

Model-Based Reasoning in Scientific Discovery

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Preface

The volume is based on the papers that were presented at the International Conference *Model-Based Reasoning in Scientific Discovery (MBR'98)*, held at the Collegio Ghislieri, University of Pavia, Pavia, Italy, in December 1998.

The papers explore how scientific thinking uses models and explanatory reasoning to produce creative changes in theories and concepts.

The study of diagnostic, visual, spatial, analogical, and temporal reasoning has demonstrated that there are many ways of performing intelligent and creative reasoning that cannot be described with the help only of traditional notions of reasoning such as classical logic. Traditional accounts of scientific reasoning have restricted the notion of reasoning primarily to deductive and inductive arguments. Understanding the contribution of modeling practices to discovery and conceptual change in science requires expanding scientific reasoning to include complex forms of creative reasoning that are not always successful and can lead to incorrect solutions. The study of these heuristic ways of reasoning is situated at the crossroads of philosophy, artificial intelligence, cognitive psychology, and logic; that is, at the heart of cognitive science.

There are several key ingredients common to the various forms of model-based reasoning to be considered in this book. The models are intended as interpretations of target physical systems, processes, phenomena, or situations. The models are retrieved or constructed on the basis of potentially satisfying salient constraints of the target domain. In the modeling process, various forms of abstraction are utilized. Evaluation and adaptation take place in light of structural, causal, and/or functional constraints. Simulation can be used to produce new states and enable evaluation of behaviors and other factors.

The book also addresses some of the main aspects of the nature of abduction, connecting it to the central epistemological question of hypothesis withdrawal in science and model-based reasoning, where abductive inferences exhibit their most appealing cognitive virtues.

The various contributions of the book are written by interdisciplinary researchers in philosophy, artificial intelligence, and cognitive science who are

Models and Diagrams within the Cognitive Field

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Abstract: My objective in this paper is to argue that research on modeling within science and technology should be cautious about approaching models in isolation but should regard them as part of a complex, generative field. While there certainly may be rhetorical purposes for isolating a particular model to bring into relief a particular "way of seeing" in the history of science, caution is essential if such a presentation of models doesn't become more a caricature of science. The plethora of books representing the history of science through a series of icons or great figures is an example. Others examples can be found in the misleading assimilation of Kuhn's idea of paradigms (Hoyningen-Huene, 1993; Nersessian, 1998). After making several brief comments about model-based reasoning, I will notice what might be learned from *reading* about the generative cognitive field in which models emerge. I will conclude my comments by making several comments on the relation between models and diagrams.

1. MODELS AND CONTEXT

Whether one considers the papers presented at a recent conference devoted to "Model-Based Reasoning in Scientific Discovery" at the University of Pavia or surveys recent literature on scientific modeling, one is struck by the multiple vantage points from which models in science are approached. In his book on magnets, the seventeenth-century polymath Anasthasius Kircher describes a thought experiment in which a statue, located on a stage, is placed on movable pedestal operated by magnet hidden from the audience. When a magnet is turned beneath the floor of the stage, the statue moves. To complicate his experiment, Kircher notices that multiple mirrors behind the statue generate a seemingly infinite number of reflected images from the vantage point of individuals seated in the audience. Kircher's splendidly baroque experiment reminds the reader that there are multiple ways for viewing phenomena but unless one comprehends the fundamental elements of cause and effect defined by the magnet the audience will be kept guessing (Kircher, 1643). The multiple images of the turning statue offer an interest-

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ing analogy to the multiple ways for approaching the use of models in science. In the broadest sense, a distinction may be made between research directed toward to experimental deployment of models (Gooding, 1999; Wimsatt and Schank, 1999), the increasing connection between modeling and visualization technologies within computer environments (Thagard, 1999), to work that would identify what might be called the logics of modeling and the pedagogical role of models. The range includes patterning within biological system (Pennock, 1999) to the administrative enforcement of models within scientific projects (Freedman, 1999).

The observation that there are models "all the way up and all the way down" (a comment made by Ronald Giere at the Pavia conference) deserves consideration especially since the large majority of studies have looked at modeling within the context of particular case studies from the history of science. The comment is suggestive and even a bit enigmatic. While there may be models "all the way down," it is not simply a matter of general pluralism. I think it is important to emphasize the continuum of modeling that takes place in cognition. Furthermore, it may be useful to recognize how reading provides an important analog for approaching such a continuum of modeling. Before I turn to reading in particular, it is useful to ask whether the discussions about cognitive modeling are not imitating discussions which have already taken place in the study of poetics?

Aristotle's analysis of genres in poetry can hardly be separated from his analysis of animals. The question we are asking must be posed not on the level of the individual work but as a question of the field. The interest in ordering the written forms of science really marks the development of a poetic of science. The desire to establish a hierarchy of such forms points as well to an idea of development and the assembly of more complex forms of communication.¹ For example, while just as we might speak of a poetic of science that would create a taxonomy of forms, so it might be possible to speak of a genealogy of scientific forms that presupposes an idea of evolving complexity and purpose. Indeed, here it is appropriate to underscore that the very effort to establish such orders within literature are regarded as part of *scientia* through the early modern period and continue to be embraced as such within the heritage of *Geisteswissenschaften* (Bambach, 1995; Gadamer, 1987). It is possible to see the interest in modeling in philosophy of science as an impulse to develop a typology of models that parallel literary typology.

The implications are important: for it suggests that models in science point to a desire to analyze scientific discourse. Do we have literary analysis

¹ Russian interest in the genres of scientific and technical communication as defined in a Euro-American setting provide an intriguing site for the location of such taxonomies. See Knoespel (1999).

turned inside out? It is hardly surprising that historical surveys of such forms provoke ideas of evolving order.² It is valuable to make a comparison between the taxonomic structures identified in literature and the impulse to create taxonomies of writing in science because in both cases the historical field provides examples that lead to the description of models. Beyond the taxonomies of the written forms of science, there have been multiple impulses to consider the topoi, or figures, that have been used in science. For example, efforts to identify the use of metaphor in science are part of an evolving impulse to formulate a tropology for science. The recognition that it is possible and even necessary to assume a "rhetoric" of science is another element of such a tropology (Gross, 1990; Bazerman, 1988). One of the most significant components of such work has been the recognition that the elements that comprise such a tropology may also emerge within the non-natural or created languages associated with science. Modeling in literature is displayed by a developed practice of collecting of topoi or figures which are assumed to contribute to the evolving constitution of literature.³

From the vantage point of modeling, efforts to identify taxonomies or tropologies within science as it has been practiced reminds us that scientific models are hardly isolated but continually in play with one another. Kuhn's work on Copernicus offers a good example (Kuhn, 1957). In contrast to broad overviews of the history of science that often give the impression that the change between Ptolemaic and Copernican views of the universe occurred quickly, Kuhn's work reminds one that the shift from one model to another took place innumerable times if viewed from the vantage point of the individuals who constituted to the scientific community. The modeling practice associated with taxonomies and tropology pertains fundamentally to our own acts of interpreting historical evidence rather than defining the actual use of models in the practice of science. From the vantage point of practice, it is important to make a distinction between status of a model as a vehicle that reveals something about how science was practiced in contrast to the model as an instrument that shows how science is being practiced.⁴ The distinction is important because it shows that models may assume different roles as the mediate between interpreting the past and the future. It is pre-

² See the interesting history of mathematics included in the introductory essay of Wallis (1685). Wallis's history provides a rudimentary tropology for mathematics that bears comparison to Vico. Although Vico receives much credit for delineating ideas of evolving order within natural languages, he does not take up the idea of evolving orders within symbolic languages.

³ A substantial example of topoi in literature is found in Curtius (1963).

⁴ See Latour (1987). While Latour's discussion of modalities is in part indebted to Greimas, his discussion of inscription devices does not really take up the physical intervention of different forms of writing or of graphic representation within techno-scientific literature.

cisely for this reason that models can function both as rituals that represent the way something has been done or as projective forms that may lead to reorientation.³ Just as the idea of modeling in science may function in historical analysis of science or in the practice of science, so the idea of modeling within the field of literature has a function that may be associated either with interpretation or with creation. But while such a comparison is certainly appropriate, reading itself provides an even better analog to the binary function of the model in science.

2. THE MODEL OF READING

I want to consider a model of reading which provides a synthetic structure for approaching modeling within science. The model is proposed by Cesare Segre and in itself combines several components from formalist linguistics (Segre, 1979, pp. 1-56). As we read we are continually in the process of generating and evaluating hypothesis. On a fundamental level each word we read is the consequence of a learned ability to recognize letters and form words. The recognition of individual words leads to the formation of sentences and the mental practice that we associate with meaning. The act of reading involves not simply the activation of meaning on the level of the sentence but an evolving formulation of hypothesis about what we are reading which are ever under revision as we continue through a text. If we wish, we think about reading as the movement of an arrow that discards possible meanings at the same time that it makes projections about what will be encountered next on the horizon of reading. The process which I have described is truly multilayered because it involves both the chronological assimilation of sentences and their reformulation into the ideational or narrational structure of the text. Even though the text has been read it may receive multiple interpretations in as much as comprehension of the plot or fabula may not at all be synonymous with an understanding or interpretation of the narrative. There is a sense in which the process of reading is never completed.

Although the process described by Segre may be augmented (Iser, 1974, 1978), even its simplest formulation provides a vehicle that may be used to approach modeling within science. As I noticed above, the act of reading inevitably functions as a moment of mediation on an evolving ho-

³ Kurz and Martignon (1998) observed the place ritual within mathematical practice in a paper presented at the Pavia Conference. I have also benefited from discussions with Elke Kurz on her recent visit to Georgia Tech.

zison. Such mediation is hardly passive but involves a process of formulation and reformulation.

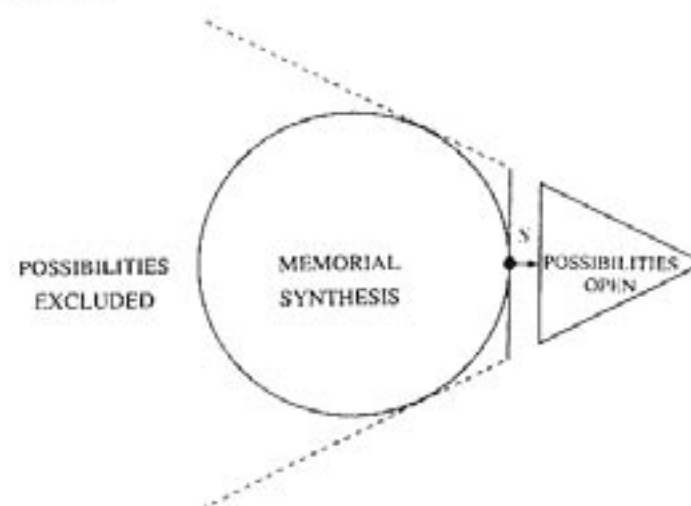


Figure 1. Segre model of reading.

Even though it may seem that such a process ceases when the text has been completed, it is evident that the text either may be read again or that it comes under interrogation as one reads other texts. A similar practice occurs in the practice of science for the construction of model is first grounded on one's previous experience and second, continually under examination given one's evolving experience. While there are broad similarities, differences also appear in the referential assumptions associated with the model of reading and the deployment of the model in scientific practice. Although the act of reading may have multiple referents (i.e., the landscape in a novel by Jane Austen or of a planet in a work of science fiction), the referent of the scientific model is assumed to be a symbolically mediated link to nature. Another difference appears in condensed forms of representation found in scientific modeling. Rather than being narrative structures alone, the scientific model is often formed in a metalinguistic setting.

Isaac Newton's "Trinity College Notebook" provides remarkable examples of the formulation of a working model or diagram (I will return to the distinction between the two of them below) (Newton, 1992). In addition to serving as an important document within the history of science, the notebook provides a rich collection of cognitive problems in the practice of science. From an array of problems that range from comets to quantity, I would like to consider Newton's effort to describe turbulence.

Of Reflection-Refractiōn-&Undulation
Of violent motion

Violent motion is made [continued] either by ye aire or by motion [a force] im-
prest. Or by the naturall gravity in ye body moved. Not by ye aire since ye aire
~~since ye aire~~ crowds more uppon ye thing projected before, yn behind, & must
therefore rather hinder ~~it-but-if-ye-aire-helps-it-why-doth-ye-thing-at-last-fall~~ for
you may observe in water yt a thing moved in it doth carry ye same water behind
it along wth it as in a cone or at least ye water is moved from behind it wth but a
small force as you may observe by ye motes in ye water suppose (a) to be ye
boddy moved: (b. d. e. f.) to be ye water moving behind (a) to give it place. (c)
ye water behind (a) followinig it & going along wth it. The if ye water at (f) ran
so violently against ye backside of (a) it would beate away ye water at (a) wth
violence but yt water is moved very slowly from behind a. as you if it be moved
away: as you may perceive by



Figure 2.

ye motes in ye water. ~~Again-this-wil~~ the like must happen in aire if you say no I
answer must yn move (a) forwards in water. So if hot leade drop into water yt
pte wch is behind (a) will be pointed. Ye fore pte round wch would be otherwise
if ye aire pressed as much on it before hind as behindfore. Thirdly how can ye
aire continue ye motion of a globe on its axis [...] (pp. 367-68)



Figure 3.

Newton's text reminds us that correction and clarification is an aspect of formulation. The words that are crossed out are important as a record of Newton's thought process. Newton's drawings, however, serve as the focal point and orient the way that we approach the text. The drawings are remarkable because they show Newton providing a mathematical framework for the movement of water around a small obstruction. The emended text accompanies the two drawings as a commentary and should be distinguished both from the drawing of turbulence and the symbolic inscriptions that impose a schema of potential interpretation on the phenomena. Significantly, it is the symbolic mathematical language used to describe the phenomena that provides the link with the commentary. It is precisely Newton's effort to formulate the problem through symbols that is so interesting. The formulation of the problem, however, appears neither in the text or the drawings alone but in their interaction. Once the problem is figured out, however, the drawing may become the representation of the problem. While diagrams or models participate in the mediation of the narrative, they also stand out and serve as a focal points or registers provoking further investigation. In effect, drawings or diagrams inevitably function as memorial devices as well for they seize the strains of the possible just as they let others go. By simultaneously opening and excluding possibilities, they anticipate the course of a projected exploration. Every drawing becomes a potential site for discovery. The drawings organize future discourse.⁶

Our efforts to understand Newton's problem are also shaped by our knowledge of Newton and our understanding of the development of science. Each shapes a horizon of expectation. The fact that the problem appears in a notebook of person recognized as a icon of science shapes our expectation as we read. The more we know about Newton, the more detailed our expectations may be. Another set of expectations comes from the way we situate the problem within the history of science. Who else sought to represent turbulence mathematically in the seventeenth century? Although there still may be historians of science who believe they can recreate Newton's own expectation, it is more prudent to recognize that our efforts to understand the past are inextricably shaped by our own experience.

A conception of reading as a process of continuous hypothesis formulation and evaluation especially when it includes the creation of meaning through metalinguistic forms provides a useful ground for approaching modeling within science. Just as models are constructed in the practice of reading

⁶ An analogous function is found in literature where the figurative becomes posed as an interpretive problem that needs to be explained. Drawings, however, do not speak entirely for themselves but invite written or oral elaboration. The drawings – and here we may also say diagrams – are analogous to figures of speech such as metaphor: both are intuitive and provoke elaboration on another level.

they are formed in the practice of science. While scientific models may be articulated through natural language, they are defined through drawings or diagrams. What is of utmost importance, however, is that the practice of modeling is not static but involves a continuous conversation with other possibilities. Above all, reading provides a ground for approaching the generative field in which modeling occurs in science.

3. DIAGRAMMATICS AND THE FIELD OF GRAPHIC REPRESENTATION

I have suggested that the discussion of models within science cannot take place without recognition of the prevalence of modeling within cognition. Furthermore, I have suggested that reading provides a vehicle for approaching the omnipresence of models in experience. In the following paragraphs, I want to suggest that rather than using the term model too broadly, it is useful to distinguish between different forms of graphic representation in science. In particular, it is useful to identify a progression within the field of graphic representation. Such a progression includes multiple symbolic forms. (The study of these symbolic forms and their relation might be referred to as *diagrammatics*).

In turning my attention to diagrammatics, I want to refer to my earlier comments on reading. However, at this moment, I also want to register the differences between reading and writing. As an extension of writing, modeling in science should be regarded as an active process which is fundamentally projective. As in the case of reading, modeling looks not only to the future but carries an implicit rejection of other possibilities. It is significant that the modeling process in science at an earlier stage may be accurately described as process of reading especially when the observer thought of himself as copying out patterns that had been written by God (Bono, 1995). In fact a distinction between the modeling process used in reading (interpretation of meaning) and the modeling process used in writing (the construction of meaning) is crucial in as much it indicates a particular relation to nature. It is possible to view western science as fundamentally shaped by hermeneutical strategies that would "read" natural structures and then suppress the very technological strategies that show the ways nature is also being written.⁷ By

⁷ Vulcan provides mythographic analog especially if one considers his contradictory identity in the Middle Ages. While being viewed as a discoverer and fabricator as well as his association with ingenuity. This identity is contradicted by another that portrays him as someone who is ashamed when he ejaculates prematurely when he is in the presence of Venus. See Wetherbee (1972).

emphasizing the centrality of diagrammatics, we are calling attention not to an act of interpretation but to an act of intervention.

In his recent book, *Les enjeux du mobile: mathématique, physique, philosophie*, Gilles Châtelet surveys the ways diagrams have been used in the invention of geometric space.⁸ The following are among the functions that may be associated with diagrams:

- *Diagrams constitute technologies that mediate between other technologies of writing.* The physicality of the diagram is also an extension of the literal technologies used in their construction. "J'ai donc ainsi en quelque sorte propulsé une main par la pensée et on serait tenté de dire que la pince ou le compas donnent un *point de vue* à la main, en associant à la saisie un angle sous lequel l'intervalle est "vu." (p. 221) "Nous pouvons apprécier tout ce qui sépare la règle du compas et de l'angle. La règle implique une mise bout à d'unités étalons, une manipulation d'un morceau de direction. La règle est un transfert qui a été gelé - un barre" (pp. 221-222).

[“Hence I have thereby as it were propelled a hand by thought and one might be tempted to say that the pincers or compasses give a *point of view* to the hand, by associating an angle in which the interval is 'seen' with the grasp” (5.3). “We get the full measure of what distinguishes the ruler from the compasses and the angle. The ruler implies an end-to-end placement of standard measuring units, a manipulation of a piece of direction. The ruler is a transfer that has been frozen - a bar” (5.3)].

- *Diagrams create space for mathematical intuition.* “On pourrait parler à son propos d'une technique d'allusions” (p. 33). “Une philosophie du physico-mathématique ne saurait ignorer cette pratique symbolique en amont du formalisme, pratique de condensation et d'amplification d'intuition” (p. 34).

[“We could describe this as a technique of allusions” and “A philosophy of the physico-mathematical cannot ignore this symbolic practice which is prior to formalism, this practice of condensation and amplification of the intuition” (Introduction, p. 17)].

- *Diagrams are not static but project virtuality onto the space which they seek to represent.* “Faraday bouleversé la physique en décidant de ne plus les voir comme des figures subsidiaires, mais comme des

⁸ All quotes are from Gilles Châtelet (1993). Translations are from the forthcoming English translation to be published by Kluwer in 1999 under the title *Configuring Space*. Page reference are to preliminary page-proof in which each chapter is paginated separately.

incitations à provoquer l'espace, comme des diagrammes, comme des expériences en pointillé faisant allusion à des expériences 'réelles' qui rendent flagrantes des actions latentes. Les lignes de force ne sont ni 'réelles' ni 'artificielles'; elles ne mathématisent pas les forces; elles ne plaquent pas du géométrique sur du physique, elles, substituent de reprendre ses droits" (pp. 241-42).

["Faraday turns physics on its head by deciding no longer to see them (lines of force) as subsidiary figures, but as *incitements to provoke space*, as diagrams, as *dotted-line* experiments alluding to 'real' experiments that manifest latent actions. Lines of force are neither 'real' or 'artificial'; they do not mathematize forces; they do not pin geometrical onto physical, rather they substitute an idea, but elastic and tough, network, which allows virtuality to reclaim its rights" (5.21)].

Diagrams represent a visual strategy for entailment. "L'horizon n'est ni une borne qui interdit ou sollicite un dépassement, ni une barre inscrite dans le ciel en pointillé. Une fois qu'il a été décidé, on emporte toujours son horizon avec soi. C'est le côté exaspérant de l'horizon: décapant comme le visible, tenace comme une odeur, compromettant comme un tact, il n'habille pas les choses d'apparences, mais imprègne tout ce que nous nous sommes résolus à saisir" (p. 92). "Saisir une dimension, c'est inventer un diagramme où s'équilibrent la pure dispersion de ce que Hegel appelait *aussereinandersein* (l'étant l'un à côté de l'autre simplement extérieur) et la pétulance de l'intensif: le déploiement de celui-ci nourrit la mobilisation et le redressement de celui-là, et réciproquement" (pp. 172-173).

["The horizon is neither a boundary marker that prohibits or solicits transgression, nor a barrier drawn in a dotted line across the sky. Once it has been decided, one always carries one's horizon away with one. This is the exasperating side of the horizon: corrosive like the visible, tenacious like a smell, compromising like touch, it does not dress things up with appearances, but impregnates everything that we are resolved to grasp" (2.22). "To grasp a dimension is to invent a diagram where the pure dispersion of what Hegel called *aussereinandersein* (the 'being outside one another') and the exuberance of the intensive balance one another out: the unfolding of the latter nourishes the mobilization and straightening of the former, and vice versa" (4.19)].

Diagrams are mediating vehicles which means that they cannot only be recovered but rediscovered. While they mediate between other technologies of writing, they may also mediate or reveal links between problems. "Rien n'est plus fécond, tous les mathématiciens le

savent, que ces obscures analogies, ces troubles reflets d'une théorie à une autre, ces furtives caresses, ces brouilleries inexplicables; rien aussi ne donne plus de plaisir au chercheur. Un jour vient où l'illusion se dissipe; le pressentiment se change en certitude [...]. Heureusement pour les chercheurs, à mesure que les brouillards se dissipent sur un point, c'est pour se reformer sur un autre" André Weil as cited by Châtelet (p. 28).

["Nothing is more fertile, all mathematicians know, that these obscure analogies, these murky reflections of one theory in another, these furtive caresses, these inexplicable tiffs; also nothing gives as much pleasure to the researcher. A day comes when the illusion vanishes: presentiment turns into certainty [...]. Luckily for researchers, as the fogs clear at one point, they form again at another" (André Weil as cited by Châtelet, Introduction, p. 11)].

Diagrams have a pedagogical force that could be integrated into mathematical education. "Les lignes de force de Faraday réussissent à s'appropriier ce que nous proposons d'appeler des expériences diagrammatiques et à donner un statut à cette langue du 'parler avec les mains', du 'sens physique' dont les plus grands électrogéomètres ont deviné la puissance d'entraînement et qui sait saisir l'instant de la solidification de la métaphore, au moment où l'opération lui dispute la souveraineté. Cette langue se nourrit de gestes bien plus que de formes mathématiques déjà disponibles et possède une puissance allusive propre, transversale aux chaînes déductives de la physique mathématique et capable d'illuminer des pans entiers de la géométrie. Il y a une vocation expérimentale intrinsèque du champ qui le soustrait aux prétentions de l'entendement (en ce sens il est irréductible à une saisie transcendantale) et aux appétits des causalités. Il n'y a pas, au sens propre, d'application des lignes de champs, mais une étonnante pédagogie par allusions qui introduisent d'emblée à un espace élastique et à jouer de son aptitude à renter" (p. 244).

["Faraday's lines of force succeed in appropriating what we are proposing to call *diagrammatic experiments* and in giving a status of this language of 'speaking with the hands', of the 'physical sense' whose driving power was sensed by the greatest electrogeometers and which can grasp the instant when the metaphor solidifies, when the operation contends with it for sovereignty. This language feeds on gestures much more than on already available mathematical forms and possesses a particular allusive power, which can traverse the deductive chains of mathematical physics and illuminate whole sections of geometry. The field has an in-

trinsic experimental mission that protects it from the pretensions of the understanding (in this sense it is irreducible to a transcendental grasp) and from the appetites of causalities. There is, in the literal sense, no "application" of the lines of fields, but rather an astonishing pedagogy by allusions which straight away introduces an elastic space and place with its capacity to resonate" (5.23)].

Although I cannot do justice to Châtelet's discussion in the space that I have here, even the identification of these functions demonstrates what I have referred to above as the generative field of graphic representation of science. Their resonance may be demonstrated by noting that each has particular relevance to Newton's representation of the turbulence problem cited above. Rather than spelling each out in detail, I would make several further comments applicable both to Châtelet's discussion and the example from Newton. Diagrams should not be thought of only within a rigid and controlled terrain of mathematics, but should also be approached as ludic forms. In effect, diagrams may be approached as aspects of "play" in the sense that Piaget described the ways children explore space through gestures and drawings (Piaget, 1962, 1973). As the example of Paul Klee and Cy Twombly show, ludic aspects of diagrams are also found in art (Barthes, 1985a, 1985b). It is hardly misleading to view Newton's drawings as a form of playful and puzzling interaction with his experience.

In my earlier discussion of reading, I observed that graphic representations were complemented, at an initial stage, by a written text. The narrative setting for graphic representation may also be determined by speech. The question of how we move between or integrate different symbolic codes – the problem of translating between the narrative and diagrammatic matter of mathematical discourse – has been raised by many scholars (Rotman, 1993, 1995). I want to suggest that we learn something important about these negotiations by paying attention to speech. Although we readily acknowledge the place of oral tradition in the transmission of Homer or of speech in the shift from philology to linguistics, the importance of orality in the transmission of mathematics and science has remained oddly bracketed. Reminding ourselves of the orality of our inquiry may sound like a truism. I don't think it is. The integrative function that relates the diagram to the text is one that occurs through speech. The centrality of speech in performing these translations is exhibited everyday in classrooms and laboratories around the world. We must be prepared to conceive of orality not simply as a phenomenon that may help us understand a particular experiment but as a constant phenomenon that contributes substantially to science.⁹ There is a sense in which the texts

⁹ The function of orality in the practice of science is the subject of a current project entitled *Deaf Science*.

assembled by the history of science amount to cues or a score waiting to be performed or enacted.

Diagrams are controlled by modalities. These modalities must be approached as having aspects that are both written and oral. If we approach the broad range of graphic representation within science and technology as a generative field, we see that technology may be thought of as a progression of states which involve the continuous interaction of diagrams or models. Rather than viewing technology as jump from an idea to an artifact it would be constituted by a process of increasingly complex sign systems. We need to think of technology as a continuous set of interactions with signs that become increasingly reified. One way to enter this zone is to think of diagrams as devices that mark a process of becoming. Diagrams might also be thought of as providing access to a trace of thinking – somewhat analogous to efforts to describe the transformation of matter from one stable state to another.¹⁰ From such a vantage point diagrams are interstitial structures. The architectural blue-print would be an example. There are multiple mediating drawings in the development of most structure and artifacts.

Diagrammatics pertains not simply to the limited use of drawings in scientific texts but identifies a cognitive field concerning with the use of figures in the mediation of meaning. From such a vantage point, figures are not neutral but reveal matrices through which meaning is negotiated on an individual and social level. What the Renaissance regarded as "thinking in pictures" is not simply allegorical but an indication of the cognitive field in which meaning emerges (Gombrich, 1989; Fletcher, 1964). Allegory is not only an interpretive strategy for dealing with a hierarchy of meanings (the control and moderation of meaning) but a practice that permits us to see the coordination of emergent models and emergent meaning. Allegory assumes commentary whether associated with a written or graphically portrayed narrative. In effect, allegory creates a setting for the emergence of meaning with symbolic languages. It is important, of course, that Renaissance painters were also mathematicians (Baxandall, 1972). Painting in effect also works as a symbolic language that provokes commentary. Nicholas of Cusa's use of a self-portrait by Roger van der Weyden to demonstrate the omnipresence of God is an example (Cassirer, 1972). Paintings, like diagrams, identify the cognitive space in which meaning is generated.

Somewhat more abstractly, we may say that technologies of representation simultaneously have the capacity to reveal and transform space. While oriented by language, our thought process is shaped in fundamental ways by

¹⁰ The notion of a "trace" within natural languages has been shaped by Jacques Derrida in various works. The idea of a "trace" or within non-phonetic symbolic languages deserves further consideration. See Derrida (1974, 1981).

pattern recognition and pattern manipulation. Models and diagrams embody strategies of writing that function as vehicles for constituting idiosyncratic coherence and meaning. But beyond such individual meanings, they also work as vehicles for the constitution of shared meaning within groups and finally, as mechanisms for the exploration and social constitution of transhistorical meaning that give coherence to the practices of science. Perhaps it is appropriate for us to think of ourselves as members of the Kircher-like audience commenting not only on the multiple angles from which "models" may be viewed but on the broad field of representations from which they emerge.

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