943, pp. 214-235.

_____. (1905), "On Thought Experiments." in *Knowledge and Error*. Dordrecht D. Reidel, 1975, pp. 134-147.

Mani, K. and Johnson-Laird, P.N. (1982), "The Mental Representation of Spatial Descriptions." *Memory and Cognition* 10: 181-187.

McNamara, T.P. and Sternberg, R.J. (1983), "Mental Models of Word Meaning." *Journal of Verbal Learning and Verbal Behavior* 22: 449-474.

Morrow, D.G., Bower, G.H., and Greenspan, S.L. (1989), "Updating Situation Models during Narrative Comprehension." *Journal of Memory and Language* 28: 292-312.

Nersessian, N.J. (1988), "Reasoning from imagery and analogy in scientific concept formation." in *PSA 1988, (eds.) A. Fine & J. Leplin*. East Lansing, MI., Philosophy of Science Association.

_________. (1991a), "Why do thought experiments work?" *Proceedings of the Cognitive Science Society 13*. Hillsdale, NJ: Lawrence Erlbaum, pp. 430-38.

_________. (1991b), "The Cognitive Sciences and the History of Science," in *Conference on Critical Problems and Research Frontiers in the History of Science and Technology. Madison, WI: HSS and SHOT, pp. 92-116.*

_________. (1992), "How Do Scientists Think? Capturing the Dynamics of Conceptual Change in Science." in *Cognitive Models of Science*, (ed.) R. Giere. *Minnesota Studies in the Philosophy of Science 15*. Minneapolis: U. of Minnesota Press, pp. 3-44.

_________. in press. "Abstraction via Generic Modeling in Concept Formation in Science." in *Idealization in Science*, (eds.) N. Cartwright & M.R. Jones. Amsterdam: Editions Rodophi.

_________. in process. *Creativity and Conceptual Change: A Cognitive Constructivist View*. (to be published by MIT/Bradford Books).

Norton, J. (1991), "Thought Experiments in Einstein's Work." in Horowitz and Massey, pp. 129-148.

Perrig, W. and Kintsch, W. (1985), "Propositional and Situational Representations of Text." *Journal of memory and Language* 24:503-518.

Shapin, S. (1984), "Pump and Circumstance: Robert Boyle's Literary Technology." *Social Studies of Science* 14: 481-520.

Shephard, R. (1988), "The Imagination of the Scientist." in *Imagination and the Scientist*, (eds.) K. Egan and D. Nadaner. NY: Teachers College Press, pp. 153-185.

Sorenson, R. (1992), *Thought Experiments*. Oxford: Oxford University Press.

Wimsatt, W. (1990), "Taming the Dimensions—Visualization in Science." in *PSA 1990*, vol. 2, (eds.) A. Fine, M. Forbes, and L. Wessels. East Lansing, MI.: PSA, pp. 111-135.

PSA 1992

PROCEEDINGS OF THE 1992
BIENNIAL MEETING
OF THE
PHILOSOPHY OF SCIENCE
ASSOCIATION

volume two

Symposia and Invited Papers

edited by

DAVID HULL,
MICKY FORBES
&
KATHLEEN OKRUHLIK

1993
Philosophy of Science Association
East Lansing, Michigan