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# MODEL-BASED AND MANIPULATIVE ABDUCTION IN SCIENCE

ABSTRACT. What I call *theoretical abduction* (sentential and model-based) certainly illustrates much of what is important in abductive reasoning, especially the objective of selecting and creating a set of hypotheses that are able to dispense good (preferred) explanations of data, but fails to account for many cases of explanation occurring in science or in everyday reasoning when the exploitation of the environment is crucial. The concept of *manipulative abduction* is devoted to capture the role of action in many interesting situations: action provides otherwise unavailable information that enables the agent to solve problems by starting and performing a suitable abductive process of generation or selection of hypotheses. Many external things, usually inert from the epistemological point of view, can be transformed into what I call *epistemic mediators*, which are illustrated in the last part of the paper, together with an analysis of the related notions of "perceptual and inceptual rehearsal" and of "external representation".

KEY WORDS: abduction, action-based reasoning, model-based reasoning, scientific discovery

## 1. INTRODUCTION

An interesting and neglected point of contention about human reasoning is whether or not concrete manipulations of external objects influence the generation of hypotheses. I am focusing on the first features of what I call *model-based* and *manipulative abduction* showing how we can find in scientific and everyday reasoning methods of constructivity based on internal and external models and action-based reasoning. I am analyzing the problem in the light of the so-called historical-cognitive method (Nersessian, 1998). While it tries to integrate findings from research on cognition and findings from historical-epistemological research into models of actual scientific practices, assessments of the fit between cognitive findings and historical-epistemological practices aid in elaborating richer and more realistic models of cognition. There are interesting parallels

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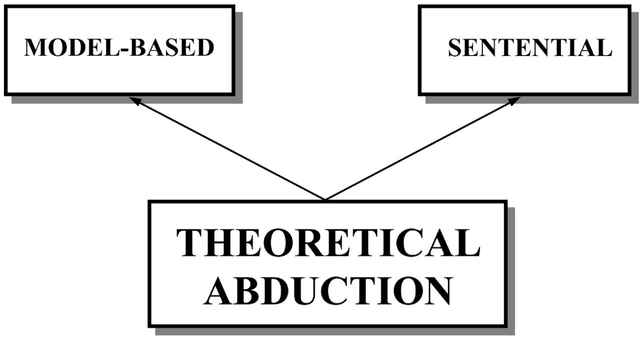


*Figure 1.* Theoretical abduction.

that can be exploited by philosophers of science, cognitive scientists, and AI researchers, the relevance of the concept of abduction can contribute to a central issue in cognitive science: hypothesis formation both in science and in everyday reasoning.

## 2. SENTENTIAL ABDUCTION

It is well known that many reasoning conclusions that do not proceed in a deductive manner are *abductive*. What I call *theoretical* (sentential and model-based) abduction (Figure 1) (Magnani, 1999a) is, from a cognitive point of view, an internal process of reasoning.

Many reasoning conclusions that do not proceed in a deductive manner are *abductive*. For instance, if we see a broken horizontal glass on the floor we might explain this fact by postulating the effect of wind shortly before: this is not certainly a deductive consequence of the glass being broken (a cat may well have been responsible for it). Hence, theoretical abduction is the process of *inferring* certain facts and/or laws and hypotheses that render some sentences plausible, that *explain* or *discover* some (eventually new) phenomenon or observation; it is the process of reasoning in which explanatory hypotheses are formed and evaluated. Moreover, we have to remember that although explanatory hypotheses can be elementary, there are also cases of composite, multipart hypotheses.

First, it is necessary to show the connections between abduction, induction, and deduction and to stress the significance of abduction to illustrate the problem-solving process. I think the example of diagnostic reasoning is an excellent way to introduce abduction. I have developed with others (Ramoni et al., 1992) an epistemological model of medical reasoning, called the *Select and Test Model* (ST-MODEL) (Magnani, 1992) which can be described in terms of the classical notions of abduction, deduction and induction; it describes the different roles played by such basic inference types in developing various kinds of medical reasoning (diagnosis, therapy planning, monitoring) but can be extended and regarded also as an illustration of scientific theory change. The model is consistent with the Peircian view about the various stages of scientific inquiry in terms of "hypothesis" generation, deduction (prediction), and induction.

The type of inference called abduction was studied by Aristotelian syllogistics, as a form of ἀπαγωγή, and later on by mediaeval reworkers of syllogism. A hundred years ago, Peirce interpreted abduction essentially as an "inferential" *creative process* of generating a new hypothesis. Abduction and induction, viewed together as processes of production and generation of new hypotheses, are sometimes called reduction, that is ἀπαγωγή.

There are two main epistemological meanings of the word abduction: (1) abduction that only generates "plausible" hypotheses (*selective* or *creative*) and (2) abduction considered as *inference to the best explanation*, which also evaluates hypotheses (Figure 2).

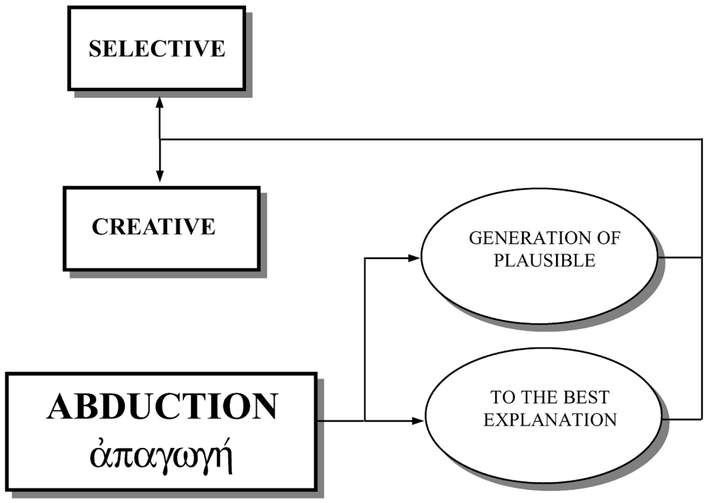


*Figure 2.* Creative and selective abduction.

To illustrate from the field of medical knowledge, the discovery of a new disease and the manifestations it causes can be considered as the result of a creative abductive inference. Therefore, creative abduction deals with the whole field of the growth of scientific knowledge. This is irrelevant in medical diagnosis where instead the task is to *select* from an encyclopedia of pre-stored diagnostic entities (Ramoni et al., 1992). We can call both inferences ampliative, selective and creative, because in both cases the reasoning involved amplifies, or goes beyond, the information incorporated in the premises.

All we can expect of our "selective" abduction, is that it tends to produce hypotheses for further examination that have some chance of turning out to be the best explanation. Selective abduction will always produce hypotheses that give at least a partial explanation and therefore have a small amount of initial plausibility. In the syllogistic view (see below) concerning abduction as inference to the best explanation advocated by Peirce one might require that the final chosen explanation be the most "plausible".

Since the time of John Stuart Mill (1843), the name given to all kinds of non deductive reasoning has been induction, considered as an aggregate of many methods for discovering causal relationships. Consequently *induction* in its widest sense is an ampliative process of the generalization of knowledge. Peirce (1955a) distinguished various types of induction: a common feature of all kinds of induction is the ability to compare individual statements: using induction it is possible to synthesize individual statements into general laws – inductive generalizations – in a defeasible way, but it is also possible to confirm or discount hypotheses. Following Peirce, I am clearly referring here to the latter type of induction, that in the ST-MODEL is used as the process of reducing the uncertainty of established hypotheses by comparing their consequences with observed facts. This perspective on hypothesis testing in terms of induction is also known in philosophy of science as the "hypothetico-deductive method" (Hempel, 1966) and is related to the idea of confirmation of scientific hypotheses, predominant in nepositivistic philosophy but also present in the falsificationist tradition (Popper, 1959).

*Deduction* is an inference that refers to a logical implication. Deduction may be distinguished from abduction and induction on the grounds that only in deduction is the truth of the conclusion of the inference guaranteed by the truth of the premises on which it is based. Deduction refers to the so-called non-defeasible arguments. It should be clear that, on the contrary, when we say that the premises of an argument provide partial support for the conclusion, we mean that if the premises were true, they would give us good reasons – but not conclusive reasons – to accept the conclusion. That is to say, although the premises, if true, provide some evidence to support the conclusion, the conclusion may still be false (arguments of this type are called inductive, or abductive, arguments).

All these distinctions need to be exemplified. To describe how the three inferences operate, it is useful to start with a very simple example dealing with diagnostic reasoning and illustrated (as Peirce initially did), in *syllogistic terms*:

1. If a patient is affected by a pneumonia, his/her level of white blood cells is increased.
2. John is affected by a pneumonia.
3. John's level of white blood cells is increased.[1]
   (This syllogism is known as Barbara).

By deduction we can infer (3) from (1) and (2). Two other syllogisms can be obtained from Barbara if we exchange the conclusion (or Result, in Peircian terms) with either the major premise (the Rule) or the minor premise (the Case): by induction we can go from a finite set of facts, like (2) and (3), to a universally quantified generalization – also called categorical inductive generalization, like the piece of hematologic knowledge represented by (1). Starting from knowing – selecting – (1) and "observing" (3) we can infer (2) by performing a selective abduction. The abductive inference rule corresponds to the well-known fallacy called affirming the consequent (simplified to the propositional case)

$$\frac{\begin{array}{c}\varphi \rightarrow \psi \\ \psi\end{array}}{\varphi}$$

It is useful to give another example, describing an inference very similar to the previous one:

1. If a patient is affected by a beta-thalassemia, his/her level of hemoglobin A2 is increased.
2. John is affected by a beta-thalassemia.
3. John's level of hemoglobin A2 is increased.

Such an inference is valid, that is not affected by uncertainty, since the manifestation (3) is pathognomonic for beta-thalassemia (as expressed by the biconditional in $\varphi \leftrightarrow \psi$). This is a special case, where there is not abduction because there is not "selection" (in general clinicians have to deal with manifestations which can be explained by different diagnostic hypotheses) in this special case the inference rule corresponds to

$$\frac{\begin{array}{c}\varphi \leftrightarrow \psi \\ \psi\end{array}}{\varphi}$$

Thus, *selective abduction* is the making of a preliminary guess that introduces a set of plausible diagnostic hypotheses, followed by deduction to explore their consequences, and by induction to test them with available patient data, (1) to increase the likelihood of a hypothesis by noting evidence explained by that one, rather than by competing hypotheses, or (2) to refute all but one.

If during this first cycle new information emerges, hypotheses not previously considered can be suggested and a new cycle takes place. In this case the *nonmonotonic* character of abductive reasoning is clear and arises from the logical unsoundness of the inference rule: it draws defeasible conclusions from incomplete information. All recent logical accounts ("deductive") concerning abduction have pointed out that it is a form of nonmonotonic reasoning. It is important to allow the guessing of explanations for a situation, in order to discount and abandon old hypotheses, so as to enable the tentative adoption of new ones, when new information about the situation makes them no longer the best.

Uncertainty and imperfect information are fundamental characteristics of the knowledge relative to hypothetical reasoning. The nonmonotonic character of the ST-MODEL arises not only from the above mentioned nonmonotonic character of deductive inference type involved in it, but also from the logical unsoundness of the ascending part of the cycle guessing hypotheses to be tested. Finally, we have to remember that in the ST-MODEL the first meaning (see above) of the word abduction is adopted: abduction that only generates "plausible" hypotheses (of course in this case *selective*).

Many attempts have been made to model abduction by developing some formal tools in order to illustrate its computational properties and the relationships with the different forms of deductive reasoning. Some of the formal models of abductive reasoning are based on the theory of the *epistemic state* of an agent (Boutilier and Becher, 1995), where the epistemic state of an individual is modeled as a consistent set of beliefs that can change by expansion and contraction (*belief revision framework*). This kind of *sentential frameworks* seems to exclusively deal with selective abduction[2] (diagnostic reasoning) and relates to the idea of preserving *consistency*. If we want to provide a suitable framework for analyzing the most interesting cases of conceptual changes in science we do not have to limit ourselves to the *sentential* view of theoretical abduction but we have to consider a broader *inferential* one which encompasses both sentential and what I call *model-based* sides of creative abduction.

Hence, if we want to deal with the nomological and most interesting creative aspects of abduction we are first of all compelled to consider the whole field of the growth of scientific knowledge. Related to the high-level types of scientific conceptual change (Thagard, 1992) are different varieties of *model-based abductions* (see, for examples, Magnani, 1999b).

## 3. MODEL-BASED ABDUCTION

What exactly is model-based abduction from a philosophical point of view? Peirce stated that all thinking is in signs, and signs can be icons, indices, or symbols. Moreover, all *inference* is a form of sign activity, where the word sign includes "feeling, image, conception, and other representation" (*CP* 5.283), and, in Kantian words, all synthetic forms of cognition. That is, a considerable part of the thinking activity is *model-based*. Of course model-based reasoning acquires its peculiar creative relevance when embedded in abductive processes.

For Peirce a Kantian keyword is synthesis, where the intellect constitutes in its forms and in a harmonic way all the material delivered by the senses. Surely Kant did not consider synthesis as a form of *inference* but, notwithstanding the obvious differences, I think synthesis can be related to the Peircian concept of inference, and, consequently, of abduction. After all, when describing the ways the intellect follows to unify and constitute phenomena through imagination Kant itself makes use of the term *rule* (Kant 1929, A140, B179-180, 182), and also of the term *procedure* (*ibid*.). We know that rules and procedures represent the central features of the modern concept of inference.

Most of these forms of "constitution" of phenomena are creative and, moreover, characterized in a model-based way. Let me show some examples of model-based inferences. It is well known the importance Peirce ascribed to diagrammatic thinking, as shown by his discovery of the powerful system of predicate logic based on diagrams or "existential graphs". As we have already stressed, Peirce considers inferential any cognitive activity whatever, not only conscious abstract thought; he also includes perceptual knowledge and subconscious cognitive activity. For instance in subconscious mental activities visual representations play an immediate role.

We should remember, as Peirce noted, that abduction plays a role even in relatively simple visual phenomena. *Visual abduction*, a special form of non verbal abduction, occurs when hypotheses are instantly derived from a stored series of previous similar experiences. It covers a mental procedure that tapers into a non-inferential one, and falls into the category called "perception". Philosophically, *perception* is viewed by Peirce as a fast and uncontrolled knowledge-production procedure. Perception, in fact, is a vehicle for the instantaneous retrieval of knowledge that was previously structured in our mind through inferential processes. Peirce says: "Abductive inference shades into perceptual judgment without any sharp line of demarcation between them" (Peirce, 1955b, p. 304). By perception, knowledge constructions are so instantly reorganized that they become habitual and diffuse and do not need any further testing: "[...] a fully accepted, simple, and interesting inference tends to obliterate all recognition of the uninteresting and complex premises from which it was derived" (*CP* 7.37). Many visual stimuli

– that can be considered the "premises" of the involved abduction – are ambiguous, yet people are adept at imposing order on them: "We readily form such hypotheses as that an obscurely seen face belongs to a friend of ours, because we can thereby explain what has been observed" (Thagard, 1988, p. 53). This kind of image-based hypothesis formation can be considered as a form of *visual* (or *iconic*) *abduction*. Of course such subconscious visual abductions of everyday cognitive behavior are not of particular importance but we know that in science they may be very significant and lead to interesting new discoveries (Magnani et al., 1994; Shelley, 1996). If perceptions are abductions they are withdrawable, just like the scientific hypotheses abductively found. They are "hypotheses" about data we can accept (sometimes this happens spontaneously) or carefully evaluate.

Peirce gives an interesting example of model-based abduction (Magnani, 1999a, 2001a) related to sense activity: "A man can distinguish different textures of cloth by feeling: but not immediately, for he requires to move fingers over the cloth, which shows that he is obliged to compare sensations of one instant with those of another" (*CP* 5.221); this idea surely suggests that abductive movements also have interesting *extra-theoretical* characteristics and that there is a role in abductive reasoning for various kinds of manipulations of external objects (cf. the following section on "action-based, manipulative abduction"). One more example is given by the fact that the perception of tone arises from the activity of the mind only after having noted the rapidity of the vibrations of the sound waves, but the possibility of individuating a tone happens only after having heard several of the sound impulses and after having judged their frequency. Consequently the sensation of pitch is made possible by previous experiences and cognitions stored in memory, so that one oscillation of the air would not produce a tone.

To conclude, all knowing is *inferring* and inferring is not instantaneous, it happens in a process that needs an activity of comparisons involving many kinds of models in a more or less considerable lapse of time. All sensations or perceptions participate in the nature of a unifying hypothesis, that is, in abduction, in the case of emotions too: "Thus the various sounds made by the instruments of the orchestra strike upon the ear, and the result is a peculiar musical emotion, quite distinct from the sounds themselves. This emotion is essentially the same thing as a hypothetic inference, and every hypothetic inference involved the formation of such an emotion" (*CP* 2.643).

Following Nersessian (1999), I use the term "model-based reasoning" to indicate the construction and manipulation of various kinds of representations, not necessarily sentential and/or formal. She proposes the so-called cognitive history and philosophy of science approach, which affords a reframing of the problem of conceptual formation and change in science that not only provides philosophical insights but also pays attention to the practices employed by real human agents in constructing, communicating and replacing representation of a domain. Common examples of model-based reasoning are constructing and manipulating visual representations, thought experiment, analogical reasoning, but also the so-called "tunnel effect" (Cornuéjols et al., 2000), occurring when models are built at the intersection of some operational interpretation domain – with its interpretation capabilities – and a new ill-known domain.

We have to remember that visual and analogical reasoning are productive in scientific concept formation too, where the role they play in model-based abductive reasoning is very evident; scientific concepts do not pop out of heads, but are elaborated in a problem-solving process that involves the application of various procedures: this process is a *reasoned process*. Visual abduction, but also many kinds of abductions involving analogies, diagrams, thought experimenting, visual imagery, etc. in scientific discovery processes, can be just called *model-based*. Additional considerations about the intersections between abduction and model-based reasoning (especially in experiment and thought experiment) are illustrated by Gooding (1996): the ability to integrate information from various sources is crucial to scientific inference and typical of all kinds of model-based reasoning also when models and representations are "external", like verbal accounts, drawings, various artifacts, narratives, etc.

We know that scientific concept formation has been ignored because of the accepted view that no "logic of discovery" – either deductive, inductive, or abductive algorithms for generating scientific knowledge – is possible. The methods of discovery involve use of *heuristic* procedures (Peirce was talking of creative abduction as the capacity and the "method" of making good conjectures); cognitive psychology, artificial intelligence, and computational philosophy have established that heuristic procedures are reasoned (see the following section). Analogical reasoning is one such problem-solving procedure, and some reasoning from imagery is a form of analogical reasoning: Holyoak and Thagard (1995) elaborated an analysis of analogical reasoning that encompasses psychological, computational, and epistemological aspects. Hence the role of visual abduction and visual imagery in scientific discovery is very interesting.

What happens when the abductive reasoning in science is strongly related to extra-theoretical actions and manipulations of "external" objects? When abduction is "action-based" on *external models*? When thinking is "through doing" as illustrated in the simple case above of distinguishing the simple textures of cloth by feeling? To answer these questions I will delineate the features of what I call *manipulative abduction* by showing how we can find in scientific and everyday reasoning methods of constructivity based on external models and actions.

## 4. MANIPULATIVE ABDUCTION

*Manipulative* abduction (Figure 3) happens when we are thinking *through* doing and not only, in a pragmatic sense, about doing. For instance, when we are creating geometry constructing and manipulating a triangle, like in the case given by Kant in the "Transcendental Doctrine of Method" (Magnani, 2001b). It refers to an extra-theoretical behavior that aims at creating communicable accounts of new experiences to integrate them into previously existing systems of experimental and linguistic (theoretical) practices. Gooding (1990) refers to this kind of concrete manipulative reasoning when he illustrates the role in science of the so-called "construals" that embody tacit inferences in procedures that are often apparatus and machine based. The embodiment is of course an expert manipulation of objects in a highly constrained experimental environment, and is directed by abductive movements that imply

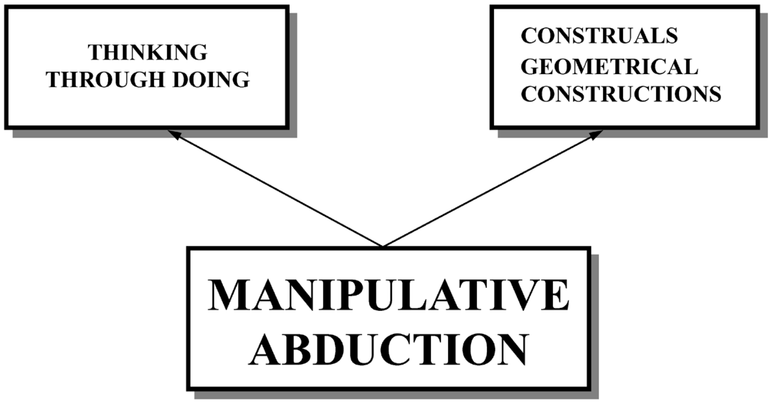


*Figure 3.* Manipulative abduction.

the strategic application of old and new *templates* of behavior in some cases connected with extra-rational components, for instance emotional, esthetical, ethical, and economic.

The hypothetical character of construals is clear: they can be developed to examine or discard further chances, they are provisional creative organization of experience and some of them become in their turn hypothetical *interpretations* of experience, that is more theory-oriented, their reference is gradually stabilized in terms of established observational practices. Step by step the new interpretation – that at the beginning is completely "practice-laden" – relates to more "theoretical" modes of understanding (narrative, visual, diagrammatic, symbolic, conceptual, simulative), closer to the constructive effects of theoretical abduction. When the reference is stabilized the effects of incommensurability with other established observations can become evident. But it is just the construal of certain phenomena that can be shared by the sustainers of rival theories. Gooding (1990) shows how Davy and Faraday could see the same attractive and repulsive actions at work in the phenomena they respectively produced; their discourse and practice as to the role of their construals of phenomena clearly demonstrate they did not inhabit different, incommensurable worlds in some cases. Moreover, the experience is constructed, reconstructed, and distributed across a social network of negotiations among the different scientists by means of construals.

To illustrate this process – from manipulations, to narratives, to possible theoretical models (visual, diagrammatic, symbolic, mathematical) – in a previous work (Magnani, 2001a) I have considered some observational techniques and representations made by Faraday, Davy, and Biot concerning Oersted's experiment about electromagnetism. They were able to create consensus because of their conjectural representations that enabled them to resolve phenomena into stable perceptual experiences. Some of these narratives are very interesting.

It is difficult to establish a list of invariant behaviors that are able to describe manipulative abduction in science. As illustrated above, certainly the expert manipulation of objects in a highly constrained experimental environment implies the application of old and new *templates* of behavior that exhibit some regularities. The activity of building construals is highly conjectural and not immediately explanatory: these templates are hypotheses of behavior (creative or already cognitively present in the scientist's mind-body system, and sometimes already applied) that abductively enable a kind of epistemic "doing". Hence, some templates of action and manipulation can be *selected* in the set of the ones available and pre-stored, others have to be *created* for the first time to perform the most interesting creative cognitive accomplishments of manipulative abduction.

Moreover, I think that a better understanding of manipulative abduction at the level of scientific experiment could improve our knowledge of induction, and its distinction from abduction: manipulative abduction could be considered as a kind of basis for further meaningful inductive generalizations. Different generated construals can give rise to different inductive generalizations.

Some common features of these tacit templates (Figure 4) that enable us to manipulate things and experiments in science are related to: (1) sensibility to the aspects of the phenomenon which can be regarded as *curious* or *anomalous*; manipulations have to be able to introduce potential inconsistencies in the received knowledge (Oersted's report of his well-known experiment about electromagnetism is devoted to describe some anomalous aspects that did not depend on any particular theory of the nature of electricity and magnetism; Ampère's construal of experiment on electro-

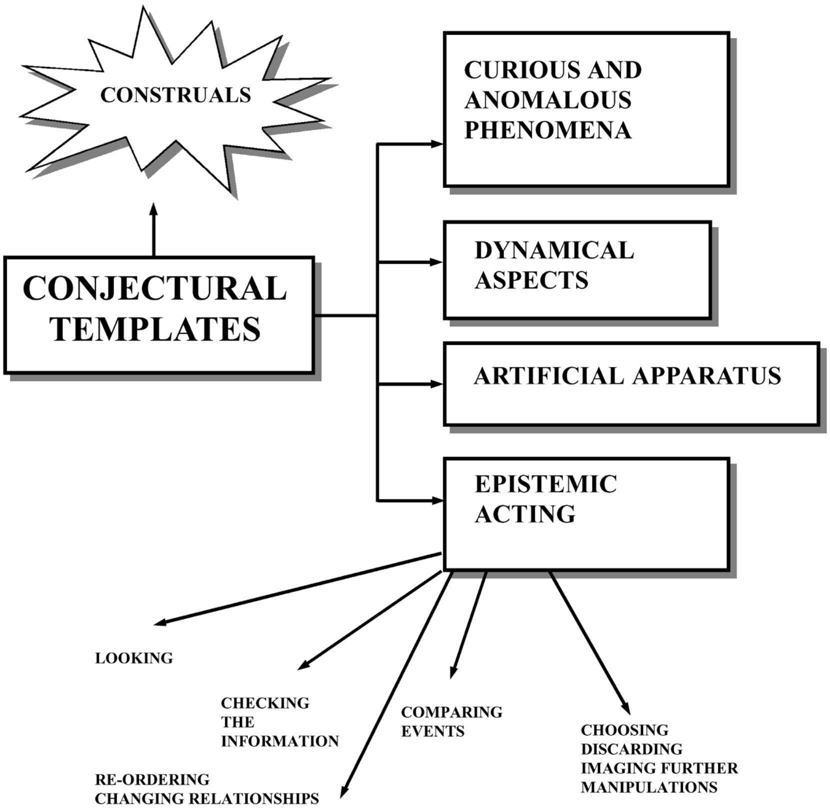


*Figure 4.* Conjectural templates.

magnetism – exploiting an artifactual apparatus to produce a static equilibrium of a suspended helix that clearly shows the role of the "unexpected"); (2) preliminary sensibility to the *dynamical* character of the phenomenon, and not to entities and their properties, common aim of manipulations is to practically reorder the dynamic sequence of events in a static spatial one that should promote a subsequent bird's-eye view (narrative or visual-diagrammatic); (3) referral to experimental manipulations that exploit *artificial apparatus* to free new possibly stable and repeatable sources of information about hidden knowledge and constraints (Davy well-known set-up in terms of an artifactual tower of needles showed that magnetization was related to orientation and does not require physical contact). Of course this information is not artificially made by us: the fact that phenomena are made and manipulated does not render them to be idealistically and subjectively determined; (4) various contingent ways of epistemic acting: *looking* from different perspectives, *checking* the different information available, *comparing* subsequent events, *choosing*, *discarding*, *imaging* further manipulations, *re-ordering* and *changing relationships* in the world by implicitly *evaluating* the usefulness of a new order (for instance, to help memory).[3]

The whole activity of manipulation is devoted to build various external *epistemic mediators*[4] that function as an enormous new source of information and knowledge. Therefore, manipulative abduction represents a kind of redistribution of the epistemic and cognitive effort to manage objects and information that cannot be immediately represented or found internally (for example exploiting the resources of visual imagery).[5]

If we see scientific discovery like a kind of opportunistic ability of integrating information from many kinds of simultaneous constraints to produce explanatory hypotheses that account for them all, then manipulative abduction will play the role of eliciting possible hidden constraints by building external suitable experimental structures. So external well-built structures (Biot's construals for example) and their contents in terms of new information and knowledge, will be projected onto internal structures (for instance models, or symbolic – mathematical – frameworks) so joining the constructive effect of theoretical abduction. The interplay between manipulative and theoretical abduction consists of a superimposition of internal and external, where the elements of the external structures gain new meanings and relationships to one another, thanks to the constructive explanatory theoretical activity (for instance Faraday's new meanings in terms of curves and lines of force). This interplay expresses the fact that both internal and external processes are part of the same epistemic ecology.[6]

### 4.1. *Epistemic Mediators*

Recent research, taking an explicit ecological approach to the analysis and design of human-machine systems (Kirlik, 1998), has shown how expert performers use action in everyday life to create an *external* model of task dynamics that can be used in lieu of an internal model: "Knowing of not, a child shaking a birthday present to guess its contents is dithering, a common human response to perceptually impoverished conditions". Not only a way for moving the world to desirable states, action performs an epistemic and not merely performatory role: people structure their worlds to simplify cognitive tasks but also in presence of incomplete information or of a diminished capacity to act upon the world when they surely have less opportunities to know. *Epistemic action* can also be described as resulting from the exploitation of latent constraint in the human-environment system. This additional constraint grants additional information: in the example of the child shaking a birthday present he "takes actions that will cause variables relating to the contents of the package to covary with perceptible acoustic and kinesthetic variables. Prior to shaking, there is no active constraint between these hidden and overt variables causing them of carry information about each other". Similarly, "one must put a rental car 'through its paces' because the constraints active during normal, more reserved driving do not produce the perceptual information necessary to specify the dynamics of the automobile when driven under more forceful conditions" (Kirlik, 1998). Moreover, a very interesting experiment is reported concerning short-order cooking at a restaurant grill in Atlanta: the example shows how cooks at various level of expertise use external models in the dynamic structure of the grill surface to get new information otherwise inaccessible.

We know that theoretical abduction certainly illustrates much of what is important in abductive reasoning, especially the objective of selecting and creating a set of hypotheses (diagnoses, causes, hypotheses) that are able to dispense good (preferred) explanations of data (observations), but fails to account for many cases of explanations occurring in science or in everyday reasoning when the exploitation of the environment is crucial. The concept of manipulative abduction is devoted to capture the role of action in many interesting situations: action provides otherwise unavailable information that enables the agent to solve problems by starting and performing a suitable abductive process of generation or selection of hypotheses.

Also natural phenomena can play the role of external artifactual models: the stars are not artifacts, but under Micronesian navigator's manipulations of the images of them, the stars acquire a structure that "becomes one of the most important structured representational media of the Micronesian system" (Hutchins, 1995, p. 172). The external artifactual models are endowed with functional properties as components of a memory system crossing the boundary between person and environment (for example they are able to transform the tasks involved in allowing simple manipulations that promote further visual inferences at the level of model-based abduction).

Not all epistemic and cognitive mediators are preserved, saved, and improved, as in the case of the ones created by Galileo at the beginning of modern science (see the following subsection). For example, in certain non epistemological everyday emergency situations some skillful mediators are elaborated to face possible dangers, but, because of the rarity of this kind of events, they are not saved and stabilized. Hutchins (1995, pp. 317–251) describes the interesting case of the failure of an electrical device, the gyrocompass, crucial for navigation, and the subsequent creation of substitutive contingent cognitive mediators. These cognitive mediators consist of additional computations, redistributions of cognitive roles, and finally, of the discovery of a new shared mediating artifact in terms of divisions of labor – the so-called modular sum that is able to face the situation.

Finally, we have to observe that many external things that usually are inert from the epistemological point of view can be transformed into epistemic or cognitive mediators. For example we can use our body: we can talk with ourselves, exploiting in this case the self-regulatory character of this action, we can use fingers and hands for counting,[7] we can also use external "tools" like writing, narratives, others persons' information, concrete models and diagrams, various kinds of pertinent artifacts. Hence, not all of the cognitive tools are inside the head, sometimes it is useful to use external objects and structures as epistemic devices. We indicated above that Micronesian navigator's stars, that are natural objects, become very complicated epistemic artifacts, when inserted in the various cognitive manipulations (of seeing them) related to navigation.

### 4.2. *Experiments and the "World of Paper"*

Already in the *Dialogues Concerning the Two Chief World Systems* (1632), accentuating the role of observational manipulations Galileo presents an anatomist that, manipulating a cadaver, is able to get new, not speculative, information that goes beyond the "world of paper" of the Peripatetic philosophy. It is well known that recent philosophy of science has paid a great attention to the so-called theory-ladenness of scientific facts (Hanson, Popper, Kuhn). Nevertheless a lot of new information in science is reached by observations and experiments, and experiments are the fruit of various kinds of artifactual manipulations: the different strategies correspond to the expert manipulations of objects in a highly constrained experimental environment, directed by *abductive* movements that imply the application of old and new extra-theoretical *templates* of behavior.

With Galileo's achievements, we observe that human "scientific" thinking is related to the manipulation of a material and experimental environment that is no longer natural. Knowledge is finally seen as something cognitively distributed across scientists, their internal "minds", and external artifacts and instruments. Experiments and instruments embody in their turn external crystallizations of knowledge and practice. Modern science is made by this interplay of internal and external. An immediate consequence of Galileo's ideas is the critique of the authority, that advocated the knowledge relevance of a "world of paper", mainly internal from the cognitive point of view. Gooding observes: "It is ironical that while many philosophers admire science because it is empirical as well as rational, philosophical practice confines it to the literary view that Galileo rejected" (1990, p. xii). Galileo's "book of nature" and his systematic use of the telescope are the revolutionary *epistemic mediators* that characterize the cognitive power of the new way of producing intelligibility.

### 4.3. *Manipulative Templates*

We still know very little about what governs the action-based abduction. In section 4 above we already described some central "tacit templates" which characterize manipulative reasoning in science. From the general point of view of everyday situations manipulative abductive reasoning exhibits other very interesting features (Figure 5): (1) action elaborates a *simplification* of the reasoning task and a redistribution of effort across time when we "need to

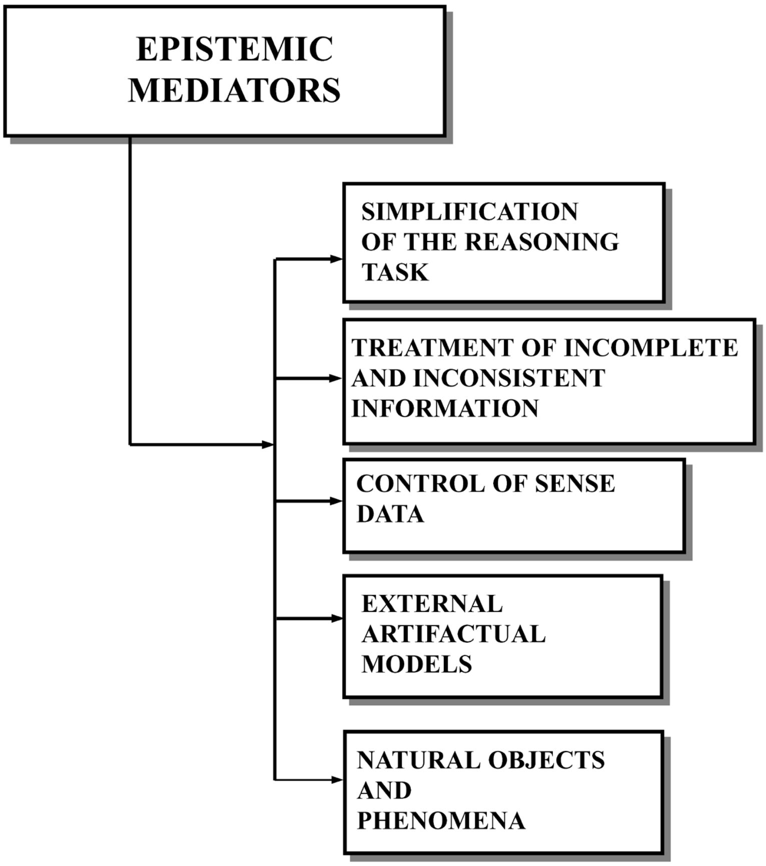


*Figure 5.* Epistemic mediators.

manipulate concrete things in order to understand structures which are otherwise too abstract" (Piaget, 1974), or when we are in presence of *redundant* and unmanageable information; (2) action can be useful in presence of *incomplete* or *inconsistent* information – not only from the "perceptual" point of view – or of a diminished capacity to act upon the world: it is used to get more data to restore coherence and to improve deficient knowledge; (3) action as a *control of sense data* illustrates how we can change the position of our body (and/or of the external objects) and how to exploit various kinds of prostheses (Galileo's telescope, technological instruments and interfaces) to get various new kinds of stimulation: action provides some tactile and visual information (e.g., in surgery), otherwise unavailable; (4) action enables us to build *external artifactual* *models* of task mechanisms instead of the corresponding internal ones, that are adequate to adapt the environment to agent's needs: experimental manipulations exploit *artificial apparatus* to free new possible stable and repeatable sources of information about hidden knowledge and constraints.

## 5. PERCEPTUAL AND INCEPTUAL REHEARSAL

Let's consider this example taken from the history of science, dealing with the role of internal (perceptions) and external representations (apparatus). When Faraday was in front of the chaotic "perceived" behavior of the movement of magnetized needles suspended close to current-carrying wires, he had to gradually refine both the experimental process and the conceptual representation of the underlying nature of the motions involved. By imposing a circular schema upon the seen phenomena of the motion of the needles, he was then able to build in turn an external configuration (apparatus) in which the motions were actually circular. A perceptual incoherence was turned into perceptual coherence. In other epistemic settings Faraday found a great difficulty in making sense to a particular "seen" phenomenon, like in the case of the discovery of electromagnetic induction – the fact that changing magnetic fields induces currents in nearby conductors. Only by handling hundred of experiments Faraday established the boundaries of the effects and tested various hypotheses about their character (Tweney, 1996).

Following Ippolito and Tweney (1995) the concept of *inceptual rehearsal* is useful to cognitively illustrate situations like the one previously indicated. "Perceptual rehearsal", as the "saturation of one or more of the senses with all the aspects of the phenomenon of interest to the discoverer is a means of defeating the impact of unexpected sights" (p. 435). It is the ability to see complex patterns (and old problems from a new angle) using various kinds of manipulations of the external world, generating perceptions (and so critical constraints) to serve his mind's eye. For example, in the case of Faraday, the experiments amount to considering very simple physical setups and making them move spatially again and again, as if he were perceptually rehearsing the phenomena. That is Faraday had to see in his mind's eye the phenomena at hand, and he then had to modify the phenomena to perform "tests" of his hypotheses. After the perceptual rehearsal his mind internally considered the rehearsed impressions to start inceptions, which incorporated the constraints gained by perceptual rehearsal. He then was able to build apparatus to "instantiate" those hypotheses, and, finally, through the subsequent "inceptual rehearsal", some selected aspects of his perceptual experiences were magnified and improved.

These presymbolic (sometimes unconscious, i.e. not represented – Miller, 1992) inceptions form the background for the construction of a new mental model, by transforming and recasting ("independently" of the visual and experimental apparatus) the perceptual elements in a way which favors the heuristics used to arrive to the final "symbolic" solution of the given problem: "Once Faraday had distilled the structure of these optical deceptions, he constructed a geometrical mental model to envision the interfunctioning of the human eye and the real world, a model that explained how the optical deceptions worked" (Ippolito and Tweney, 1995, p. 450). These inceptions are "perceptual-like internal cognitions that serve as semi-abstract test beds for Faraday's theory", like in the case of Faraday's exploration of optical deception of 1831, a prototype of this kind of cognitive process (Tweney, forthcoming). Manipulative interchanges with the environment (experiments, models, apparatus, diagrams, cultural entities such as mathematical tools), where subsymbolic processes dominate, are very important: rarely scientific creativity can be understood in terms of a simple process of recombination of symbols, these are just the product of scientific creative thought.

## 6. EXTERNAL REPRESENTATIONS

Certainly a big portion of the complex environment of a thinking agent is internal, and consists of the proper software composed of the knowledge base and of the inferential expertise of that individual. Nevertheless, any cognitive system is composed by a "distributed cognition" among people and "external" technical artifacts (Hutchins, 1995; Norman 1993).

In the case of the construction and examination of diagrams in scientific reasoning, specific experiments serve as states and the implied operators are the manipulations and observations that transform one state into another. The scientific outcome is dependent upon practices and specific sensory-motor activities performed on a nonsymbolic object, which acts as a dedicated external representational medium supporting the various operators at work. There is a kind of an epistemic negotiation between the sensory framework of the scientist and the external reality of the object. This process involves an external representation consisting of written symbols, shapes, and figures that are manipulated "by hand". The cognitive system is not merely the mind-brain of the person performing the scientific task, but the system consisting of the whole body (cognition is *embodied*) of the person plus the external physical representation. In scientific discovery the whole activity of cognition is located in the system consisting of a human together with external objects.

An external representation can modify the kind of computation that a human agent uses to reason about a problem: the Roman numeration system eliminates, by means of the external signs, some of the hardest parts of the addition, whereas the Arabic system does the same in the case of the difficult computations in multiplication (Zhang and Norman, 1994; Zhang, 1997). The capacity for inner reasoning and thought results from the internalization of the originally external forms of representation. In the case of the external representations we can have various objectified knowledge and structure (like physical symbols – e.g. written symbols, and objects – e.g. three-dimensional models, shapes and dimensions), but also external rules, relations, and constraints incorporated in physical situations (spatial relations of written digits, physical constraints in geometrical diagrams and abacuses) (Zhang, 1997). The external representations are contrasted to the internal representations that consist of the knowledge and the structure in memory, as propositions, productions, schemas, neural networks, models, prototypes, images.

All external representations, if not too complex, can be transformed in internal representations by memorization. But this is not always necessary if the external representations are easily available. Internal representations can be transformed in external representations by externalization, that can be productive "if the benefit of using external representations can offset the cost associated with the externalization process" (p. 181). Hence, contrarily to the received view in cognitive science (Newell, 1990), not all cognitive processes happen in the internal model of the external environment. The information present in the external world can be directly picked out without the mediation of memory, deliberation, etc. Moreover, various different external devices can determine different internal ways of reasoning and cognitively solve the problems: as it is well-known even a simple arithmetic task can completely change in presence of an external tool and representation.

The external representations are not merely memory aids: they can give people access to knowledge and skills that are unavailable to internal representations, help researchers to easily identify aspects and to make further inferences, they constrain the range of possible cognitive outcomes in a way that some actions are allowed and other forbidden. The mind is limited because of the restricted range of information processing, the limited power of working memory and attention, the limited speed of some learning and reasoning operations; on the other hand the environment is intricate, because of the huge amount of data, real time requirement, uncertainty factors. Consequently, we have to consider the whole system, consisting of both internal and external representations, and their role in optimizing the whole cognitive performance of the distribution of the various subtasks.

## 7. GEOMETRICAL CONSTRUCTION IS A KIND OF MANIPULATIVE ABDUCTION

It is well-known that in the history of geometry many researchers used internal mental imagery and mental representations of diagrams, but also self-generated diagrams (external) to help their thinking. For example, it is clear that in geometrical construction many of the requirements indicated by the manipulative templates (section 4 above) are fulfilled. Geometrical constructions present situations that are curious and "at the limit". They are constitutively dynamic, artificial, and offer various contingent ways of epistemic acting, like looking from different perspectives, comparing subsequent appearances, discarding, choosing, re-ordering, and evaluating. Moreover, they present the features typical of manipulative reasoning illustrated above, such as the simplification of the task and the capacity to get visual information otherwise unavailable.

Let's quote an interesting Peirce's passage about constructions. Peirce says that mathematical and geometrical reasoning "consists in constructing a diagram according to a general precept, in observing certain relations between parts of that diagram not explicitly required by the precept, showing that these relations will hold for all such diagrams, and in formulating this conclusion in general terms. All valid necessary reasoning is in fact thus diagrammatic" (*CP*, 1.54). Not dissimilarly Kant says that in geometrical construction of external diagrams "[...] I must not restrict my attention to what I am actually thinking in my concept of a triangle (this is nothing more than the mere definition); I must pass beyond it to properties which are not contained in this concept, but yet belong to it" (Kant, 1929, A718-B746, p. 580).

We have seen that manipulative abduction is a kind of abduction, usually model-based, that exploits external models endowed with delegated (and often implicit) cognitive roles and attributes.

1. The model (diagram) is *external* and the strategy that organizes the manipulations is unknown *a priori*.
2. The result achieved is *new* (if we, for instance, refer to the constructions of the first creators of geometry), and adds properties not contained before in the concept (the Kantian to "pass beyond" or "advance beyond" the given concept, Kant, 1929, A154-B193/194, p. 192).[8]

Moreover, in the construction of mathematical concepts many external representations are exploited, both in terms of diagrams and of symbols. I am interested in my research in the diagrams which play an *optical* role – microscopes (that look at the infinitesimally small details), telescopes (that look at infinity), windows (that look at a particular situation), a *mirror* role (to externalize rough mental models), and an *unveiling* role (to help to create new and interesting mathematical concepts, theories, and structures).[9] I describe them as the *epistemic mediators* (cf. the section 4 above) able to perform various abductive tasks (discovery of new properties or new propositions/hypotheses, provision of suitable sequences of models able to convincingly verifying theorems, etc.).[10]

## 8. CONCLUSION

The main thesis of this paper is that abduction is a significant kind of scientific reasoning, helpful in delineating the first principles of a new theory of science. The interdisciplinary character of abduction is central and its fertility in various areas of research evident. The study of the high-level methods of abductive reasoning is situated at the crossroads of philosophy, epistemology, artificial intelligence, cognitive psychology, and logic. The various aspects of abduction I have described provide a better understanding of the processes of explanation and discovery in science. Their analysis certainly increases knowledge about creative and expert inferences that complete the epistemological and cognitive examination of important features of scientific reasoning.

Some research in the area of artificial intelligence has shown that methods for discovery could be found that are computationally adequate for abductively rediscovering – or discovering for the first time – empirical or theoretical laws and theorems.[11] Moreover, the study of diagnostic, visual, spatial, analogical, and temporal reasoning has demonstrated that there are many ways of performing intelligent and creative tasks that cannot be described with only the help of classical logic. However, non-standard logic has shown how we can provide rigorous formal models of many kinds of abductive reasoning such as the ones involved in defeasible, heterogeneous, and uncertain inferences (Magnani, Nersessian and Pizzi, 2002). Abduction is also useful in describing the different roles played by the various kinds of medical reasoning, from the point of view both of human agents and of computational programs that perform medical tasks such as diagnosis (Magnani, 2001a, chapter 4). Finally, concrete manipulations of external objects influence the generation of hypotheses: what I call manipulative abduction shows how we can find methods of constructivity in scientific and everyday reasoning based on external models and "epistemic mediators".

I think the cognitive activity of abduction can be further studied in many areas of model-based reasoning (Magnani and Nersessian, 2002), such as the ones involving creative, analogical, spatial inferences, and the exploitation of external representations and mediators, both in science and everyday situations, so that this can extend the epistemological and the psychological theory.

## NOTES

1. The famous syllogistic example given by Peirce is:

    1. All beans from this bag are white.
    2. These beans are from this bag.
    3. These beans are white.

2. As illustrated above, we have to distinguish between selective and creative abduction. Abduction that merely *selects* from an encyclopedia of pre-stored hypotheses is called selective. Abduction that generates *new* hypotheses (Magnani, 1992) is called creative.
3. Further aspects of experiment design and its relationship with the problem of communication in science during the transition from the personal to the public domain are given in Gooding and Addis (1999): only a small subset of many observations and measurements performed by individuals of research teams acquire the status of real and public phenomena. Moreover, additional properties of the agent in a scientific experimental setting are described: (1) ability to discriminate between observed results, (2) ability to make judgments about the likelihood of the occurrence of a result, (3) flexibility of the agent's change in perception of the world and his consequent capacity to respond to new information, (4) degrees of competence to build an experiment and observe the results, from novices to experts.
4. I derive this expression from the cognitive anthropologist Hutchins (1995), that coins the expression "mediating structure" to refer to various external tools that can be built to cognitively help the activity of navigating in modern but also in "primitive" settings. Any written procedure is a simple example of a cognitive "mediating structure" with possible cognitive aims: "Language, cultural knowledge, mental models, arithmetic procedures, and rules of logic are all mediating structures too. So are traffic lights, supermarkets layouts, and the contexts we arrange for one another's behavior. Mediating structures can be embodied in artifacts, in ideas, in systems of social interactions [. . .]" (pp. 290–291).
5. It is difficult to preserve precise spatial relationships using mental imagery, especially when one set of them has to be moved relative to another.
6. It is Hutchins (1995, p. 114) that uses the expression "cognitive ecology" when explaining the role of internal and external cognitive navigation tools. More suggestions on manipulative abduction can be derived by the contributions collected in the recent Morgan and Morrison (1999), dealing with the mediating role of scientific models between theory and the "real world".

7. Another example is given by the gestures that are also activated in talking, sometimes sequentially, sometimes in an overlapping fashion.
8. Of course in the case we are using diagrams to demonstrate already known theorems (for instance in didactic settings), the strategy of manipulations is not necessary unknown and the result is not new.
9. The epistemic and cognitive role of optical diagrams in "perceiving the infinite and the infinitesimal world" in the calculus is illustrated in Magnani and Dossena (2002).
10. For an analysis of the role of diagrammatic thinking and external representations (mirror and unveiling diagrams) in geometry and in the discovery on non-Euclidean Lobachevskyan geometry cf. Magnani (2001b, 2002).
11. On the recent achievements in the area of the machine discovery simulations of abductive creative tasks cf. Magnani, Nersessian and Pizzi, 2002.

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