Epistemic Mediators and Chance Morphodynamics

Lorenzo Magnani
Department of Philosophy and
Computational Philosophy Laboratory,
University of Pavia, 27100 Pavia, Italy, and
Georgia Institute of Technology,
Atlanta, GA, 30332–0345, USA
`lmagnani@cc.gatech.edu`

Matteo Piazza and **Riccardo Dossena**
Department of Philosophy and
Computational Philosophy Laboratory,
University of Pavia, 27100 Pavia, Italy
`mpiazza@pure-reason.unipv.it`
`rdossena@pure-reason.unipv.it`

Abstract

The recent epistemological and cognitive studies concentrate on the concept of *abduction*, as a means to originate and refine new ideas. Traditional cognitive science and computational accounts concerning abduction aim to illustrate discovery and creativity processes in terms of *theoretical* and "internal" aspects, by means of computational simulations and/or abstract cognitive models. We will illustrate in this paper that some typical internal abductive processes are involved in *chance discovery* and *production* (for example through radical innovations). Nevertheless, especially concrete manipulations of the external world constitute a fundamental passage in chance discovery: by a process of *manipulative abduction* it is possible to build prostheses (*epistemic mediators*) for human minds, by interacting with external objects and representations in a constructive way. In this manner it is possible to create *implicit* knowledge through doing and to produce various opportunity to find, for example, anomalies and fruitful new risky perspectives. This kind of embodied and unexpressed knowledge holds a key role in the subsequent processes of scientific comprehension and discovery. The paper describes some of the "templates" of manipulative behavior which account for the most common cognitive and epistemic acting related to chance discovery and chance production. The last part of the paper is devoted to illustrate chance discovery from the perspective of dynamical systems. Chance discovery and production can be viewed as a kind of event related to the transformations of the *attractors* responsible of the cognitive system performances.

Theoretical and Manipulative Reasoning

Science is one of the most explicitly constructed, abstract, and creative forms of human knowledge. In the twentieth century Kuhnian ideas about irrationality of conceptual change and paradigm shift (Kuhn 1962) brought philosophers of science to distinguish between a *logic of discovery* and a *logic of justification*, and to the direct conclusion that a logic of discovery, and then a *rational* model of discovery, cannot exist.

Today researchers have by and large abandoned this attitude by concentrating on the concept of *abduction* pointed out by C.S. Peirce as a fundamental mechanism by which it is possible to account for the introduction of new explanatory hypotheses in science.

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. There are two main epistemological meanings of the word abduction (Magnani 2001): 1) abduction that only generates "plausible" hypotheses ("selective" or "creative") and 2) abduction considered as inference "to the best explanation", which also evaluates hypotheses. 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.

Theoretical abduction[1] certainly illustrates much of what is important in creative abductive reasoning, in humans and in computational programs, but fails to account for many cases of explanations occurring in science when the exploitation of environment is crucial. It fails to account for those cases in which there is a kind of "discovering through doing", cases in which new and still unexpressed information is codified by means of manipulations of some external objects (*epistemic mediators*). The concept of *manipulative abduction*[2] captures a large part of scientists thinking where the role of action is central, and where the features of this action are implicit and hard to be elicited: action can provide otherwise unavailable information that enables the agent to solve problems by starting and by performing a suitable abductive process of generation or selection of hypotheses.

Many attempts have been made to model abduction by developing some formal tools in order to illustrate its com-

---

[1] Magnani (Magnani 2001; 2002a) introduces the concept of theoretical abduction. He maintains that there are two kinds of theoretical abduction, "sentential", related to logic and to verbal/symbolic inferences, and "model-based", related to the exploitation of internalized models of diagrams, pictures, etc., cf. below in this paper.

[2] Manipulative abduction and epistemic mediators are introduced and illustrated in (Magnani 2001).

putational properties and the relationships with the different forms of deductive reasoning (Bylander *et al.* 1991). Some of the formal models of abductive reasoning are based on the theory of the *epistemic state* of an agent (Boutilier & 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*). These kinds of logical models are called sentential (Magnani 2001).

They exclusively deal with selective abduction (diagnostic reasoning)[3] and relate to the idea of preserving *consistency*. Exclusively considering the sentential view of abduction does not enable us to say much about creative processes in science, and, therefore, about the nomological and most interesting creative aspects of abduction. It mainly refers to the *selective* (diagnostic) and merely *explanatory* aspects of reasoning and to the idea that abduction is mainly an inference *to the best explanation* (Magnani 2001).

Change and Chance

The internal side of abductive reasoning

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: the *model-based* sides of creative abduction (cf. below).

From the Peirce's philosophical point of view, 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" (Peirce 1931 58, 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, so that we can individuate a *model-based abduction*.

Hence, it is in terms of *model-based abduction* (and not in terms of sentential abduction) that we have to think to explain complex processes like scientific conceptual change. Related to the high-level types of scientific conceptual change (Thagard 1992) are different varieties of *model-based abductions* (Magnani 1999). Following Nersessian (Nersessian 1999), the term "model-based reasoning" is used to indicate the construction and manipulation of various kinds of representations, not mainly sentential and/or formal, but mental and/or related to external mediators.

Mental models (Johnson-Laird 1983) perform a kind of internal model-based reasoning. Other examples of model-based reasoning are constructing and manipulating visual representations, thought experiment, analogical reasoning, but also the so-called "tunnel effect" (Cornuéjols, Tiberghien, & Collet 2000), occurring when models are built at the intersection of some operational interpretation domain - with its interpretation capabilities - and a new ill-known domain.

Finding inconsistencies by radical innovation

It is well-known that the derivation of inconsistencies contributes to the search for alternative, and possibly new, hypotheses (Popper 1959; Lakatos 1970).

Surely surprise and curiosity are related to the detection of inconsistencies (Magnani 2001, chapter 6). *Internal* model-based abductive ways of generating a hypothesis that explains some phenomenon or conceptual problem that produced the question are heuristically linked to the activity itself both of *finding* that certain puzzling phenomenon or that particular conceptual problem or of *eliciting* that certain "hidden" phenomenon or conceptual problem. Hence, they are related to the activity of finding and producing chance. We will see (cf. section "Extracting chance through manipulative abduction") that also from the perspective of a kind of reasoning we can call *external* (i.e. manipulative) typical templates of epistemic acting are still devoted to generate inconsistencies and curiosities as new *trends* to reach - abduce - new hypotheses.

In *Against Method*, Feyerabend (Feyerabend 1975) attributes a great importance to the role of contradiction. He establishes a "counterrule" which is the opposite of the neoposititivistic one that it is "experience", or "experimental results" which measures the success of our theories, a rule that constitutes an important part of all theories of corroboration and confirmation. The counterrule "[...] advises us to introduce and elaborate hypotheses which are inconsistent with well-established theories and/or well-established facts. It advises us to proceed counterinductively" (p. 20). *Counterinduction* is seen more reasonable than induction, because appropriate to the needs of creative reasoning in science. We know that counterinduction, that is the act of introducing, inventing, and generating new inconsistencies and anomalies, together with new points of view incommensurable with the old ones, is congruous with the aim of inventing "alternatives" ("proliferation of theories is beneficial for science"), is very important in all kinds of creative abductive reasoning. Moreover, counterinduction, as the introduction of inconsistencies and conflicts, promotes the chance discovery for further epistemic growth.

We have illustrated above that from the Peirce's philosophical point of view, all inference is a form of sign activity, where the word sign includes "feeling, image, conception, and other representation" (Peirce 1931 58, 5.283). That is, a considerable part of the inference activity is model-based. Hence, many model-based ways of reasoning are performed in a manipulative way by using external tools and mediators (cf. the following section). *Manipulative abduction* (Magnani 2001) happens when we are thinking through doing and not only, in a pragmatic sense, about doing. So the idea of manipulative abduction goes beyond the well-known role of experiments as capable of forming new scientific laws by means of the results (the nature's answers to the investigator's question) they present, or of merely playing a predictive role (in confirmation and in falsification). Manipulative abduction refers to an extra-theoretical behavior that aims at

---

[3] As previously indicated, it is important to distinguish between *selective* (abduction that merely selects from an encyclopedia of pre-stored hypotheses), and *creative* abduction (abduction that generates new hypotheses).

creating communicable accounts of new experiences to integrate them into previously existing systems of experimental and linguistic (theoretical) practices. The existence of this kind of extra-theoretical cognitive behavior is also testified by the many everyday situations in which humans are perfectly able to perform very efficacious (and habitual) tasks without the immediate possibility of realizing their conceptual explanation.

In the following section manipulative abduction will be considered from the perspective of the relationship between unexpressed knowledge and external representations. The power of model-based reasoning and abduction (both theoretical and manipulative) mainly depends on their ability to extract and render explicit a certain amount of important information, unexpressed at the level of available data. They have a fundamental role in the process of transformation of knowledge from its *tacit* to its *explicit* forms, and in the subsequent knowledge elicitation and use. It is in this process that chance discovery, promotion, and production is central. Let us describe how this happens in the case of "external" model-based processes.

Extracting Chance through Manipulative Abduction

Chance and unexpressed knowledge

As pointed out by Polanyi in his epistemological investigation, a large part of knowledge is not explicit, but tacit: we know more than we can tell and we can know nothing without relying upon those things which we may not be able to tell (Polanyi 1966).

As Polanyi contends, human beings acquire and use knowledge by actively creating and organizing their own experience: tacit knowledge is the practical knowledge used to perform a task. The existence of this kind of not merely theoretical knowing behavior is also testified by the many everyday situations in which humans are perfectly able to perform very efficacious (and habitual) tasks without the immediate possibility of realizing their conceptual explanation: they are not "theoretically" *aware* of their capabilities. In some cases the conceptual account for doing these things was at one point present in the memory, but now has deteriorated, and it is necessary to reproduce it, in other cases the account has to be constructed for the first time, like in creative experimental settings in science.

Hutchins (Hutchins 1995) illustrates the case of a navigation instructor that for 3 years performed an automatized task involving a complicated set of plotting manipulations and procedures. The insight concerning the conceptual relationships between relative and geographic motion came to him suddenly "as lay in his bunk one night".

We can find a similar situation also in the process of scientific creativity. Too often, in the cognitive view of science, it has been underlined that conceptual change just involves a *theoretical* and "internal" replacement of the main concepts. But usually researchers forget that a large part of this processes are instead due to *practical* and "external" *manipulations* of some kind, prerequisite to the subsequent work of theoretical arrangement and knowledge creation. When these processes are creative we can speak of manipulative abduction (cf. above).

Scientists need a first "rough" and concrete experience of the world to develop their systems, as a *cognitive-historical* analysis of scientific change (Nersessian 1992) and (Gooding 1990) has carefully shown.

Traditional examinations of how problem-solving heuristics create new representations in science have analyzed the frequent use of analogical reasoning, imagistic reasoning, and thought experiment from an internal point of view.[4] However attention has not been focalized on those particular kinds of heuristics, that resort to the existence of *extra-theoretical* ways of thinking (*thinking through doing*, cf. (Magnani 2002b)). Indeed many cognitive processes are centered on *external representations*, as a means to create communicable accounts of new experiences ready to be integrated into previously existing systems of experimental and linguistic (theoretical) practices.

For example, in the simple case of the construction and examination of diagrams in elementary geometrical reasoning, specific experiments serve as states and the implied operators are the manipulations and observations that transform one state into another. The geometrical outcome is dependent upon practices and specific sensory-motor activities performed on a non-symbolic 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 problem solver and the external reality of the diagram (Magnani 2002a). 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.

This process involves an external representation consisting of written symbols and figures that for example are manipulated "by hand". The cognitive system is not merely the mind-brain of the person performing the geometrical task, but the system consisting of the whole body (cognition is *embodied*) of the person plus the external physical representation. In geometrical discovery the whole activity of cognition is located in the system consisting of a human together with diagrams.

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. The capacity for inner reasoning and thought results from the internalization of the originally external forms of representation (Zhang 1997).

The external representations are not merely memory aids: they can give people access to knowledge and skills that are

---

[4] The empirical "in vivo" recent research by Dunbar (Dunbar 1999), in many molecular biology and immunology laboratory in US, Canada and Italy, has demonstrated the central role of the unexpected in creative abductive reasoning. "Scientists expect the unexpected".

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. They increase the chance discoverability. 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.

The extra-theoretical dimension of chance discovery: templates of epistemic acting and epistemic mediators

We have introduced above the notion of *tacit knowledge*. Now we propose an extension of that concept. There is something more important beyond the tacit knowledge "internal" to the subject - considered by Polanyi as personal, embodied and context specific. We can also speak of a sort of tacit information "embodied" into the whole relationship between our mind-body system and suitable external representations. An information we can extract, explicitly develop, and transform in knowledge contents, to solve problems.

Peirce gives an interesting example of model-based abduction 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" (Peirce 1931 58, 5.221). This surely suggests that abductive movements have also interesting extra-theoretical characters and that there is a role in abductive reasoning for various kinds of manipulations of external objects. *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 these considerations suggest, then, that there exist a creative form of thinking through doing, fundamental as much as the theoretical one: *manipulative abduction* (see (Magnani 2001) and (Magnani 2002a)). As already said *manipulative* abduction happens when we are thinking *through* doing and not only, in a pragmatic sense, about doing.

Various templates of manipulative behavior exhibit some regularities. The activity of manipulating external things and representations 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.

Some common features of the tacit templates of manipulative abduction, 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 and so to open new possible reasoning opportunities (Oersted's report of his well-known experiment about electromagnetism is devoted to find describe some anomalous aspects that did not depend on any particular theory of the nature of electricity and magnetism); 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 into a static spatial one that should promote a subsequent bird's-eye view (narrative or visual-diagrammatic), fruitful for further outcomes; 3. referral to experimental manipulations that exploit *artificial apparatus* to free new possible stable and repeatable sources of information about hidden knowledge and constraints (Davy set-up in term of an artifactual tower of needles showed that magnetization was related to orientation and does not require physical contact); 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).

Gooding (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 the strategic application of old and new *templates* of behavior mainly connected with extra-theoretical components, for instance emotional, esthetical, ethical, and economic.

The whole activity of manipulation is devoted to building various external *epistemic mediators* 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]

From the point of view of everyday situations manipulative abductive reasoning and epistemic mediators exhibit very interesting features: 1. action elaborates a *simplification* of the reasoning task and a redistribution of effort across time (Hutchins 1995), when we need to 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 enables us to build *external artifactual models* of task mechanisms instead of the corre-

---

[5] It is difficult to preserve precise spatial and geometrical relationships using mental imagery, in many situations, especially when one set of them has to be moved relative to another.

sponding internal ones, that are adequate to adapt the environment to agent's needs. 4. 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. Also natural phenomena can play the role of external artifactual models: under Micronesians' manipulations of their images, 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). The cognitive process is *distributed* between a person (or a group of people) and external representation(s), and so obviously *embedded* and *situated* in a society and in a historical culture.[6]

Mirroring hidden properties through optical diagrams

An interesting epistemological situation we have recently studied is the one concerning the chance discovery role played by some special epistemic mediators in the field of non-standard analysis, an "alternative calculus" invented by Abraham Robinson (Robinson 1966), based on infinitesimal numbers in the spirit of Leibniz method. It is a kind of calculus that uses an extension of the real numbers system $\mathbb{R}$ to the system $\mathbb{R}^*$ containing infinitesimals smaller in the absolute value than any positive real number. We maintain that in mathematics diagrams play various roles in a typical abductive way. Two of them are central:

- they provide an intuitive and mathematical *explanation* able to help the understanding of concepts difficult to grasp, that appear hidden, obscure, and/or epistemologically unjustified, or that are *not expressible* from an intuitive point of view;
- they help *create* new previously unknown concepts.

In the construction of mathematical concepts many external representations are exploited, both in terms of diagrams and of symbols. We are interested in our research in 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 create new and interesting mathematical concepts, theories, and structures).[7]

The role of an "optical microscope" that shows the behavior of a tangent line is illuminating. In standard analysis, the change dy in y along the tangent line is only an approximation of the change Δy in y along the curve. But through an optical microscope, that shows infinitesimal details, we can see that $dy = \Delta y$ and then the quotient $\Delta y / \Delta x$ is the same of dy/dx when $dx = \Delta x$ is infinitesimal (see Figure 1 and, for details, (Magnani & Dossena 2002)). This removes some difficulties of the representation of the tangent line as limit of secants, and introduces a more intuitive conceptualization: the tangent line "merges" with the curve in an infinitesimal neighborhood of the contact point.

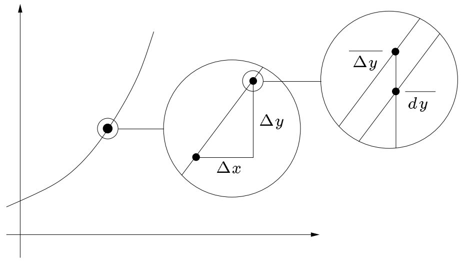

Figure 1: An optical diagram shows an infinitesimal neighborhood of the graph of a real function.

Only through a second more powerful optical microscope "within" the first (we calls this kind of epistemic mediators *microscopes within microscopes*), we can see the difference between the tangent line and the curve. Under the first diagram, the curve looks like the graph of

$$f'(a)x,$$

i.e., a straight line with the same slope of its tangent line;[8] under the second, the curve looks like

$$f'(a)x - \frac{1}{2}f''(a).$$

This suggests nice new mental representations of the concept of tangent line: through the optical lens, the tangent line can be seen as the curve, but through a more powerful optical lens the graph of the function and the graph of the tangent are distinct, straight, and parallel lines. The fact that one line is either below or above the other, depends on the sign of $f''(a)$, in accordance with the standard real theory: if $f''(x)$ is positive (or negative) in a neighborhood, then f is convex (or concave) here and the tangent line is below (or above) the graph of the function.

---

[6] Magnani (Magnani 2001, chapter 6) stresses the importance of the so-called preinventive forms in abductive reasoning. Intuitively an anomaly is something surprising, as Peirce already knew "The breaking of a belief can only be due to some novel experience" (Peirce 1931 58, 5.524) or "[...] until we find ourselves confronted with some experience contrary to those expectations" (Peirce 1931 58, 7.36). Therefore it is not strange that something anomalous can be found in those kinds of structures the cognitive psychologists call *preinventive*. Cognitive psychologists have described many kinds of preinventive structures (typically unstable and incomplete - on structural stability cf. below section "Chance morphodynamics") and their desirable properties, that constitute particularly interesting ways of "irritating" the mind and stimulating creativity (Finke, Ward, & Smith 1992): they are certainly of interest for change discovery and production.

[7] The epistemic and cognitive role of mirror and unveiling diagrams in the discovery of non-Euclidean geometry is illustrated in (Magnani 2002a).

[8] This is mathematically justified in (Magnani & Dossena 2002).

However, this easily mirrors a sophisticated *hidden* property. Let f be a two times differentiable function and let a be a flex point of it. Then $f''(a) = 0$ and so the second microscope shows again the curve as the same straight line: this means that the curve is “very straight” in its flex point a. Of course, we already know this property – the curvature in a flex point of a differentiable two times function is null – which comes from standard analysis, but through optical diagrams we can find it immediately and more easily (the standard concept of curvature is not immediate).

Some diagrams could also play an unveiling role, providing new light on mathematical structures: it can be hypothesized that these diagrams can lead to further interesting creative results.

We stated that in mathematics diagrams play various roles in a typical abductive way. We can add that:

- they are *epistemic mediators* able to perform various abductive tasks in so far as
- they are *external representations* which provide explanatory and abductive results also fruitful in some aspects of chance production.

Chance Morphodynamics

We have seen that the “bodily” manipulation of external objects is central to delineating new conceptual perspectives and solutions (cf. the previous section concerning the features of the tacit templates of manipulative abduction and external epistemic mediators). Hence, an *intentional* “action” in the world is able to add a *prosthesis* to the mind, by expanding its possibilities and by suggesting new information worth to be analyzed.

Traditional cognitive science accounts refer to the *computational* perspective, that describes cognition as the operation of a special mental “computer” that computes different internal symbolic representations. This approach is considered too reductive, since it is based on the functionalist hypothesis (which cannot render the *external dimension* of cognition), and on a computation of static entities.

Interesting insights on the problem of hypotheses generation and chance production and discovery, in terms of *dynamical* evolution of complex systems, come from a different contrasting approach: the dynamical approach to cognitive science. We can use the mathematical tools of dynamical systems to study cognition by thinking to a cognitive system not just as a computer, but as a dynamical system, consisting of mind, body, and external environment, mutually and simultaneously influencing and coevolving. This also justifies the pragmatic and “embodied” aspects of cognition. This kind of cognitive modeling is able to describe abductive processes as *embedded* dynamical entities “unfolding” in time. Hence, by means of the tools provided by a dynamical modeling it is possible to underline the importance of manipulative skills in scientific cognition (Port & van Gelder 1995).

A dynamical system can be considered a set of quantitative variables that changes continually and concurrently in time in accordance with dynamical laws described by some set of equations. It is the *state* of the system that changes: that is, the overall look of the system in a certain instant. We can study the behavior of the system by analyzing the change in its states. If a system can be described dynamically, this means it has *n* characteristics (e.g. position, mass, etc. - in the case of classical physical systems) evolving simultaneously in time. These characteristics can be measured, in any given instant, and associated to a real number. Therefore, the overall state of the system can be thought as an ordered set consisting of *n* real numbers, and the state space can be thought as isomorphic to a space of real numbers, the *n* dimensions of which correspond to the different system characteristics (the *phase space*). The evolution of the system in time corresponds to a sequence of points, a *trajectory*, inside the phase space. This sequence can usually be described mathematically as a function of time, considered an independent variable, giving a solution to the system of differential equations. The idea that the behavior of the system can be understood *geometrically* by a trajectory of points in a space, that is, describable in terms of positions and change of positions in a space of possible overall states, it is the central insight of dynamical systems theory. We can then describe the system in terms of *attractors*, *stability*, and *catastrophes*, features largely invisible from a classical perspective, but fundamental to describe some cognitive processes underlying abduction.

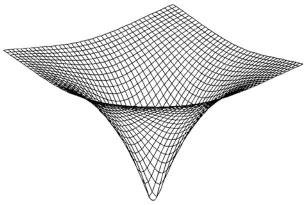

Figure 2: An intuitive visual model of the idea underlying the concept of attractor. Think of a marble rolling on a plane as far as it falls in a hollow like that in the picture. The marble will rotate inside it; then it will reach the resting position, at the bottom. Attractor is the stationary point corresponding to that position.

We speak about *chance morphodynamics* when considering chance discovery and production in the light of the “geometrical” framework above. The main idea is that a complex system, as the cognitive one, can be described in terms of a configurational structure. That is, different mental states are defined by their geometrical relationships within a larger dynamical environment. This suggests that the system, in any given instant, possesses a general *morphology* we can study by observing how it changes and develops. The term *morphodynamics* refers to those theories whose aim is to explain morphologies and iconic, schematic, Gestalt-like aspects of structures, whatever their underlying physical substrate may be, using the mathematical theory of dynamical systems (Thom 1980).

To set the morphology of the system it is interesting to identify mental states with *attractors*. Some dynamical systems are so complex, behaving non-linearly and erratically, jumping from a point in the space of their states to another very different in a brief time (as the states of the atmosphere). However, notwithstanding these sudden changes, a dynamical system has a series of states, the attractors, which tend to remain stable (Figure 2). A system can have a lot of attractors, contemplating more than a single stable state, arranged in some topological way.

The arrangement of attractors can be thought as controlled by the setting of the parameters in the equations that govern the system's dynamics. The shape and location of attractors change as these parameters vary. There could be certain critical settings of parameters where complete *qualitative* discontinuities and transformations in the arrangement of attractors occur (they can move, disappear or emerge). These discontinuities are responsible for the evolution of mental processes.

The concept of attractor, together with the interesting concepts of *adumbration* and *anticipation*, studied in the philosophical tradition of phenomenology[9] (see below), can offer interesting insights to understand how external representations and action support the "mind" in discovering and unveiling new chances (Magnani & Piazza 2002).

Imagine the overall state space of the cognitive system as a geometrical surface in which possible mental states (represented by attractors) interact. Like in the case of the intuitive representation of the relativistic conception of gravitation, we can see this surface as a flat horizontal rubber sheet. Attractor corresponds to the *attractive* zone in which we can imagine to place a large sphere. Its weight will stretch the sheet down and distort the system. Therefore, if we imagine the behavior of the cognitive system as a small ball that moves inside the rubber sheet, we can easily see how the structure, the "shape" of the space, affects its motion. The parameters responsible for the behavior of the system determine the "weight" of the attractor, then the shape of the surface, (one of the influencing factors is just what here is called manipulative abduction). This process is assimilable to the notion of *anticipation* (see below) developed in Husserl's phenomenology.

Chance anticipation

The philosophical tradition of phenomenology fully recognizes the important role of perceptual and kinesthetic data in the generation of "idealities" and mental constructs. For example, in phenomenological words, perception is a "structured" *intentional* constitution of the external objects, established by the rule-governed activity of consciousness. The modality of appearing in perception is already markedly structured: it is not that of concrete material things immediately given, but it is mediated by sensible schemata constituted in the temporal continual mutation of *adumbrations*. So at the level of "presentational perception" of pure lived experiences, only partial aspects (adumbrations [*Abschattungen*]) of the objects are provided. Therefore, a further activity of unification of the different adumbrations to establish they belong to a particular and single object (noema) is required. The appearances are the objects as they are intuitively and immediately given (by direct acquaintance) in the constituting multiplicity of the so-called adumbrations, endowed with a morphological character. When we see a - potential, we cannot foretell what it is - spherical form from one perspective, we are adumbrating it.

Adumbrations are multiple and infinite, and there is a potential co-givenness of some of them (those potentially related to single objects). Adumbrations, as rough information that has to be further processed, influence the parameters governing the cognitive system, in the sense that they are responsible for its shifts in the state space. They are incomplete and partial so for the complete givenness of an object a temporal process is necessary. *Anticipations* are the operations necessary to manage adumbrations that have to be performed by objective transcendence. Just because defeasible, anticipations correspond to a kind of non-intuitive intentional expectation. When we see a spherical form from one perspective (as an adumbration), we will assume that it is effectively a sphere, but it could be also a hemisphere (an example already employed by Locke). Anticipations share with visual and manipulative abduction various features: they are highly conjectural and nonmonotonic, so wrong anticipations have to be replaced by other plausible ones. Moreover, they constitute an activity of "generate and test" as a kind of "manipulative" cognition: indeed the finding of adumbrations involves kinesthetic controls, sometimes in turn involving manipulations of objects; but the activity of testing anticipations also implies kinesthetic controls and manipulations.

Finally, not all the anticipations are informationally equivalent and work like attractors for privileged individuations of objects: they foretell subsequent new *trends*. In this sense the whole activity is toward "the best anticipation", the one that can display the object in an optimal way. Prototypical adumbrations work like structural-stable systems, in the sense that they can "vary inside some limits" without altering the apprehension of the object. Like in the case of selective abduction (see above, section "Theoretical and manipulative reasoning"), anticipations are able to select possible paths for constituting objects, actualizing them among the many that remain completely tacit. Like in the case of creative abduction, they can construct new ways of aggregating adumbrations, by delineating the constitution of new objects/things. In this case they originate interesting new "attractors" that give rise to new "conceptual" generalizations. Particular manipulative actions favor or inhibit anticipations and so play the role "opportunities" or "risks" related to chance discovery.

Let us illustrate a simple astronomical example coming from the analysis of the evolution of the cognitive system expressing classical physics: new problems arose after Uranus was accepted to be a planet. Uranus' orbit could not be accurately predicted from Newtonian theory. In fact, by looking at the predicted orbit with a telescope, it was not possible to observe any astronomical body. This was an interesting *anomaly* to be solved. To explain this inconsistency, Adams and Leverrier, in the first half of the nineteenth century, introduced the *ad hoc* hypothesis that this anomaly could be explained by postulating the existence of another still unob-

---

[9] The so-called *naturalized phenomenology* aims to support phenomenology with scientific explanations, neurophysiological, mathematical, physical, etc. (Petitot 1999).

served planet. This is a case of productive *ad hoc* hypothesis guessing: this mere (audacious) hypothesis promotes a new chance for discovering a hidden object. In 1846 Galle decided to point his telescope in the direction indicated by the new hypothesis to effectively determine the existence of the planet. He actually "discovered" Neptune. It was the *decision* to use an external artifact able to "prosthesize" scientists' cognitive skills to produce a further scientific *chance*, concerning the empirical discovery.

Metaphorically we can say that the telescope, as an external tool manipulated by the scientist, "bumped" against the existing attractor accounting for the belief in the orbit of Uranus as predicted by the Newtonian theory. This brought to a catastrophic rearrangement of attractors, that is to the discovery of a new planet and to the development of a new conception of the solar system.

CONCLUSION

It is clear that the manipulation of external objects helps human beings in chance discovery and production and so in their creative tasks. We have illustrated the strategic role played by the so-called traditional concept of "implicit knowledge" in terms of the recent cognitive and epistemological concept of manipulative abduction, considered as a particular kind of abduction that exploits external models endowed with delegated cognitive roles and attributes. Abductive manipulations operate on models that are external and the strategy that organizes the manipulations is unknown *a priori*. In the case of "creative" manipulations of course the result achieved is also *new*, and adds properties not contained before.

We have described various "templates" of manipulative behavior which account for the most common cognitive and epistemic behaviors related to chance discovery and chance production. We have stressed the importance of producing inconsistencies by radical innovation at the level of internal abductive processes but also in the case of manipulative thinking, where epistemic mediators constitute interesting ways of finding anomalies and "curious" events, unexpected dynamical features of phenomena, contingent ways of epistemic acting, and manage incomplete data and information to anticipate new trends and hidden objects and properties.

Finally, we have said that some aspects of chance discovery and production can be usefully grasped through the perspective of dynamical systems. Chance production can be viewed as a kind of event related to the transformations of the *attractors* responsible of the cognitive systems. In the context of naturalized phenomenology we have described chance anticipation in the light of catastrophic rearrangement of attractors. A perspective that can be further developed for example to treat other interesting aspects of scientific discovery (conceptual change and scientific revolutions).

References

Boutilier, C., and Becher, V. 1995. Abduction as belief revision. *Artificial Intelligence* 77:43–94.

Bylander, T.; Allemang, D.; Tanner, M.; and Josephson, J. 1991. The computational complexity of abduction. *Artificial Intelligence* 49:1991.

Cornuéjols, A.; Tiberghien, A.; and Collet, G. 2000. A new mechanism for transfer between conceptual domains in scientific discovery and education. *Foundations of Science* 5(2):129–155. Special Issue on 'Model-based Reasoning in Science: Learning and Discovery', ed. by L. Magnani, N.J. Nersessian, and P. Thagard.

Dunbar, K. 1999. How scientists build models in vivo science as a window on the scientific mind. In Magnani, L.; Nersessian, N.; and Thagard, P., eds., *Model-Based Reasoning in Scientific Discovery*. New York: Kluwer Academic/Plenum Publishers. 85–99.

Feyerabend, P., ed. 1975. *Against Method*. London-New York: Verso.

Finke, R.; Ward, T.; and Smith, S. 1992. *Creative Cognition. Theory, Research, and Applications*. Cambridge, MA: MIT Press.

Gooding, D. 1990. *Experiment and the Making of Meaning*. Dordrecht: Kluwer.

Hutchins, E. 1995. *Cognition in the Wild*. Cambridge, MA: MIT Press.

Johnson-Laird, P. 1983. *Mental Models*. Cambridge, MA: Harvard University Press.

Kuhn, T. 1962. *The Structures of Scientific Revolutions*. Chicago: University of Chicago Press.

Lakatos, I. 1970. Falsification and the methodology of scientific research programs. In Lakatos, I., and Musgrave, A., eds., *Criticism and the Growth of Knowledge*. Cambridge: Cambridge University Press. 91–195.

Magnani, L., and Dossena, R. 2002. Perceiving the infinite and the infinitesimal world: unveiling and optical diagrams and the construction of mathematical concepts. Forthcoming in *Foundations of Science*.

Magnani, L., and Piazza, M. 2002. Morphodynamical abduction: causation by attractors dynamics of explanatory hypotheses in science. Forthcoming in *Foundations of Science*.

Magnani, L. 1999. Inconsistencies and creative abduction in science. In *AI and Scientific Creativity. Proceedings of the AISB99 Symposium on Scientific Creativity*, 1–8. Edinburgh: Society for the Study of Artificial Intelligence and Simulation of Behaviour, University of Edinburgh.

Magnani, L. 2001. *Abduction, Reason, and Science. Processes of Discovery and Explanation*. New York: Kluwer Academic/Plenum Publishers.

Magnani, L. 2002a. Epistemic mediators and model-based discovery in science. In Magnani, L., and Nersessian, N., eds., *Model-Based Reasoning: Science, Technology, Values*, 305–329. New York: Kluwer Academic/Plenum Publishers.

Magnani, L. 2002b. Thinking through doing, external representations in abductive reasoning. In *AISB 2002 Symposium on AI and Creativity in Arts and Science*. London: Imperial College.

Nersessian, N. 1992. How do scientists think? Capturing the dynamics of conceptual change in science. In Giere, R., ed., *Cognitive Models of Science*, Minnesota Studies in the Philosophy of Science, 3–44. Minneapolis: University of Minnesota Press.

Nersessian, N. 1999. Model-based reasoning in conceptual change. In Nersessian, N.; Magnani, L.; and Thagard, P., eds., *Model-based Reasoning in Scientific Discovery*, 5–22. New York: Kluwer Academic/Plenum Publishers.

Peirce, C. 1931–58. *Collected Papers*. Cambridge, MA: Harvard University Press. 1–6, ed. by C. Hartshorne and P. Weiss, 7-8, ed. by A.W. Burks.

Petitot, J. 1999. Morphological eidetics for a phenomenology of perception. In Petitot, J.; Varela, F.; Pachoud, B.; and Roy, J.-M., eds., *Naturalizing Phenomenology*. Stanford, CA: Stanford University Press. 330–371.

Piaget, J. 1974. *Adaption and Intelligence*. Chicago: University of Chicago Press.

Polanyi, M. 1966. *The Tacit Dimension*. London: Routledge & Kegan Paul.

Popper, K. 1959. *The Logic of Scientific Discovery*. London, New York: Hutchinson.

Port, R., and van Gelder, T., eds. 1995. *Mind as Motion. Explorations in the Dynamics of Cognition*. Cambridge, MA: MIT Press.

Robinson, A. 1966. *Non-Standard Analysis*. Amsterdam: North Holland.

Thagard, P. 1992. *Conceptual Revolutions*. Princeton: Princeton University Press.

Thom, R. 1980. *Modèles Mathématiques de la Morphogenèse*. Paris: Christian Bourgois. English translation by W.M. Brookes and D. Rand, *Mathematical Models of Morphogenesis*, Ellis Horwood, Chichester.

Zhang, J. 1997. The nature of external representations in problem-solving. *Cognitive Science* 21(2):179–217.