Chapter 2
The Role of Paradigms in Science: A Historical Perspective

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Philosophy of science without history of science is empty;
history of science without philosophy of science is blind

(Lakatos, 1971:91).

The studies of Thomas Kuhn gave a new interpretation of the philosophy of science (1977, 1978, 1983, 1995). This new kind of approach consists of a total reorganization even of the linguistic ways, to approach the whole scientific enterprise as well as that of individual scientists, so that even today the notion of "paradigm" is an essential one. To make use of the category "paradigm" implies, of course, the risk inherent in its polysemy, but this is also an advantage because it allows a more free and effective application of the concept in different historical periods and even more in different fields of knowledge.

When Kuhn elaborated his analysis of the particular form of human knowledge, i.e., science, he had in mind the developments in specific disciplines such as chemistry, physics, and astronomy, which were the sources of the vast majority of examples presenting it as evidence of its allegations in *The Structure of Scientific Revolutions*. Of these sciences he chose to treat also the moments of their historical development in which they had offered the paradigms that are predominantly presented as such to nonspecialist audiences. The reference here is of course the "new chemistry," Newtonian physics or Copernican revolution, for in the text even recurrence of the theme of relativity of Einstein could not have the same significance of the work of Newton, who entered the stock of more shared knowledge of humankind.

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That it is just to observe the new epistemological thought of Kuhn was based on a deep knowledge of the history of science and of the hard sciences above all; but the system that belonged to it is efficient thanks to its surprising ductility, by which it was possible to apply it to the history of economics or social sciences, as many papers had showed in the past decades. So, for many scholars the term “paradigm” seems to be unused in the original sense in historiography, while one can meet it in a very different contexts (Cerretta, 2007) thanks to its elusive polysemic nature (Barbano, 1999:254).

Before exploring the role that paradigms have historically played in the evolution of the paradigms of science, it is appropriate, to avoid any opportunities for confusion, to distinguish some elements that are characteristic of the scientific paradigm, and therefore must remain clear for the entire chapter.

We stick to the idea that a paradigm is a sort of methodological and conceptual universe in which the scientist can operate. As a universe it includes a self-coherent repertoire of scientific theories, no exact models, tools and even styles of thought of a historical period, which delimit the set of concepts and methods which can provide the scientist to do his job. Often the paradigm stems from a successful system, or a discovery that has shown its fertility either theoretical or experimental, that is shared as examples of answers to his research, but even more questions. This is because the structure of the paradigm is already providing the codified part of the knowledge system which is shared by all scientists who adhere to the implied methodology to look for the result that, according to coordinates of the paradigm, is expected to further confirm the explanatory power of the paradigm itself.

As an example we can use the mechanistic paradigm which was much current especially in the seventeenth and eighteenth centuries, when most of the scientific community acknowledged as the sole explanation of natural phenomena the movement or combination of movements of bodies in space. This paradigm, when applied to physics, implied that all what occurs in nature is the revelation of the laws of mechanics, and everything was interpreted according to the terms of quantities like force, mass, and energy. Referring also to what is described in the Preface, the framework given by the mechanistic paradigm can accommodate different styles of interpretation or theories, starting from the same conceptual tools, diverging interpretation of a field of phenomena, but without leaving the boundaries of the system, which in the chosen example, explains the phenomena with the combination of matter and movement. The symbolic value of the mechanistic paradigm is that it was widely extended to all natural sciences and to physiology as psychology where it provided successful clues to investigate important phenomena like the transmission of sensations, in a purely mechanical way (Abbagnano, 2001). On the other hand, the “mechanistic paradigm” slowed down the acceptance of the revolutionary ideas of Arrhenius who at the end of the nineteenth century introduced the concept of electrolytic dissociation, strongly opposed by the classical thermodynamics advocate. As a paradox, Ostwald, who was developing another paradigm, that of energetics contributed to such acceptance (Guerra & Capitelli, 2009).

After these premises is now our intention to show schematically, rather than argue, the changing paradigms in the history of natural science going beyond the

Fig. 2.1 Niccolò Tornioli (Siena, 1598 – Roma, 1651), *Gli astronomi-The Astronomers, oil on canvas*, cm 148×218,5, Inv. 269, Galleria Spada, Rome, 1640 ca

Poincarè conventionalism (Poincarè, 1905). We will not discuss these systems completely for different reasons, especially to avoid two major risks: to stick to a narration of rather remote times, and stray too far from more familiar scientific ideas that best convey the general sense of the speech, and re-proposing the classical case studies such as Newton, Galileo, and Copernicus, who immediately illustrate the point, but for which reappears the evidence that Kuhn hooked to his theories. Finally, a historical narrative of the history of scientific paradigms will never be complete in the sense of creating a harmonious succession of stages that lead naturally into one another, because the gap between paradigms is generally accomplished with fractures, the emergence of new forms and new ways to view these forms, in short, the communication of knowledge is comparable to the translation of a rigid body in Euclidean space (Fleck, 1983:192) (Fig. 2.1).

We therefore opted for the selection of several topics of particular interest in the history of natural sciences, they are explained by the worldviews, which gave a specific direction to the research in those historical moments. In this way scientists specifically interpreted certain phenomena with reference to the general view, which would therefore also oriented research and future results. Indeed, it is possible to recognize the establishment of a paradigm in science when the members of the scientific community for a period no longer feel obliged to justify the foundation of their education or seek alternatives (Buzzoni, 2008).

We will reference to the paradigm with the terms "worldview" and "style of thinking," not only because they seem more intuitive without impoverishing the sense, but also because these terms are used by other philosophers of science who also read the way science as a succession of paradigms and the time of the alternation is condensed into what we call scientific revolutions. We would thus only briefly refer to the relationship between Kuhn's thought and reflections of the bacteriologist Ludwik Fleck (1896–1961), an issue that has occupied many epistemologists, given the formidable connections (Campelli, 1999), but we are here not so much interested in this debate, but rather to highlight how the idea of this volume deals with the paradigms in various fields which is then also eligible in the perspective of a partial (opposed to full) adhesion to the Kuhnian tradition.

Fleck already before Kuhn talked about a *Denkstil*, a collective style of thinking, that for every age is the criteria that discriminate concepts eligible for a certain field of knowledge and explains how researchers can work within it, which just as the paradigm must be a shared and prescriptive structure. So a scientific theory is not in itself a logical system, even if it aspires to be so, it is nothing but a unit provided with a style, and this restricts the creative freedom of the scientist, but at the same time it makes the job easier because certain limits, however, allow the researcher to take for granted the basic assumptions (Campelli, 1999:13). The outcome of this approach is that the scientist's own style of thinking is obvious, while the alternative ways of thinking appear to him like fancy constructions and it is here that scientific disputes on the interpretation of the same phenomenon start, because in this optics it is not possible to decide on the basis of a single experiment, considered as the typical concept of "experimentum crucis." Contrairly, in order to give a decisive opinion, we need a whole system of trial and error for compliance to style.

A somewhat extreme illustration of the effect of the above on the history of science lies in the consideration that an illness like syphilis could not exist by itself but a concept developed and historically determined in a collective thought.

So the language confusion (Baldini, 1986:78) which went around with time by creating the concept of paradigm is due to the ambiguity of the great communicators as T. Kuhn, that is, their willingness to invent subtle and elusive, although effective slogans, which actually end to be sources of separations in the community (Campelli, 1999:6).

For example, in the studies of black body radiation of the second half of the nineteenth century (Kirchhoff, 1860), one can see that the choice of the scientist to observe it from the viewpoint of thermodynamics or electromagnetism or the probabilistic theory of the kinetics of gas has changed the scientific interpretation of the phenomena observed. In 1873, Maxwell showed that radiation incident normally on a surface would exert pressure on it while Bartoli in 1875 gave a proof of the independence of black body radiation on thermodynamics, without reference to any particular theory of light, obtaining a significant methodological result. Boltzmann, in the wake of these two works, derived in 1884 the famous law that bears his name. It has been said that black body radiation was not the most pressing problems in those decades: first was the source of irreversibility, the problem of specific heat of polyatomic gases, and the problem of the luminiferous ether. And then there was the need to explain the nature of the electron, of X-ray (Roentgen, 1896), and radioactivity (Bequerel, 1896). However, in the work of Planck on the radiation from a cavity most clearly emerge those traits of this new way of doing science, the revolution in the scientific paradigm in which quantum mechanics has its full completion.

The new way of doing science asks to abandon the reductionist methodology, according to which the study of any reality problem is due to the fundamental laws of dynamics or electromagnetism. The new methodology will be to identify new physical principles, experimentally detectable (not too difficult given the vastness of the data in those years), which should not necessarily refer to specific models and, extrapolating from their original context, to elevate the general laws of physics. In this optics, the black body problem is resolved by Planck. While this originally was strictly a thermodynamic problem, and the initial studies concerned the distribution of energy and entropy between the oscillators of the wall without any use of statistical methods, in 1901, when it became clear that we need to give a foundation to the law of the theoretical black body spectrum, Planck proposed the quantization of energy and founded his remarks on the statistical significance of entropy introduced by Boltzmann. The derivation by Planck of radiation law is nowadays regarded as the beginning of modern physics, Planck's law assuming a revolutionary character against the Kuhn's ideas (Kuhn, 1978). The real revolution was made by Boltzmann 20 years before in the development of statistical mechanics when his energy packets can be considered as an anticipation of quantum packets. On the other hand, the mixing between Boltzmann and Planck ideas was at the basis of their conflict (Lindley, 2001).

We add a short reflection on the Newtonian paradigm. Of course it has been for several centuries the reference for all the sciences, reinforcing the idea that gravitational and electric forces were able to explain other types of attractions, such as the interparticle attraction in the event of chemical reactions. Even today the laws codified in 1687 in *Philosophiae Naturalis Principia Mathematica* represent for us the basis of classical physics. Anyway, after the work of Newton, his theories were not easily accepted due to the gravity, mainly interpretated as an occult force, like those successfully used in science during the 16th century. It means that theories of Newtonians were perceived less "modern" than the mechanistic ones, which needed only the concepts of matter and motion to explain phenomena. But with the wave theory and the resumption of the ether, was solved in a way beyond the embarrassment of the surreptitious return of the occult force.

The success of Newtonian physics had as one of the many effects that to establish for a long and fruitful period the idea that mechanics should be the culmination of all the others, in order to match its explanatory scope. The application of the paradigm of a Newtonian world also means that the revolution of Lavoisier was born, in a certain sense, with the ambition of being able to vindicate an idea of chemistry intended primarily as a record of quantitative aspects, that is why we always remember in texts on the history of chemistry the efforts of Antoine Laurent Lavoisier (1743–1794) to use the balance of the experiments (analysis + synthesis) and attempts to prepare the calorimeter. Yet earlier, under the current system based on phlogiston, a theory invalidated by Lavoisier (Guerra & Capitelli, 2009), the chemistry seemed to be more explanatory, since it had the possibility of referring to "principles" of quality carriers. The transition to the new paradigm of the French chemistry was more the result of attention given to measured quantities, inspired from the successes of physics at the time, that a renewed interest in the opportunities of chemistry.

Indeed, after the work of Lavoisier on the path taken by the chemical discipline would lead to a re-evaluation of qualitative aspects, in most studies on the foundations will then be aimed at the explanation of the qualities revealed by the substances. Moving shortly to contemporary science, the mechanistic paradigm is now current in chemistry. The possibility of using fast computers to calculate directly molecular properties from first principles convinced most scientists, especially in sectors like chemical physics and metal-organic chemistry, that accurate calculations of numerical data are essential to chemical understanding. A look to contemporary journal papers will show that the use of theoretical calculations based on quantum-mechanical methods like density functional theory (DFT) or similar is often considered an essential part of chemical understanding. While the range of possibilities offered by such a quantitative chemistry is incredibly vast, one should not forget that the mechanistic paradigm has its limits, and the history of science registered them, while it appears that contemporary chemists are again unaware of such limits in their enthusiasm.

To state a case, the use of fully quantitative methods reduces the chemical understanding to the recognition of results produced by an algorithm. Interpretive ideas such as the interaction of atomic orbitals, the Lewis theory, or more advanced logical-linguistic concepts used in inorganic and organic chemistry cannot be completely exchanged, in terms of semantic value of the chemical structure, with an approach that actually transforms the theory into a kind of numerical experiment, semantically poor, as it is often recognized by the specialists themselves. Although the use of such methods asks the chemist a considerable understanding of mathematics and physics as well as numerical techniques and computer programming, these competences are not, as such, enriching in terms of chemical understanding of nature. Therefore, some prudence is in order, and one should not forget Mach's advice on the risk of considering all phenomena as manifestations of a mechanics. Fortunately the Lewis' bonding concept, based on the two electron exchange, still resists towards "ab initio" quantum mechanical description of chemical bonding in chemical practice and interpretation (Guerra & Capitelli, 2009).

In a volume of 1978, Robotti significantly traced the dynamic development of the conception of the first atomic models, in order to connect them to the world-views prevailing in those years. The proof of this point of departure is given by studying the changes that these models have undergone, the intermediate stages, corresponding to changes in the broader vision of science and methodological rules which meant that individual scientists were geared toward a certain reading of the experimental data, the result of theoretical choices (Robotti, 1978:10).

At the end of the eighteenth century gained great prominence in the scientific world the research on electricity, especially after the discovery of Luigi Galvani (1737–1798) on animal electricity and the work of Alessandro Volta (1745–1827). Without going into too much detains, one can easily imagine how the scientific community was attracted by the potential of the electrical phenomenon in general. For many decades, the focus was on applications of the "electric fluid," but with epochal success, as when Humphry Davy (1778–1829) by observing the action of electricity on chemical compounds established the invalidity of the role of universal acidifying character that Lavoisier had attributed to oxygen (from which the very term “oxygen,” the Greek for “acid principle,” Russian “Kislorod” and German “Sauerstoff” bearing the same meaning). In fact, following the invention of the battery by Volta, Davy succeeded since 1807 in the most demanding decompositions, up to the most discussed of hydrochloric acid, which has always considered the most acidic substance at all, which is devoid of the element oxygen (Testi, 1940:106). For Lavosier in fact, the 33 elementary substances he identified were combined together to obtain compounds with increasing degrees of acidity on the amount of oxygen contained in them (Lavoisier, 1789).

However, despite the remarkable results of applications scientists during the first half of the nineteenth century, the first approaches to unveil the behavior of electricity do not illuminate its nature, theory still lacking a clear-cut formulation based on experimental data. A change came in 1873 when James Clerk Maxwell (1831–1879) was able to give a unitary explanation of the whole corpus of causes and effects of electrical phenomena in the *Treaty on electricity and electromagnetism;* according to Robotti this persuaded many scientists to focus on a particular type of investigation: the study of the behavior of a rarefied gas in the presence of an electric discharge. The scenario was then represented by a renewed interest for a number of phenomena that had managed to gather around the idea of electricity, on which he worked for some time, but that still does not, however, suggest a decisive solution to its nature.

Consequently, the search had to move towards the investigation of the interactions between electricity and matter, was regarded as a simpler, namely gas, and was part of experiments in this sense that Joseph John Thomson (1856–1949) had signs of the existence of charged particles smaller than the atom (electrons). This led to the real possibility of a complex structure of the atom, since until that time the term “atomism” still meant that matter was made up of tiny particles, but not further divisible, according to the classical etymology of the word. This does not mean that the opposite hypothesis of composite particles in them had never been contemplated for some time, e.g., in the kinetic theory of thermal phenomena, where the origin of the observed properties could not be understood without referring to an internal structure of the atom, as was suggested by a more general study of electricity.

The next step was the creation of two models of the atom at the beginning of the twentieth century due to Thomson and Ernest Rutherford (1871–1937), but although there were all conditions to make reference to Planck’s theory on the quantization of energy this was not taken into account, according to Robotti, because those ideas were held in serious consideration only by a small contingent of scientists who dealt with the physics of black body (Robotti, 1978:24).

The “construction” of the atom was also influenced by certain conflicting positions on how to look at a hierarchical level lower than that of the paradigm, scientific theories. This directed the choices of the majority of scientists convinced that physics had to deal with the phenomena perceived by the senses and that the atom was a pure mathematical model. In this context, one can mention the famous debate between Ernst Mach (1838–1916) and Ludwig Boltzmann (1844–1906) on the nature of atoms (Guerra & Capitelli, 2009).

Let us return to the production of an electric discharge in a gaseous medium, which provides an illuminating case study. The structure of an electric discharge was found to have a quite complex structure with several luminous and dark regions which were explained only by a long interdisciplinary research involving atomic physics, electrostatics, and kinetic theory. In this interpretative effort a main step was to consider the productive value of the new mechanics, which allowed to determine the probability of atom ionization by electron impact, a crucial factor for the self-sustainment of the ionized condition of the gas (Loeb, 1934). An interesting open question is the very low recognition of the substantial relation of these studies with radioactivity: in chemistry two class phenomena: the chemical reactions produced by electric discharges (plasma chemistry) and those produced by ionizing radiations (radiation chemistry) have been traditionally and still are studied by two very weakly connected communities. Also laser chemistry, i.e., the chemistry activated by lasers, which could provide a link between plasma, radiation, and photochemistry (the science of chemical reaction produced by light absorption) is still a discipline basically independent of plasma and radiation chemistry.

It is interesting, in this context, to mention the attempt of the Soviet scientists L. T. Bugaenko, M. G. Kuzmin, and L. S. Polak to unify conceptually the three fields of photochemistry, radiation chemistry, and plasma chemistry in a single scientific discipline to be named “High Energy Chemistry” (Bugaenko, Kuzmin, & Polak, 1988). Not surprisingly, despite the foundation of a relatively important chemical journal with this title, such a bold effort was left basically unnoticed by the scientific community.

Experiments were also made in an indirect way on hot metal filaments, which were used to determine the charge/mass ratio of particles to lead to a direct proof of the existence of smaller constituents of the atom (Loeb, 1934). Dropping the assumption that the atom was the ultimate constituent of matter, it was necessary to establish the nature of such small particles (Jeans, 1901). This led back to the question of the interpretation of atomic spectra, which until then were considered, which much overlooking of the subject, to be possibly explained by the oscillation of the atom as an indivisible particle. This allowed the gradual introduction of the magnitude of these ions and other types of forces. The finding of charged material particles present equally in all atoms led to the hypothesis that the different chemical properties of elements were originated from the different electronic configurations of atoms (Robotti, 1978:58).

As mentioned earlier, another research parallel to the intrinsic nature of the atom was based on the theme of the radioactivity, as the only suitable means to obtain information about processes occurring inside the atom (Bellone, 1998:325; Soddy, 1912).

The decision to investigate a particular area of course suggested the desirability to promote a model or unconsciously represented adherence to a paradigm that favored a certain field of inquiry rather than another, e.g., the interest of Kelvin (1824–1907) to resolve questions related to electricity led him to devise a static model of the atom in which the “positive power” could be equally distributed uniformly within the atom or a smaller sphere which was part of it. Instead, Thomson’s mathematical model based on dynamics orbits could better explain (still much less satisfactory than successive models) issues such as the frequency of the emitted radiation of the chemistry of the elements. In short, much depended on the studies in which the scientist had been formed, that they did see an issue as more decisive than any other.

A similarly complex situation arose in the effort to the interpretation of experimental data and the scattering of spectral lines: Bohr moved away from the strong paradigm of mechanics and classical electromagnetism and started to build the structure of Planck's law, intended as a postulate.

Probably, Niels Bohr (1885–1962) is left reasonably groped by new lines of research because previously he had devoted himself to study slightly different from his colleagues, had in fact studied the atomic theory in relation to metals, where he had frequently observed phenomena that made him doubt about the interpretive power of classical mechanics and electromagnetism, as demonstrated in several stages of his dissertation (Robotti, 1978:228). On this same light one could draw a difference between the chemical conception of atoms, strongly connected to observation, and that of physicists, which was mostly a dynamic object. This chemical attitude towards atoms and molecules is largely lost nowadays, as discussed earlier. It is also important to observe that the "physical atom," especially in the golden age of nuclear physics between 1930 and 1950, was much studied for its nucleus and for the nuclear transmutations which actualized the alchemical "Phylosopher's Stone" but whose negation was an essential interpretive principle in the classical chemistry. Of course there are exceptions to this view; chemical transmutation were and are essential in the important field of nuclear chemistry, while the specialist of what is now called "physics of matter" studied the structure of atoms and molecules by methods which are essentially equivalent to those used in chemical physics and theoretical inorganic chemistry. In this context we want to underline that until 1930s atomic and nuclear physics were treated at the same level. Majorana nuclear forces were derived by the corresponding quantum mechanical exchange forces used to explain chemical bonding. The statement "chemistry is completely understood on the basis of quantum mechanics" held by well famous scientists including Dirac and Fermi shifted atomic physics research toward nuclear physics, creating a sort of monadism between chemistry and physics. In a certain sense, the dualism between chemistry and physics comes back to the ideas of Berthelot who in the nineteenth century defined chemistry as a positive science while physics was too much based on speculative and metaphysical ideas.

To complete this chapter, we will introduce two modern paradigms arising in the spirit of energetics. One example is Haken's synergetic, which comprises, in turn, more or less explicit adherence to the Darwinian paradigm (Swenson, 1992), let us see how.

The set of phenomena that present themselves to our experience can be regarded as so many systems composed of parts that act together under the limitation imposed by boundary conditions that determine the changes or limitations to which the system can respond or not to qualitative changes of their structure or its behavior (Haken, 1990:39). Synergetics deals with these changes, which can be the occurrence of a new motion characteristic of a fluid such as water, the emergence of a new

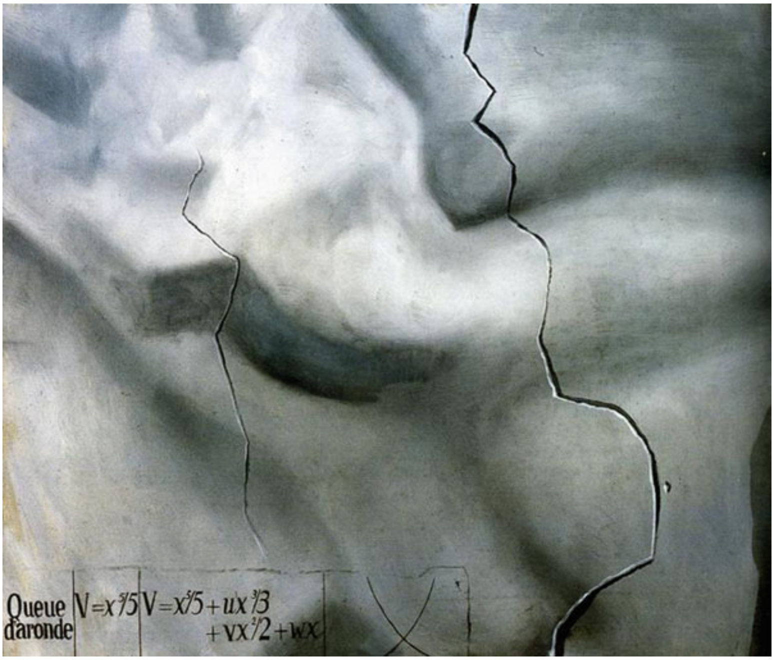

Fig. 2.2 Salvador Dalì, *Ratto topologico d'Europa – Omaggio a René Thom*, Oil on canvas, Fundación Gala-Salvador Dalí, Figueres, 1983

theory in a scientific discipline, or approval of a form or an image from our brains. The reaction of the system can be decomposed into modes, similar to the oscillation or Fourier modes in acoustics, only some of which continue to perpetuate their qualitative effects. Haken embraced the option of a generalized Darwinism because in his view only a few modes win the competition to determine the emergent properties of the observed system. In these terms, it is possible to use images and idea from the dynamic of continua to understand the development of structures in the world and even formulate a basic theory of creativity (Longo, 2009).

A second related attempt is the historically well known "catastrophe theory" (Thom, 1972) where the shapes of biological structures were interpreted as due to "regime conflicts" associated to a dynamics derived from a potential, in mechanical terms. While this attempt to explain by a single theory (although based on a non-trivial topology) phenomena like tissue specialization, earthquakes, social changes, language, mental illness, the action of man on matter fascinated scientists, laymen and even artists (Fig. 2.2) this theory is now mostly discredited from the technical point of view since its mathematical assumptions have been shown to be inadequate to describe most systems. In his most popular book, Haken discusses catastrophe theory as an example to illustrate the rise and decay of a scientific paradigm in terms of its synergetics.

The two theories share the ambition to provide a dynamic theory of mind. For example in the process of storing images in the brain, they store a lot for any perceived object, but then an image is identified with the observed object: “Once formed, the visual thinking behaves like a particle described by a state ‘quantum’ nonstationary in the attention potential (…) In simple terms, in the course of his wanderings, it may happen that the visual thinking to fall into a minimum of the attention potential” (Haken, 1990:45). Thom’s book ends with reference to the Zeeman’s model for memory, which is one of the inspiration of the theory (Zeeman will become later one of the public advocates of catastrophe theory of which offered a more defendable version closer in style to hard sciences).

Conclusion

We have shown a few cases of changing paradigms in sciences, focusing mainly on the problem of the nature of atoms and molecules. The reason for this choice is based on the easy evidence of the role of other structures, not experimental but paradigmatic, which drive scientist to devote attention to towards certain scientific topics and to consider those peculiar methodologies and solutions they actually adopt in specific works. We mostly ignore whether there is a logical or computable reason accounts for this state of matters, but for many events in the history of natural sciences this seems to be the right interpretation of the behavior of scholars’ community. What we have written here may contribute to provide the reader with some arguments towards such demonstrations and with conceptual tools to profit of this important interpretive concept in different contexts.

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