Chapter 1

FUNDAMENTAL TENETS OF MODELING THEORY

Modeling theory is promoted in this book as a pedagogical theory for science education. It is thereby concerned with cognitive processes and curriculum aspects leading students at different educational levels to the formation of particular knowledge and skills commonly associated with scientific theory and practice. As such, we acknowledge in our proposed theory that, in content and respective skills, scientific knowledge is distinguished in specific respects from other forms of knowledge, just as we acknowledge that there are common factors underlying the formation of knowledge of any type in humans' minds. In the same way, we acknowledge that various scientific disciplines have many features in common, just as we recognize that they may be distinguished from one another in some aspects. This is at least a practical position that stands as long as there are demarcation lines among these disciplines that are commonly recognized within the broad scientific community, as well as within the educational community, and irrespective of how artificial or how blurred these lines may sometimes seem to be. Nevertheless, we stand firmly in our theory for the position that various scientific disciplines share by and large enough common features to bear the common label of "science", and to be set apart all together from other forms of human endeavors. These features constitute the main concern of modeling theory, both as a theory of science and as a theory of science education.

Science is primarily concerned with the development of human knowledge (subject matters and processes) that helps us to understand the real world as objectively as possible and interact with this world as constructively as possible. Science education is primarily concerned with helping people to develop ways of knowing and learning that are as closely aligned as possible with scientific judgment and inquiry. Various science educators, teachers included, thus need to have a basic understanding and appreciation of the intricacies that govern the relationship between what we know and the things we know about in the real world, both as ordinary people and as scientists. Such knowledge, that is in part the object of this chapter, is indispensable for educators to guide science students in efficacious learning paths.

The nature of human knowledge about the real world has long been debated among philosophers, and most recently among cognitive researchers. Viewpoints have ranged between two extreme positions, mostly distinguished by their ontological and their epistemological premises. At one end of the spectrum lays *positivism*, a philosophical school that finds its roots in the works of Aristotle (384-322 BC), and various forms of which were held by August Comte (1798-1857), Claude Bernard (1813-1878), Ernst Mach (1838-1916), Bertrand Russell (1872-1970), and Rudolf Carnap (1891-1970). The main ontological premise of most positivists is that no physical object exists unless it can be humanly perceived. The epistemological consequence is that the physical world is knowable, and that it is the way it is perceived by our senses. Our knowledge of this world is thus conceived to constitute a photographic replica of whatever may be directly exposed to our senses. At the opposite end of the spectrum lays *nominalism*, a philosophical school that is commonly associated with the works of Henri Poincaré (1854-1912) and that finds its roots in the less radical works of Emmanuel Kant (1724-1804), Friedrich Hegel (1770-1831), and Friedrich Schelling (1775-1854). The main premise of nominalists is that the reality of physical things and events in the universe is completely independent of any human perception or conception, and that it is humanly unknowable. We thus can develop knowledge *about* but not *of* the physical world, nominalists argue, knowledge that consists of pure fabrications of our brains and that does not correspond in any form to this world.

In the middle of the spectrum are many *realism* schools that hold, to various degrees, that the real world is independent of human perception but that it is knowable in specific respects and to certain extents. As presented in this chapter, modeling theory is based on a number of tenets regarding the real world and our knowledge about this world, tenets that draw on certain aspects of *scientific realism* as advocated primarily by Mario Bunge (1967), Ronald Giere (1988), Rom Harré (1961), and George Lakoff (1987). The tenets also draw on certain foundations of non-realist schools that have valuable implications to science education, primarily those underlying the work of Thomas Kuhn (1970).

Major tenets and aspects of modeling theory pertaining to human knowledge in general are discussed in the first four sections of this chapter. Those pertaining specifically to scientific knowledge are discussed in the following four sections. Pedagogical consequences are discussed throughout this book, but primarily in Chapter 3. Discussion is limited, in this and following chapters, to those tenets and related cognitive and philosophical aspects that bear directly on the pedagogical concerns of this book, in line with Gruender's (2001) principle of demarcation:

> *If the application or resolution of an issue in the history or the philosophy of science has no implications, however general, for current work in the science of a field or for its teaching, then it is not one which scientists or science teachers have a professional duty to trouble themselves about.*

1.1 PHYSICAL REALITIES AND HUMAN COGNITION

> *In the absence of human intervention, physical systems exist, interact, and evolve, producing certain phenomena in the universe, all independently of human existence and activity. Humans can eventually come to realize the existence of such systems and phenomena, and develop about them ideas of variable degrees of viability.*

We hold in modeling theory a clear distinction between two worlds, the physical universe (or the real world) and human mind (or the mental world). The physical universe, i.e., the real world about which science is concerned, consists of physical systems (i.e., material systems, including biological ones) that interact and evolve in ways that give rise to specific phenomena. As discussed in § 2.1, a *physical system* is an entity in the real world that may consist of a single physical object or of many physical objects that interact with one another in specific ways. A *phenomenon* is an event, a *change* in spacetime, or a series of events that could result from the interaction among the constituents of a particular system and/or among different systems. An atom, the human body, the solar system are examples of physical systems. Electromagnetic radiation, human reproduction, planets' movement around a sun, are examples of physical phenomena.

Physical systems and phenomena, hereafter referred to as *physical realities*, are the object of natural sciences (e.g., physical and biological), as well as of technology and engineering. Physical realities are distinguished from *social realities* (e.g., a particular community of people and the activities of its members) that are the object of sociology and some branches of philosophy. They are especially distinguished from *intellectual* or *mental realities* that consist of cognitive structures and processes that are developed as a result of individual or collective human enterprises, and that are the object of cognition, psychology and some other branches of philosophy.

As long as humans do not intervene, whether consciously or unconsciously, with any aspect of a physical reality, the state and evolution of the reality in question remain independent of human existence and activity. This independence does not hold when humans intervene in the process, for making certain measurements, or for exploiting the reality one way or another. This is the case of technology where humans invent new systems or processes to make use of existing realities in specific respects, and/or to control or modify the state of such realities. This is also the case of ecological changes caused by human activities.

The existence and evolution of a physical reality is especially independent of whether or not humans could come to realize its existence. Yet, and as we shall see later, if a physical reality exists, humans could eventually realize its existence and develop particular ideas about it. They can do this: (a) *empirically,* i.e., through immediate perception or with the help of appropriate instruments, should they be available, or (b) *rationally*, through inference from established knowledge and related empirical data. For example, long before scientists were able to "detect" quarks in their laboratories, they inferred their existence from established knowledge about more complex atomic structure and phenomena. The same is true for distant galaxies that no one has ever "seen", not with the naked eye or with any available instrument.

The distinction we maintain between physical and mental realities does not necessarily imply total ontological independence of one another, especially not of mental realities from physical realities. We shall come back later to this point. The relative independence of the real world from the mental world in the manner postulated above should especially not be misinterpreted to imply the existence of an objective reality, a reality that our mind can eventually come to mirror in its "true" state. As our discussions throughout this book will hopefully make it clear, truth is for us a relative and partial predicate that humans can gradually develop through successive approximations (Bunge, 1973, p. 169).

The mental world of a given person includes *structures* and *processes* of two cognitive levels. In the first level are *implicit* structures and processes that are constructed involuntarily, and even unconsciously, in the person's mind, and that cannot be subject to conscious scrutiny by the same person or to direct scrutiny by others. In the second level are *explicit* structures and processes that: (a) are developed and evaluated voluntarily and consciously by the person through pure thought (intrinsic intellectual experience) and/or through an experience with physical and/or social realities, and that (b) can be communicated to other people and shared with them. The explicit part of the mental world is thereafter referred to as the *conceptual* world of a person. Modeling theory in science education is only concerned with student conceptual world, mainly in relation to physical realities and by contrast to science.

Conceptual structures include *conceptions*, i.e., concepts, theoretical statements (axioms, laws, theorems, definitions), models, theories, as well as conceptual *tools* used in the development and employment of various conceptions (e.g., language, pictures, mathematics, and related semantics and syntax). *Conceptual processes* include all conscious mental procedures, and associated norms and rules that a person follows in the construction and deployment of conceptual structures. Through practice, conceptual processes evolve gradually in their autonomy until they develop into *skills*. These are processes that are driven by internal needs and controlled by spontaneous habits, and that can be actuated autonomously outside typical situations within the context of which they were originally developed. The merits of a person's conceptions, tools and skills with regard to specific physical realities depend mostly on the extent to which they correspond to such realities and serve specific functions in their respect. Their merits primarily depend on whether they constitute knowledge or beliefs about such realities.

Knowledge consists of conceptual structures and processes that have been *corroborated* in specific respects. Corroboration consists of some sort of evidence, the most reliable of which being empirical or real world evidence that meets specific norms. Reliable evidence is an objective datum, or set of data, that is independent of personal idiosyncrasies and acceptable by a group of people according to well-defined criteria, that is open to scrutiny, and that stands firmly enough certain tests of refutability. These and other conditions for data to constitute reliable evidence from a scientific perspective are discussed in details in § 2.7. Not all evidence accepted by a given person or a given group of people is necessarily reliable; and thus, what might constitute knowledge for one person or group of people may not be considered as such by other individuals or groups. For example, when an event follows in some respects an astrological prediction, astrologers and their followers consider this to be a reliable evidence in their favor, whereas scientists and other people who do not believe in astrology consider the prediction to be a lucky guess, and the subsequent fact to be a mere coincidence or, at best, some event that can be statistically inferred. Similarly, the apparent motion of the sun still constitutes for many people reliable evidence for the sun's translation around the Earth rather than for the Earth's rotation around itself.

Beliefs are ideas that one holds about certain realities, individually or in common with others, without due corroboration. For example, when you hear somebody talk about a certain subject matter, you "know" that this person is in the process of speaking, and you can either "know" or "believe" that s/he is telling the truth or not. To know it one way or the other, you must have experienced what the person is talking about and/or possess some tangible data about the topic, like a photograph or a reliable record of some sort. In the absence of such empirical evidence, one can make an inferential judgment based on prior knowledge of the person and/or body language, and end up believing, or not, what the person is saying.

In this sense, we can speak of scientific knowledge (corroborated) but of religious beliefs (uncorroborated). In the same way, we can distinguish between student knowledge *of* a physical reality (i.e., that it exists) and *about* it (i.e., of its properties) on the one hand, and student belief in what science says about such a reality, on the other. Student knowledge would be based on some direct experience with the reality in question and/or on learning science meaningfully in the manner described in this book. In contrast, student belief would be based on authoritative instruction and following memorization by rote of scientific texts.

Once a system or a phenomenon becomes a physical reality, it makes it possible, but not necessary, for humans to know of it and about it*. Once this book has been printed, it became a physical reality that any person could know of, by seeing it on the shelf of a bookstore or by learning of its existence in a reference or through the media. One can further know what the book consists of and what it is about, by directly examining and reading it, as you are doing now, or indirectly, from a reliable third party. Seeing the book and reading it allows one to develop *experiential knowledge* about this work. Learning about it from another source may result in *traded knowledge*. The book also allows one to know of the existence of the author of this book, and perhaps to make some valid judgment about him from reading the book. This is *inferred knowledge*. Some beliefs (uncorroborated ideas) about the author and the book topics could also be generated in the process. As a theory of science, modeling theory is concerned with human knowledge, and especially scientists' knowledge. As a pedagogical theory, it is concerned with helping students turn, preferably in experiential forms, all sorts of knowledge and beliefs about physical realities into knowledge that is reliable by scientific standards.

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* Unless otherwise specified in the rest of this book, knowledge or belief "about" something refers to knowledge "of and about" it or belief "in and about it".

1.2 EXPERIENTIAL KNOWLEDGE

> *A person's new knowledge about a given physical reality exposed directly or indirectly to the person's senses results from interaction between the person and the reality. New knowledge thus depends on: (a) the existing knowledge of the person, (b) the actual (ontological) state of the reality that the person is interacting with and of its environment, (c) the condition of the person's senses and state of mind, and (d) the state of employed instruments, if any.*

The decision to read this book was triggered by your interest and other control factors in your mind that depend, in part, on your current knowledge about the topics discussed in the book. Once the book is in your hands, similar control factors will make you decide whether to read or skip particular paragraphs. While you are reading the book, you are interpreting words and sentences of your selection in terms of your current knowledge of the English language (and of other tools) and discussed topics. Without such knowledge, you would be able neither to make meaningful interpretation of what you are reading nor to determine whether or not you are offered something new to learn about. The reading process also depends on the affective state of your mind, the presence of any distracters around you, as well as on the quality of your eyes and of any seeing aids you might be using. The entire experience further depends on the book whose existence made your original decision possible, and whose layout has some influence on the ease with which you would be reading it and perhaps on what you might decide to read or to skip.

Hence, the reading experience in question is of you and of the book. The selection of what this experience involves and the process it follows depend on the state of both your mind and the book, as well as on the state of the mutual environment. The same holds for any human experience, especially when it results in knowledge development or learning. According to Johnson-Laird (1983, p.402), "our view of the world, is causally dependent both on the way the world is and on the way we are", and, according to Lakoff and Johnson (1980, p. 163), properties we attribute to physical objects "are not properties of objects *in themselves* but are, rather, interactional properties, based on the human perceptual apparatus, human conceptions of function, etc.".

Similarly, Bunge argues that empirical experience "is not a self-subsistent object but a certain *transaction* between two or more concrete systems, at least one of which is the experient organism. Experience is always of *somebody and* of *something*" (Bunge, 1967, p. 162, italics added), and the resulting knowledge "is attained jointly by experience (in particular experiment) and by reason (in particular theorizing)" (Bunge, 1973, p. 170). The transaction involves inputs from both knower and known, and the resulting knowledge reflects not only the reality of the known but also that of the knower.

The notion of experiential knowledge as resulting from a transaction, i.e., of an interaction that depends on the state of both the knower's mind and the surrounding environment including the object of study, is also at the core of Dewey's philosophy of education. Some, like Wong, Pugh, *et al.* (2001), have pushed Dewey's notion to the point of assuming that following such transaction, "both the person and world are necessarily transformed". Our interpretation is however that the world is transformed by the person as *conceived* in the mind, or even as *perceived* with senses, and not necessarily as it really exists. It is true that, sometimes, the person's environment could be physically "transformed", like when the intention is to modify the object of study or when some measurement done on the object affects the object itself. However, we do not admit that every learning activity entails a physical transformation of the "world", unless we take the person as part of it, so that when the person's mind is transformed *in* the world to which it belongs, so does the latter. Observing an object from a distance without any instrument that might affect the state of the object may help you to learn something about the object without affecting the object. As a result, your mind becomes transformed, but not the object. Similarly, information as transcribed in the selection you are now reading is not transformed because of your reading or because of some notes you might be jotting on the side. Such a physical transformation could only take place in a new edition of the book, should you kindly relay your notes to this author. Still, and because of all the influences mentioned above, and because of the limitations of our perceptual and conceptual systems, the transaction between knower and known results in knowledge (or belief) that does not mirror the perceived world. The outcome of the transaction is an *emergence* from both knower and known, i.e., a product that may share some properties of both but that also holds properties of its own that are not necessarily shared by either, and especially not the known object. For example, we attribute colors to physical objects while color is not an intrinsic property of real things but a consequence of the interaction of our visual sensory system with light in the real world.

In general, a person's experiential knowledge about a number of physical realities consists, from our point of view, of *conceptions* that could *correspond*, within certain limits, to specific structural or behavioral details in those realities. Some of these details may be common to all realities in question, while others may be particular to individual realities. From an ontological perspective, the correspondence might be: (a) *analogical*, like the picture of a familiar person we might have in our mind or like a circle drawn on a piece of paper to represent a round object, or (b) *analytical*, like the name of a person or like a point representing the person in a kinematical diagram. From an epistemological point of view, the correspondence might be subjective or objective. *Subjective* knowledge is often tainted with emergent details that are relatively detached from the real world and that may be entirely dependent on the idiosyncrasies of an individual's mental state. Such details are not necessarily reproducible or subject to similar interpretations by different people. In these and other respects, subjective knowledge is unreliable by many concerned people standards. In contrast, *objective* knowledge is characterized with details, including emergent details, that are kept in close and explicit correspondence to the real world, and detached in the best possible ways from particular human interests and mental states. When objective, experiential knowledge is shared by a group of people who can supply, by various standards, reliable evidence to their shared conceptions.

Scientific knowledge is in this respect the most objective form of experiential knowledge about physical realities. A scientific conception always corresponds to a set of physical realities in some analogical and/or analytical way, and with such a degree of precision that we can say that it reliably *represents* what it corresponds to in the real world (§ 2.7). The object of modeling theory in science education is to help students to develop norms and rules that allow them develop experiential knowledge that may be characterized as objective and reliable by scientific standards.

Our position in this matter is opposed to those who argue, with Latour and Woolgar (1979, p. 129), that scientific knowledge consists of mere artifacts “constituted through the artful creativity of scientists”, with no necessary correspondence of whatever form to existing physical realities. Giere (1988, p. 59) points out that this nominalist position regarding experiential knowledge in science “comes from the fact that [people who hold it] typically argue that there is no fundamental difference between the social sciences and the natural sciences”. Giere (*ibid*) then rightfully argues that the “general idea of ‘social construction’… can be accepted for many aspects of *social* reality. But this, by itself, provides no evidence that *natural* reality is similarly constructed”. If experiential knowledge, and especially scientific knowledge, consisted of mere conceptual inventions, and if physical realities were unknowable, “there would be no point in investigating things” in the first place (Bunge, 1973, p. 171), and, we add, there would be no point either in distinguishing science from other enterprises and thus in having separate curricula for science education.

1.3 TRADED KNOWLEDGE

> *The real world may be humanly knowable indirectly through knowledge trade, i.e., through interaction with other people and/or with public knowledge. Traded knowledge may contribute to experiential knowledge, and is sometimes indispensable for human knowledge to develop.*

Experiential knowledge about physical realities, i.e., knowledge developed through direct transaction with those realities, is perhaps the most meaningful form of knowledge. However, it is humanly impossible that all the knowledge of a person be experiential, both from a practical point of view and from a cognitive perspective. No human being can possibly know all s/he wants to learn about particular physical realities through direct transaction with those realities. Even when such a transaction is possible, knowledge development may also be affected by some social realities. There are times when knowledge may not even be developed without interaction with other people and/or with some public knowledge, i.e. knowledge of an individual person or of a community of people available through various media forms. Indeed, some knowledge, like new words and their meanings, can only be developed through such interaction. We call *traded knowledge* about a physical reality all forms of knowledge that a person develops about the reality not through direct transaction with it but following discourse with other people an/or exposure to public knowledge regarding the reality in question.

Human knowledge about physical realities is actually a mix of experiential and traded knowledge. Most of the knowledge our students develop about the real world in conventional science courses of lecture and demonstration is purely traded knowledge, and in some places all this knowledge is. Our position in modeling theory is to put more emphasis on experiential knowledge, especially at the pre-college level, and to promote student transaction with physical realities and empirical data, be it individually or in-group work. We hereby do not underestimate the importance of social factors in knowledge development, and we acknowledge unequivocally the role of public knowledge in the process, and especially the role of science textbooks. However, we admit neither that all human knowledge, including scientific knowledge, is purely traded, nor that social interaction involving other people, especially classroom peers, is always necessary or sufficient for developing meaningful knowledge.

Science education is concerned with helping students to develop knowledge about physical realities that is in line with scientific knowledge. To this end, science teachers must especially account in their courses, and on almost equal footings, for the established knowledge included in these courses (scientific subject-matter and related processes, along with underlying canons, norms and rules), and for the four dimensions involved in the development of such knowledge and listed in the experiential knowledge tenet (§ 1.2). The educational transaction facilitated by a science teacher thus involves primarily three major entities or sets of entities: (a) individual learners and their knowledge and beliefs about the world and science, (b) physical realities addressed in the course, and (c) related scientific knowledge. More specifically, knowledge (and beliefs) we are referring to, whether personal or scientific, consists of specific paradigms, and the transaction we are promoting in this book is to result in a paradigmatic evolution whereby students align their personal paradigms with those of science to certain reasonable levels.

1.4 PARADIGMS

A paradigm is, for us, a *conceptual* system that governs *explicitly* a person's *conscious* experience in a given situation, somewhat in the manner described by Kuhn (§ 1.5). The experience, though conscious, may also be affected implicitly by some mental structures and processes that are beyond the scope of this book. It may entail a single activity (thought or behavior, voluntary or involuntary) or a number of activities of one sort or another. It results in some form of *learning*, i.e., in the transformation of the involved paradigm and/or in the creation of a new one.

A paradigm, from our point of view, governs a person's conscious experience in the following respects:

1. It (the paradigm) determines the conditions that trigger every voluntary activity in the experience.
2. It sets forth standards, rules and guidelines for choosing and processing all that is necessary for the reification and continuous evaluation of the activity. This includes selection and analysis of empirical data when the experience is with physical realities.
3. It provides necessary conceptions, conceptual tools and methodology for conducting the activity, and for refining the paradigm subsequently.
4. It supplies appropriate mnemonics for consciously retrieving necessary means and method from memory.

Every human experience is thus paradigm-laden. Even blind perception (without aim) is. For, according to Kuhn (1970, p.113), "something like a paradigm is prerequisite to perception itself. What a man sees depends both upon what he looks at and also upon what his previous visual-conceptual experience has taught him to see". The paradigmatic dependence is not only about the interpretation of what one "looks at" in a perceptual experience. As mentioned in the second point above, it is foremost about sorting out primary from secondary details in a perceived reality. *Primary* details are salient details on which one decides to concentrate, and to retrieve from appropriate data for subsequent paradigm-laden analysis and interpretation. *Secondary* details are insignificant details that one decides to ignore or not to look at in the first place.

A given person possesses a number of paradigms of different natures, each tailored to a specific type of experience. These include, among others: *natural* paradigms for studying physical systems and phenomena in the universe, *technical* paradigms for conducting manual tasks with appropriate equipment, *social* paradigms for interaction with other people, and *metaphysical* paradigms (religion included, if any) for establishing beliefs about some ultimate "truths" within oneself and/or out in the cosmos, and for conducting oneself accordingly.

An individual's constellation of paradigms makes up her/his *worldview*, or world picture, somewhat in the sense advanced by Holton (1993). Holton defines a person's world view (or Weltbild) as "a generally robust, map-like constellation of the individual's underlying beliefs of how the world as a whole operates", beliefs that guide, to some degree, all opinions and actions of the person. Holton (1993, pp. 157-163) outlines his notion of worldview as the "constellation of underlying beliefs" in a concise list of 28 features. These features are virtually all attributable to our notion of worldview as the "constellation of paradigms".

Paradigms of different nature are not necessarily independent. Social paradigms are normally affected by metaphysical paradigms, technical paradigms by natural paradigms, and vice versa. Mutual dependence though does not necessarily imply coherence and consistency. As Holton (1993) argues, a person's worldview is "not necessarily internally coherent or noncontradictory". This can be reflected by a lack of coherence within the same paradigm or by a lack of consistency among different paradigms. Furthermore, a particular paradigm is "not necessarily stable over time" (Holton, 1993), and it may not be equally developed in the minds of different people. Various paradigms of a given person's worldview are not necessarily equally developed in the mind of this person. Among various paradigms possessed by a given person, those associated with the person's line of work are normally best developed. Among paradigms of the same nature held by different people, those held by concerned professionals are normally better developed than others'. That is why, for example, natural paradigms of scientists, i.e., scientific paradigms (§ 1.5), are better developed than those of lay people.

No two people can ever share exactly the same paradigm, whatever the nature of the paradigm or the profession that the two people might be having in common, and this, because of biological and cultural differences in people's history. For paradigms of a particular nature, differences are significantly more pronounced within the lay community than within a professional community guided by such paradigms. For instance, members of a given religious order (priests, nuns, pastors) share very similar religious beliefs and practice that make up the proclaimed metaphysical paradigm of their order, and more so do members of a given scientific community with respect to the natural paradigms associated with their fields of expertise. In fact, a scientific paradigm may be delimited in a specific field in such a way that we can practically ignore paradigmatic differences among scientists working in this field, and say that all those scientists share virtually the same paradigm. These scientists make up "a uniquely competent professional group [that should be recognized] as the exclusive arbiter of professional achievement… The group's members, as individuals or by virtue of their shared training and experience, must be seen as the sole possessors of the rules of the game or of some equivalent basis for unequivocal judgments" (Kuhn, 1970, p. 168).

1.5 SCIENTIFIC PARADIGMS: A MODELING PERSPECTIVE

According to Kuhn, a scientific "paradigm is what the members of a scientific community share, *and*, conversely, a scientific community consists of men who share a paradigm." (Kuhn, 1970, p. 176). However, and as Giere (1988, pp. 34ff) points out, Kuhn was so much involved in discussing the development or the evolution of scientific paradigms – and more specifically of scientific practice – in his book, that he neglected to specify paradigms with a clear structure. Kuhn recognized this fact indirectly in the epilogue of his book (1970), and in his reply (in Lakatos and Musgrave, 1970, p. 231-278) to Masterman (*ibid*, p. 59-89) who identified at least 21 different senses of the word paradigm as used by Kuhn. In an attempt to circumvent the problem, Kuhn defined a scientific paradigm as a conceptual system consisting of what he calls a "disciplinary matrix" associated with "symbolic generalizations", "beliefs in particular models", and a particular system of "values" (Kuhn, 1970, p. 182ff).

Our position regarding paradigms, and especially scientific paradigms, converges in part with Kuhn's position. We do not fully subscribe to Kuhn's work (1970), or any other work in the philosophy of science for that matter, and we acknowledge the merits of some of the criticism that this work has been subjected to (e.g., Lakatos & Musgrave, 1970). However, we believe that Kuhn's account of the development of scientific paradigms provides significant insights not only into those paradigms, but also into the natural paradigms of science students. In this respect, the cognitive implications of Kuhn's work bear for us a special value that will hopefully become evident in subsequent chapters, and especially in Chapter 3.

Scientific paradigms are natural paradigms. They are concerned only with physical systems and phenomena. Each scientific paradigm has a well-defined and exclusive scope. It can provide, in particular ways and with certain limits of *viability* (§ 2.7), particular answers to specific questions about physical realities; questions that are of interest to a particular community of scientists. Conceptual building blocks of a scientific paradigm are constructed, corroborated and deployed in the real world following generic tenets, principles and rules so as to provide nothing but reliable knowledge about this world.

We thus define a *scientific paradigm* as a natural paradigm shared by the members of a particular scientific community, of well-defined scope in the real world, and consisting of:

1. Ontological tenets about physical realities.
2. A scientific theory, or a set of theories about such realities, along with epistemological: (a) tenets that underline the nature of various conceptions that make up any scientific theory, and that establish the correspondence of theory and conceptions to the real world, and (b) principles and rules for conceptual structure and categorization, and for theory organization.
3. Specific methodology (including standards, tools, rules, guidelines, processes) for: (a) theory construction, corroboration and deployment (to borrow Hestenes' (1987) and Giere's (1988) terminology for various forms of theory implementation), and (b) continuous evaluation and refinement of all related conceptual structures and processes.
4. Axiological tenets some of which set the "value" of scientific theory and others govern scientist practice from an ethical point of view.

Among these four components of a scientific paradigm, only theory is formulated explicitly by the concerned community. In line with the position of many philosophers of science or mathematics (Casti, 1989; Giere, 1988; Harré, 1970; Hesse 1970; Wartofsky, 1968), and some science educators (Hestenes, 1987, 1992; Johsua & Dupin, 1999), a *scientific theory* is, for us, a conceptual system consisting of: (a) *a set of models* or families of models, and (b) *a set of particular rules and theoretical statements* that govern model construction and deployment and that relate models to one another and to specific patterns in the real world, and this in accordance with various tenets of the respective paradigm (§ 1.7 and § 2.6). These tenets, and, to a lesser extent, other paradigmatic components are often implicit in scientists' practice and literature. Philosophers of science have long been preoccupied in making them explicit, and cognitive scientists and science educators have lately joined them in this endeavor.

The scope of a scientific paradigm is set in accordance with the preoccupations of the scientific community with which it is associated. More specifically, it is function of the theory or set of theories that the designated community works on (§ 1.7). Each of the paradigmatic sets of tenets mentioned above is made up of two subsets, a subset of generic tenets and a subset of specific tenets. Generic subsets are common to practically all scientific communities, while specific subsets and any methodological differences that might distinguish one community from another are mainly due to the nature of respective theory. We may thus distinguish one or more paradigms within a given discipline (e.g., physics, chemistry, biology), depending on whether we group together all theories of the discipline or a limited number of those theories. For practical reasons, especially from a pedagogical point of view, and until the day we end up with a unified theory of science, we prefer to group together in a given paradigm a limited number of theories that correspond closely to one another and to the real world. This is how for example, in physics, we may group together, in what we call the *classical mechanistic paradigm*, Newtonian theory of translation, Euler theory of rotation, kinetic theory, thermodynamics, and classical electrodynamics.

Modeling theory in science education is concerned with helping students, especially those at the college and high school levels, develop natural paradigms that are *in line* with scientific paradigms (or that are *commensurable* with the latter, as we shall see in § 3.6). We do not pretend that modeling theory can help targeted populations to develop fully-fledged “scientific” paradigms by the time they graduate from high school or even college. This is an involved process that takes long years of actual scientific practice and that formal education alone can never accomplish under any educational theory, at least not by the time students graduate from college (Chapter 3).

Any scientific paradigm is distinguished from its natural counterparts held by ordinary people, students included, in virtually every aspect of the four dimensions distinguished above. Major aspects that set scientific paradigms apart from their counterparts are discussed in the following three sections. Each section is devoted to a specific philosophical dimension. These are respectively ontology (§ 1.6), epistemology (§ 1.7), and methodology (§ 1.8). Axiological issues are deferred to § 2.7. The following sections highlight our stand on scientific paradigms from a modeling perspective, and set what we believe is at stake in the educational enterprise, mainly with respect to helping students to reconsider their own paradigms and evolve into the realm of science (Chapter 3).

1.6 PATTERNS

> *Physical realities that are of particular interest to scientists exhibit universal patterns.*

The “final desideratum” of scientific research, according to Bunge (1967, p. 190), “is the disclosure of patterns”. Bunge is, of course, referring here to what we call exploratory research, and this is one of two types of scientific research, the other being inventive research. *Exploratory* research is about *describing*, *explaining*, and/or *predicting* patterns. A pattern may be reflected in the structure or behavior of a number of physical systems spread throughout space and time under certain similar conditions. Every scientific theory is originally conceived to explore certain patterns in the real world. *Inventive* research is about using the corroborated theory for pattern *reification*. This may be done by *controlling* or *modifying* existing physical realities so that they produce a specific pattern that the theory is concerned with, or by *devising* new physical realities to produce such a pattern.

Patterns treated in a given scientific theory are never restricted to the physical realities where those patterns were originally disclosed; otherwise scientific theory would lose its predictive power. Under similar conditions, a given pattern may be reproduced anywhere and at any time in the universe. The scope of any scientific theory thus extends to all physical realities in the universe that could possibly exhibit the patterns that the theory describes and explains. Some of the realities in question may not be already known by humans; scientists may eventually discover them or even predict their existence long before they are discovered, thanks to the already established patterns.

For example, in 1869, Mendeleev inferred a specific pattern in the chemical properties of about sixty elements that were known in his time, and proposed the first periodic table of the elements. Based on this pattern, he was able to predict the existence of many elements that were not then known, and he allocated specific cells in his periodic table for those elements. He was convinced that these elements would eventually be discovered, and he gave each element the name of an adjacent element that was then known with an "eka" prefix. For example, he allocated next to aluminum a cell for what he called eka-aluminum, and next to silicium a cell for what he called eka-silicium. Eka-aluminum and eka-silicium were actually discovered in 1875 and 1886 respectively, and were given the respective names gallium and germanium. The stories of the six quarks and of many astronomical objects that were long predicted before they were actually discovered testify to the importance of patterns in science.

The dominance of patterns in the universe does not exclude the existence of irregularities (or anomalies), and it does not preclude scientists' interest in such irregularities. On the contrary, irregularities are captivating to scientists. They incite them to go deeper in their investigations, and, as a result, some apparent irregularities may turn out to be disguised instances of known patterns, while others will not. The latter often lead to new discoveries, and more specifically to new patterns. The search for patterns is now getting to the heart of every scientific discipline, even those disciplines, like ecology, that are primarily interested with irregularities and weak trends, and for which the search for patterns and universal laws has always been "a touchy subject" (Harte, 2002).

Scientific theory, though, is about patterns. As Harré (1970, p. 35) argues, scientific "theories are seen as solutions to a peculiar style of problem: namely, ‘Why is it that the patterns of phenomena are the way they are?’ A theory answers this question by supplying an account of the constitution and behavior of those things whose interactions with each other are responsible for the manifested patterns of behavior [and constitution]”. Helping students to develop systematic ways for identifying, exploring and reifying patterns in the real world must thus be at the core of science education. Such ways, as we shall see next, come about by following systematic model construction and deployment.

1.7 MODEL–CENTERED EPISTEMOLOGY

> *Models are at the center of a middle-out structure of scientific theory. A scientific model is mapped onto a particular pattern in the real world so as to reliably represent the pattern in question and serve specific functions in its regard.*

Categorization is one of the most important processes, if not the most important one, in human cognition. Construction and organization of categories have thus been a focal point in cognitive research. Many cognitive scientists have shown that, in accordance with the *theory of prototypes and basic-level categories* of Eleanor Rosch, “categories are not merely organized in a hierarchy from the most general to the most specific, but are also organized so that the categories that are cognitively basic are ‘in the middle’ of a general-to-specific hierarchy… Categories are not organized just in terms of simple taxonomic hierarchies. Instead, categories ‘in the middle’ of a hierarchy are the most *basic*, relative to a variety of psychological criteria” (Lakoff, 1987, pp. 13 and 56). For example, “dog” is “in the middle” of a hierarchy between “animal” and “retriever”, just as “chair” is between “furniture” and “rocker” (Figure 1.1). Categories *in the middle* are *basic* in the sense that: (a) they ensure best a cohesive structure of human knowledge of any type, and that (b) they constitute the most accessible, efficient and reliable building blocks in knowledge construction and deployment.

The *middle-out* hierarchy extends, for us, from physical systems in the real world to conceptual systems in the paradigmatic world as indicated in Figure 1.1. Theories constitute the “content” of a scientific paradigm (§ 1.5), and models are 'in the middle' of conceptual hierarchy, between theory and concept. The model-centered, middle-out structure of scientific theory ensures theory coherence and consistency from an epistemological perspective, and it facilitates the development of scientific knowledge from a cognitive perspective.

A scientific model is to theory and concept what an atom is to matter and to elementary particles. Each elementary particle is essential in the structure of matter but its importance cannot be conceived independently of its interaction with other particles inside an atom. It is the atom and not elementary particles that give us a coherent and meaningful picture of matter, and it is the atom that displays best the role of each elementary particle in matter structure. Now, Bohr's model of the atom is essential for understanding hydrogen-like atoms, and is often referred to as a "model" in physical science textbooks. However, other scientific models are seldom referred to or even presented as such, which would give students the false impression that Bohr's model is about the only scientific "model". Furthermore, various concepts and laws are often presented episodically, one after another in a given chapter, without relating them to one another in the context of appropriate models, whether

Categories Hierarchy
(according to Eleanor Rosch & George Lakoff)

SUPERORDINATE	Animal	Furniture
BASIC LEVEL	Dog	Chair
SUBORDINATE	Retriever	Rocker

Real World Structural Hierarchy:

SUPERORDINATE	Matter	Galaxy
BASIC LEVEL	Atom	Solar System
SUBORDINATE	Elementary particle	Planet

Conceptual Hierarchy:

SUPERORDINATE	Theory
BASIC LEVEL	Model
SUBORDINATE	Concept

Figure 1.1. Middle-out hierarchies.

implicitly or explicitly. Students are thus deprived of the opportunity of developing a coherent, model-based, picture of scientific theory, and end up with a piecemeal, fragmented picture of the world. To get a feel of this picture, imagine what your knowledge about physical realities would look like should you have learned at school that matter consists of elementary particles and no mention was ever made to you about the atom.

“When viewing the content of a science, Giere (1988) argues, we find the models occupying center stage… Theoretical [i.e., conceptual] models are the means by which scientists represent the world – both to themselves and for others. They are used to represent the diverse systems found in the real world (p. 79, 80). Our models shape the way we think and talk (p. 111)”. What a scientific model represents, for us, is specifically a particular pattern in the real world that the model was originally conceived to disclose. As Harré puts it (1970, p. 35), the “chief means by which this is done [i.e., pattern disclosure] is by the making or imagining of models… The rational construction of models [is] to proceed under the canons of a theory of models” which is the epistemological theory of all scientific theories. In fact, Harré continues, scientific “theory can fruitfully be looked upon as the imaginative construction of models, according to well-chosen principles”.

There is no unique definition of the word “model” in the literature, and there is no consensus on the use of the term even among advocates of modeling theory, be it philosophers of science or science educators (Fig. 1.2). Most think of a conceptual model as a complex theoretical structure while some bring it down to the level of a diagram or a mathematical equation. Harré (1970, p. 37) rightfully warns people who “still talk of equations as models of motions and processes” that at “that rate every vehicle for thought would become a model, and a valuable and interesting distinction would be lost… It’s well to remember the old saying, if our eyes were made of green glass then *nothing* would be green”. All modelers however agree that a model is always *of* some things and *for* a specific purpose. It has a well-defined scope. The scope is delimited in terms of the set of physical realities it is a model of, as well as in terms of the model function, i.e., questions it allows us to ask about those realities and the nature of the answers it is expected to furnish.

Models are for the most part caricatures of reality, but if they are good, then, like good caricatures, they portray, though perhaps in distorted manner, some of the features of the real world... The main role of models is not so much to explain or to predict – though ultimately these are the main functions of science – as to polarize thinking and to pose sharp questions.

Mark Kac, 1969 (in Pollak, 1994)

Men do tend to employ familiar systems of relations as models in terms of which initially strange domains of experience are intellectually assimilated.

Nagel, 1979

A mental model is a knowledge structure that incorporates both declarative knowledge (e.g., device models) and procedural knowledge (e.g., procedures for determining distributions of voltages within a circuit), and a control structure that determines how the procedural and declarative knowledge are used in solving problems (e.g., mentally simulating the behavior of a circuit).

White & Frederiksen, 1990

A model is a surrogate object, a mental and/or conceptual representation of a real thing.

Andaloro, Donzelli, & Sperandeo-Mineo, 1991

A theoretical model of an object or phenomenon is a set of rules or laws that accurately represents that object or phenomenon in the mind of an observer.

Swetz & Harzler, NCTM, 1991

The term mental model refers to knowledge structures utilized in the solving of problems. Mental models are causal and thus may be functionally defined in the sense that they allow a problem solver to engage in description, explanation, and prediction. Mental models may also be defined in a structural sense as consisting of objects, states that those objects exist in, and processes that are responsible for those objects' changing states.

Hafner & Stewart, 1995

A scientific model is a set of ideas that describe a natural process. A scientific model (constructed of objects and the processes in which they participate) so conceived can be mentally "run", given certain constraints, to explain or predict natural phenomena.

Passmore & Stewart, 2002

A model is a representation, usually visual but sometimes mathematical, used to aid in the description or understanding of a scientific phenomenon, theory, empirical law, physical entity, organism, or part of an organism.

NSTA, 1995

A model represents a physical structure or process by having surrogate objects with relations and/or functions that are in correspondence with it.

Nersessian, 1995

Models are tentative schemes or structures that correspond to real objects, events, or classes of events, and that have explanatory power. Models help scientists and engineers understand how things work.

NRC, 1996

A model is a representation of structure in a physical system and/or its properties.

Hestenes, 1997

Models are mappings of functional correspondences between the structures of different domains of our knowledge... Pattern recognition also is a form of modelling.

Glas, 2002

Figure 1.2. Sample model definitions.

A *scientific model* is, for us, a conceptual system mapped, within the context of a specific theory, onto a specific *pattern* in the structure and/or behavior of a set of physical systems so as to reliably represent the pattern in question and serve specific functions in its regard. These functions may be *exploratory* (pattern description, explanation, and prediction or post-diction), or *inventive* (pattern reification in existing physical realities or in newly devised realities). Mapping is done so that the model captures the essence of the pattern, and this by concentrating on specific but not all details in the physical realities exhibiting the pattern, particularly on *primary* details that are salient to the model function.

A scientific model can be defined and situated in a specific scientific theory following a four-dimensional *schema*. Two of the four dimensions, composition and structure, set the ontology and function of the model, and the other two, domain and organization, set its scope, all in terms of the scientific theory it belongs to, and by correspondence to physical realities exhibiting the modeled pattern.

The *domain* of a scientific model includes all physical realities exhibiting the pattern in question. Model *composition* consists of conceptions representing physical constituents and respective properties that are salient to the pattern. Model *structure* spells out relevant relationships among the pattern's salient features, especially in the form of laws that set the *distinctive* descriptive and/or explanatory *function* of the model. Model *organization* establishes the relationship of this particular model to other models in the corresponding scientific theory. The four-dimensional model schema is discussed in detail in Chapter 2.

A scientific theory consists primarily of a set of models, and its function in the real world is determined by those models, chiefly by correspondence to the set of patterns that they represent in this world. A theory's coherence is ensured by the inner structure of its individual models and by the mutual relationships among those models. Lower-level conceptions (concepts, laws and other theoretical statements) gain their theoretical significance through model composition and structure. In the latter respect, Giere (1988, p. 82) further argues that there is "no direct relationship between sets of statements [lower-level conceptions] and the real world. The relationship is indirect through the intermediary of a theoretical [i.e., conceptual] model".

Some cognitive scientists, linguists and other researchers have argued that model-based epistemology is not restricted to scientific paradigms, but that it extends to all sorts of human knowledge, and even to that of some animals (Johnson-Laird, 1983, p. 405 ff.). Bower and Morrow (1990) argue that "we build mental models that represent significant aspects of our physical and social world, and we manipulate elements of those models when we think, plan, and try to explain events of that world". Meanwhile, Johnson-Laird, Hestenes and others express a more radical position. According to Johnson-Laird (1983, p. 402), "*all* our knowledge of the world depends on our ability to construct models of it", and according to Hestenes (1995) "we come to know real objects (their properties and processes) *only* by constructing models to represent them in the mind" [italics added]. A more moderate position is expressed by Lakoff (1987) who argues that we "use cognitive models in trying to understand the world. In particular, we use them in theorizing about the world, in the construction of scientific theories as well as in theories of the sort we all make up" (p. 118). "The main thesis" of Lakoff's *experiential realism* "is that we organize our knowledge by means of structures called *idealized cognitive models,* or ICMs" (*ibid*, p. 68).

In an analysis of categorization data, Lakoff (1987) shows, and Giere (1994) supports, that human categorization is based on ICMs and not on similarity between individual features. ICMs not only govern the middle-out hierarchy among categories, but they also imply similar graded structures within individual categories. In the latter respect, Giere (1994) argues that models of any scientific theory can be graded with some basic models in the middle. *Basic models* are most fundamental to develop the elementary building blocks of all models in a given scientific theory and corresponding rules of model construction and deployment. They thus need to be given special attention in science education. We shall come back to this point often in our discussion.

1.8 MODELING METHODOLOGY

Primary details of physical realities are not necessarily exposed directly to our senses. Disclosure and study of relevant patterns in the real world require some model-based

> *idealization of physical realities that is often beyond the reach of ordinary people.*

Scientific conceptions are distinguished from lay conceptions of ordinary people, not only because of epistemological differences between scientists and ordinary people, but more importantly, because of methodological differences between the two groups when it comes to investigating physical realities. In everyday life, people develop and apply experiential knowledge about all sorts of realities mostly following tacit rules of thumb. These rules are concealed in people's unconscious to a point that it is often hard, if not impossible, to subject them to scrutiny. In contrast, scientific research is done according to systematic rules that are either spelled out explicitly in scientific literature or can be disclosed through meticulous scrutiny of scientists' practice.

The difference between scientific and lay methodology has long been, and still is, at the core of debates among philosophers of science. Some philosophers read in scientists' practice, just like in that of ordinary people, a wide diversity of research methods, while others have spoken of a unique scientific methodology that is common to all scientists irrespective of their discipline or their field of specialty. Some have argued that scientific methodology is predominantly inductive while others have argued that it is predominantly deductive or hypothetico-deductive. Some have spoken for a variant of either approach, while others recognized the merits of both induction and deduction in science. Some in the last camp have also identified processes, and especially "model generation processes", that are "neither inductive nor deductive" (Clement, 1989, 1993).

Scientific exploration starts by asking a particular question about specific physical realities within the framework of an appropriate paradigm. The paradigm then helps us to formulate an appropriate hypothesis, i.e., conjecture a tentative answer to the question. The paradigm also guides our observation of the realities of interest in two respects. First, the paradigm helps us to sort out primary from secondary details, and determine, subsequently, what data are salient for assessing the hypothesis we made. Next, the paradigm helps us interpret selected data, analyze them, and decide whether they corroborate or refute the hypothesis (Bunge, 1967, pp. 162-169, 177-184; Kuhn, 1970, pp. 111, 120-124).

We will come back to hypothesis testing later in this section. An important aspect of scientific exploration is that primary details and data may not be exposed directly to our senses. About twenty-four centuries ago, Democritus (c.460-c.370 B.C.) pointed out that "nothing do we know from having seen it; for the truth is hidden in the deep" (Miller, 1985, p. 32). Unfortunately, this point was fully appreciated only about twenty centuries later when Galileo (1564-1642) warned us that ordinary lay experience that relies heavily on sense perception is often deceiving, because reliable knowledge of the world resides in primary data that are not exposed directly to our senses. This position is nowadays at the foundations of modern science. As Bunge (1967, p. 169) argues, "patterns are sought and found beyond appearance, in a reality that is supposed to be there, that must be hypothesized since it cannot be directly perceived". Science, according to Bunge, is indeed interested in "the finding and making of nonordinary" realities. These are "iceberg-like [realities]: they are mostly submerged under the surface of immediate experience". They "are not within the reach of the layman" because they "are not purely empirical" and they require "the invention of theories going beyond the systematization of experiential items and requiring consequently ingenious [conceptual tools and] test procedures". In science, Bunge adds, "theory and experience are interpenetrating rather than separate, and theory alone can lead us beyond appearances, to the core of reality" (Bunge, 1967, pp. 155-158).

Bunge's "hypothesized realities" are, from our point of view, *idealized conceptual realities* (somewhat in the sense of Lakoff's ICMs), the most effective and efficient of which are *scientific models*. Such realities may or may not be conceived by *re*construction of a set of physical realities. In the former event, the conceptual reconstruction is partial. It is done within the framework of an appropriate paradigm in order to display the best specific primary details in the corresponding physical realities and optimize their exploitation. In the latter event, i.e., when our idealized conceptual realities do not consist of conceptually *re*constructed physical realities that are known to us and are exposed to our senses in one form or another, these conceptual realities may be constructed following conjectures about the existence of some physical realities that are as yet unknown. This was for example the case when Gell-Mann first hypothesized the existence of quarks by pure rational *inference* from some mathematical manipulations, or when Bohr proposed his atomic model by analogy to the planetary model. This was also the case with Darwin, who proposed his evolution theory following a rational inference from Malthus' theory on populations' evolution as a function of natural resources, and by analogy to what was then known about natural selection among plants competing for survival in certain territories. Construction of idealized conceptual realities about unknown physical realities is indeed, as Harré argues (1970, p.40), "the creative process of science, by which potential advances are initiated, while" idealization of known physical realities "has, generally speaking a more heuristic value".

Leonardo Da Vinci (1452-1519) was perhaps the most impressive figure among those who started the campaign against the Baconian inductive approach. Da Vinci argued that this approach does not allow us to disclose primary details and relationships in the real world. Instead, he argued, and showed through practice, that to this end, we need to begin exploratory research not with data collection but with the construction of *idealized models*, including mathematical models, and then follow with mapping those models onto physical realities. Galileo (1564-1642) picked up later on Da Vinci's approach and developed it in a way that laid the early foundations of a modeling theory of science.

Modeling processes can yet be traced to the early days of scientific enterprise. In their discussion of "seven ideas that shook the universe" (from Copernican astronomy to quantum theory), Spielberg and Anderson (1995, p. 302-304) recognize that the use of models made it possible for major break-throughs to take place in the history of physics (and thus science), especially because models make it "possible to synthesize (in our minds)" major aspects of physical realities "that we might otherwise not have guessed".

Reviews of landmark works in the history of modern science, like those of Newton (Hestenes, 1992, 1997), Maxwell (Nersessian, 1995) or Darwin (Harré, 1970, 1978), and observation of scientists presently at work (Clement, 1989; Gentner & Gentner, 1983; Giere, 1988) reveal that modeling is a major form of scientific reasoning – if not "the" major form – whereby scientists generate, test and reify creative and viable ideas about physical realities through the successive refinement of generic models. A particular model is constructed, deployed and continuously evaluated within the framework of the theory it belongs to, and by correspondence to physical realities exhibiting the pattern that the model represents in the real world.

We admit that various scientific groups may have their methodological particularities. However, we maintain that they do share generic practices with one another, as well as with other creative groups, like artists. Modeling processes are the most important generic processes that scientists share and follow more systematically than any other group, though implicitly or even unconsciously at times. All modeling advocates agree, to various degrees, with Johnson-Laird (1983, p. 417-418) that we do not only use models to "make sense" of the world around us and to coherently and efficiently structure our knowledge, but we also "impose" them on ourselves as "regulative principles of behavior". However, and like in the case of "model", there is no consensus yet as to how we do so and what "model*ing*" entails in the first place. Some modelers, like Johsua and Dupin (1999, p. 17) talk of a single modeling process, while others talk of a variety of modeling processes and make a distinction, say, between model construction and model deployment (Hestenes, 1987), or of a variety of modeling "activities" considered as "variations of a single modeling process" (Hestenes, 1995). Yet they all agree that some form of modeling is always involved in any scientific activity.

Scientific knowledge is the result of transactions between the empirical world of physical realities and the rational world of scientists along the lines discussed in § 1.2. It is especially the result of continuous *empirical-rational dialectics* between physical patterns and scientific models within the framework of appropriate paradigms. Such dialectics always start with the construction of a tentative model followed by the collection of appropriate empirical data that will be analyzed to test the validity of the model and subsequently make the appropriate judgment as to the acceptance, refinement or rejection of the model. In short, scientific methodology is primarily about making, testing and using conceptual models of patterns in physical realities, with the use of various conceptual tools, and following well-defined principles and rules of engagement.

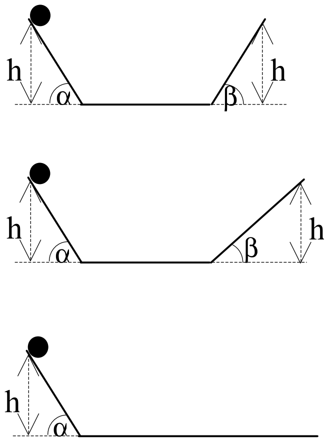
Pattern description and explanation are prime goals of the scientific enterprise. Pattern description may be carried out through *observation* of physical realities exhibiting the pattern. A *descriptive* model (§ 2.5) may be constructed to this end, that may be directly mapped onto observable data and duly corroborated. However, possible causes that explain the pattern, or the absence of any cause, cannot be determined directly through observation. One needs only to remember that explanatory concepts like force, field, and energy are not observable. Pattern explanation can only be carried out through *explanatory* models (§ 2.5) *inferred* from descriptive models the way Newton explained the motion of physical objects (Hestenes, 1992, 1995) and the way Darwin explained the evolution of species (Harré, 1970, 1978).

Model construction is often accompanied by the construction of new lower-level conceptions (concepts, specific laws). In fact, we maintain that all sorts of scientific conceptions are developed in the process of, or for the purpose of, modeling physical realities. A concept or a law is always conceived within the context of a specific model, or set of models, in order to contribute to model formulation and subsequently to theory construction and deployment. Theory construction and validation in exploratory research is, for us, primarily a process of *model induction* and corroboration. Theory deployment is a process of *model adduction* and analysis in problem solving in the traditional sense, and a process of *model deduction* in theory reification and inventive research.

Let us go back to hypothesis making and testing, which is an integral part of any scientific research, whether exploratory or inventive. A hypothesis is a conjecture, a tentative statement about a specific relationship within or among physical realities. It is more specifically, as Giere (1988, p. 80, italics added) puts it, "a statement asserting some sort of *relationship between a model and a designated real system* (or class of real systems). A theoretical hypothesis, then, is true or false according to whether the asserted relationship holds or not". The relationship, Giere continues (*ibid,* p. 81), is "*similarity* between models and real systems [in some] relevant *respects* and *degrees*". Testing a hypothesis thus consists of assessing the model-system relationship, and not the actual relationship between the elements of concerned physical realities. Otherwise, rejecting a hypothesis would be like rejecting the physical realities in question. When the outcome of hypothesis testing is positive, the relationship between model and realities is sustained and the model is corroborated (or reinforced, if it already exists). When the outcome is negative, one of the following scenarios could take place: (a) the relationship between model and realities is reconsidered while the model is preserved, (b) the relationship is sought with an alternative model without losing the original model, the issues addressed then turning out to be outside the scope of the model, (c) the model is refined (and perhaps falsified) and the relationship reevaluated.

Modeling does not always have to proceed in the empirical world. It may proceed exclusively in the rational world of scientists where most of the creative inventive research actually takes place. Hypothesis making, for example, does not have to pertain directly to empirical data (in the Baconian sense), and hypothesis testing does not always have to start in the empirical world, though it has to get there ultimately. When Galileo postulated and corroborated his version of the principle of inertia, he was not thinking directly about physical realities, but more in terms of a particle model that he contrived for a thought experiment depicted in Figure 1.3. A particle model consists of an idealized, dimensionless object of no internal structure. The particle represents all objects whose translation is not affected by their own shape and dimensions. The situation involved in Galileo's thought experiment is an altogether idealized situation. All resistive forces of the real world, like friction and air resistance, have been removed so that when the particle is on a horizontal track, it will be subject only to two forces that cancel each other out. These are the object's weight and a normal force exerted by the track. The same sort

A particle glides on a frictionless track having the shape shown in the accompanying figure. The left ramp of the track has a fixed slope of angle α, while the right ramp can be tilted to any slope angle β. Because of energy conservation, when released from a point located at a height h on the left side, the particle reaches the same height h on the right side, irrespective of the value of the angle β. The smaller β is, the longer the distance traveled by the particle on the right ramp to reach the same height h. When β is zero, the particle travels an infinite distance to reach height h. In other words, once it hits the bottom of the left ramp, the particle will be subject to no net force, and it will keep gliding indefinitely at constant speed, and in a straight line*, on the now horizontal part of the track.



* Galileo had actually thought of a curved path around the earth.

Figure 1.3. Galileo's thought experiment about the principle of inertia.

of particle model idealization was involved in the development of the Newtonian theory of mechanics. This theory, as we shall illustrate in Chapter 2, is entirely about Galilean particle models, each model describing and explaining a specific pattern in the translation of physical objects (e.g., free particle in uniform motion, forced particle in uniformly accelerated motion, bound particle in circular motion or in harmonic oscillations).

Modeling requires a number of conceptual tools for knowledge organization, depiction and representation, processing and communication. Not all tools used by scientists are as explicitly formulated as mathematics, either in scientists' minds, or in science textbooks. In fact, the most important tools advocated in our modeling theory are entirely tacit in scientists' minds and texts. These are modeling schemata. As we shall discuss in the next chapter, a *modeling schema* is an organizational tool that helps us to "define" explicitly specific conceptions, concepts or models, and "situate" them appropriately in the corresponding theory. With these schemata are associated explicit rules, especially modeling rules, for using conceptions in both the rational and the empirical worlds. These rules, as well as those associated with other tools, are the object of Chapter 4.

Mathematics offers scientists the most efficient tools of expression and rational operations. The practical utility of mathematical symbols, equations, diagrams, graphs, etc., along with associated semantics and syntax, is best realized in the construction and deployment of scientific models. In fact, and as we shall see in Chapters 4 and 5, the utility of a scientific model, and especially one of physical sciences, is primarily determined by the degree to which it can be *transformed* into a *mathematical model*. At this point, and as Harré (1978) puts it, the umbilical cord between the scientific model and the real world can be cut, and the model can be entirely processed rationally, in dissociation from the empirical world. The return to this world will only be needed to interpret and justify the outcomes. Successful modeling in the rational world is in fact, at some level, an indicator of mastery in science. Theoretical scientists often construct new scientific conceptions, models included, based entirely on theoretical premises. This is in sort what Galileo did in his thought experiment (Fig. 1.3) whereby construction and initial validation of his free particle model were first done exclusively in his rational world. Empirical corroboration followed later, actually after his death.