Chapter 1

EXPOSING AND GENERATING

Nature loves to hide.
The hidden harmony is better than the obvious.
—Heraclitus, Fragments 17 and 116 (ibid., 70, 79)

1.1 *What is a Discovery?*

I would like to start by trying to clarify or explicate the intuitive notion of discovery as it is used in everyday life and in science. This may provide us with clues for understanding the epistemological and pragmatic significance of discovery in general and of scientific discovery in particular. We may find differences among the usages of the term in everyday discourse and in science, as it happens also with scientific terms which are borrowed from ordinary language. This time, however, we are dealing with a concept which belongs to the metalanguage of science rather than to science proper.[2]

The focus of this book is on the *process* or the *act* of discovery. However, we cannot deal with the process of discovery without also considering the *object* or *product* of discovery. For example, we will be engaged with the issue of the ontological status of certain scientific discoveries; e.g., whether a certain (product of) discovery is a real entity which exists independently of the inquiring mind or whether it is our own creation.

Discovery is a "success" word. When we say we have discovered something, it means, for example, that the product of discovery is useful, that it solves a problem, explains some phenomena or that it is the lost object we have been looking for. When one tells us he saw a flying saucer, we would not say that he had discovered a flying saucer unless it was proved that what he saw was indeed an extraterrestrial vehicle. We would not say that the magnetic monopole was discovered, since its existence has not been confirmed by experiment. Phlogiston was regarded as a discovery by Stahl and his contemporaries. But since Lavoasier's revolution in chemistry, the history of science treated it as a false theory. The same can be said about the status of the aether after Einstein's revolution in physics.

A contemporary scientist who does not believe in the existence of the aether or phlogiston, would not say that the aether was discovered. But a historian of science who is aware of the fact that theories may be overthrown, that an overthrown theory may be revived in the future and that contemporary theories are not the final truths, would relativize the notion of discovery to a historical period and to some community.

We would be interested in the process of discovering a theory. This encompasses the stage of evaluation and confirmation in which the scientist finds out that the theory is successful in providing predictions, explanation, understanding or unification of phenomena. I do not use the term *confirmation* in a logical sense of proof. No theory can be proved in this sense. A confirmed theory may be overthrown or refuted (and refutation in this sense is not a logical notion either). Moreover, most scientific theories have been refuted. Both the theory of the aether and Kepler's laws were refuted. So why the latter are considered to be a great discovery and the theory of the phlogiston is not? I will turn to this question below.

Epistemological Aspects of Discovery From the epistemological point of view, discovery is a major vehicle for the growth of knowledge. And yet, our knowledge grows also by other means. As individuals, perhaps the main way we learn new things or acquire new information is by instruction or by reading. Even, and in particular, scientists learn most of what they get to know from other scientists or from the scientific literature. Personally, a scientist may make very few scientific discoveries, if any, during his lifetime; most scientific discoveries are products of collective efforts. Therefore, it is sometimes difficult to judge who participated in, or contributed to, the discovery; sometimes it is perhaps a whole community which should be credited. If the process extends over a long period of time, only the final step in the process is regarded as a discovery. Yet the contributions of the other participants are sometimes no less important than the contribution which constituted the breakthrough. The example of the electroweak unification in particle physics, which is discussed in Chapter 8, illustrates this point. The graduate student 't Hooft, who made the breakthrough which led to the theory, entered the field at a stage where almost everything was ready for the discovery, and he solved the crucial problem which was presented to him by his supervisor, Veltman. So, should we regard him as the discoverer of the theory, or only as the discoverer of the solution of the specific problem which his supervisor asked him to solve? This issue will be elaborated when the social dimension of discovery will be discussed.

On the other hand, an individual may discover something which would not count as a *scientific* discovery since it does not constitute a novelty with respect to the body of knowledge or to the system of beliefs shared by the scientific community. For example, someone might "discover" today that the earth rotates around the sun. We should refer, therefore, to the total, or collective, knowledge of a culture or a community, such as the scientific community. This would lead us to the following characterization of the act of scientific discovery: the acquisition of an item of knowledge which constitutes an increment in the body of knowledge of the scientific community.

One may discover the neutrino, a black swan, the theory of general relativity, that phlogiston theory is false, that leaves change their color, or that Mary has eaten her breakfast. The last example, however, does not seem to be a scientifc discovery—not even an ordinary discovery. In order to exclude cases such as this, we might require that the process of discovery will result in a new knowledge item, in the above sense, which is either (a) unexpected, (b) has a special interest or (c) constitutes an increment of general knowledge or a change in our general beliefs, as opposed to beliefs in particular matters. Thus, seeing a black swan may be unexpected since it may contradict a general entrenched belief (that all swans are white). A discovery may contradict an implicit generalization of which we become aware as a result of the discovery. Hence, discoveries may lead to "negative" as well as to "positive" increments of knowledge; we may acquire a new generalization, or learn that some of our general beliefs are false. All the above cases exemplify discoveries made with respect to a given body of general beliefs; a discovery is a process or an act which adds something to our system of general beliefs, changes it or solves a problem which arises in it.

In the above discussion, a sharp distinction was not made between knowledge and belief. A traditional epistemological characterization of knowledge, which can be traced back to Aristotle, is expressed by the familiar slogan: "knowledge is justified true belief." There has been a long debate centering on this definition in twentieth-century epistemology. Although it is out of the scope of this book to dwell in depth on this issue, we must take sides in the debate since discovery is a salient epistemological notion.

We do not have to accept the Popperian conception of knowledge in order to reject the above definition. Popper, in defiance of the above definition, denies that our beliefs can be justified, hence all our knowledge is conjectural. However, even if we admit some sort of justification or confirmation, we still cannot retain the qualification "true" in the above definition without excluding practically most of science from the realm of knowledge. If we do not want to exclude, for example, Newtonian physics from the corpus of eighteenth- or ninteenth-century scientific knowledge, or quantum physics from the corpus of twentieth-century scientific knowledge—in fact, if we want to retain the notion of scientific knowledge—we cannot accept the traditional definition. Scientific theories can be confirmed but cannot be "proved" beyond any doubt to be true. Newtonian theory, which was perhaps the most established scientific theory in all times, confirmed by so many observations and experiments, turned out to be strictly false. Thus, according to the traditional definition, it would not qualify as knowledge. We would not be able to say that Newtonian mechanics was part of eighteenth-century scientific knowledge, for example. And there is no reason why the fate of twentieth-century physics would be better. In science, we accept not-yet falsified conjectures as knowledge, provided they are well confirmed, in some non-logical sense of the word. Well-confirmed theories or laws may be regarded as "partially true" or may be treated as good approximations to the truth. Scientific knowledge consists mostly of partial truths and good approximations to the truth. Indeed, we may find out that something we have believed in and which has been treated as legitimate knowledge is false, or true only in a restricted domain.

No one would deny that Kepler's discovery of the laws of planetary motion was a real discovery, although the laws turned out to be strictly false. The reason for this is that in hindsight Kepler's laws are considered to be "approximately true." This means that the discovery of the laws constituted an indispensable step in a progressive research program (to use Lakatos' terminology, to which I will turn in section 1.3) which led to the highly confirmed Newton's theory from which a revised version of the laws was derived. The revised laws are considered to be a better approximation to the truth. On the other hand, the "discovery" of the aether is not treated by historians of science as a real discovery, since it did not yield a progressive research program. Both Kepler's laws and the theory of the aether were strictly false, hence, it is not the notion of truth which distinguishes between them. Rather, it is a notion such as fruitfulness, or progressiveness, which may account for the distinction. Thus, only in hindsight can we say that the discovery of Kepler's law was a real discovery. Hence, paradoxically, the notion of (absolute) truth does not prove to be helpful in characterizing knowledge. A discovery of a "false" law or theory might turn out to be an important step in the growth of scientific knowledge. Knowledge is construed here as a dynamic entity rather than as a static entity which is either true or false. The dynamic character of scientific knowledge and scientific discovery will be discussed in section 1.3.

According to Popper's falsificationism (Popper 1959), theories do have truth values, and the only possible theoretical discovery is the discovery that a theory we have (irrationally) believed to be true is false. Thus, we may say that according to Popper, scientific discovery is not a "success notion," but a "failure notion"—contrary to our intuition. Perhaps the only "positive" discovery possible, according to this view, is a discovery of a method of testing a theory.

A "discovery" might turn out to be a fake discovery. One may "discover" an oasis which turns out to be a mirage. Since the mirage is not a useful phenomenon, nor of any interest to someone lost in the desert, we would not qualify such an event as a discovery. To be sure, the discovery of the (general) phenomenon of the mirage is by all means a real discovery. A similar pattern of discovery was the discovery of the American continent. This time, however, the final result was of great interest and useful. When Columbus arrived at the American continent, he thought he had discovered a short route to India. Only later, with the identification of the object of discovery as a new continent, was the discovery completed. If A "discovers" X but mistakenly identifies it with Y, we cannot say that A discovered X, even if X turns out to be useful and of interest. Thus, a discoverer should realize the significance of his discovery, in particular, its usefulness or its special interest. As I have said, a discovery amounts to an acquisition of a new item of *knowledge*, not just to an encounter with a new object or phenomenon without identifying it or realizing its significance. Knowledge of X implies the identification of X as X. We would not say that someone who is ignorant of zoology and who encounters a bird of a species unknown to zoologists, without realizing its significance, discovered this bird. Yet, it may happen that the person who saw the bird started a chain of events leading to the identification of the new bird, for example, by reporting his observation to an ornithologist. In this case we may say that the first observer contributed to the discovery.

In the case of discovering the American continent we have a similar pattern of discovery. However, Columbus is considered to be *the* discoverer of America since, as in Kepler's case, he made the initial (and decisive) step in the process of discovery. The hard work had been already done by Columbus when the final interpretation to the discovery was given. Another example is the discovery of penicillin by Fleming. Many researchers, including Fleming himself, had encountered the same phenomenon of a bacterial culture contaminated by mold, without realizing its significance and usefulness. None of them would be considered as the discoverer of penicillin, although they encountered the same phenomenon. The discovery of X-rays was missed by several scientists. Sir William Crookes, was experimenting with an evacuated glass tube in which negatively charged cathode was embedded. He observed that some of the photographic plates enclosed in containers became fogged when the Crookes tube emitted cathode-rays, but he did not attach importance to this finding. Philip Lenard, who modified Crookes tube by inserting at the end of the tube, opposite to the cathode, a very thin alluminium window, also missed the discovery of X-rays. In 1894 he observed that about 8 cm. outside the window there appeared a glow on a paper coated with platinum cyanide. He interpreted this as resulting from a flow of "streaming electricity" (Kohn 1989, 16). Roentgen did not provide an explanation to the new phenomenon he had discovered, but he treated it as a new anomalous phenomenon which requires an explanation. He initiated the process of discovery which eventually led to the understanding of the phenomenon. Lenard, on the other hand, misinterpreted the phenomenon. Hence, he was not considered to be the discoverer.

Ontological Aspects of Discovery Besides having strong epistemological implications, the notion of discovery has important ontological aspects. Indeed, epistemology cannot be divorced from ontology. Some dictionary definitions of discovery may shed light on the ontological status attributed to the object or product of discovery. We will find in the dictionary under the item "discover" formulations such as: "to disclose a secret," "to expose (bring to light) something hidden" or "to uncover." Implicit in these connotations is that something which is hidden *from us* is discovered; its existence is independent of the process of discovery. This view is reflected in the expression: "science reveals the secrets of nature." This issue will be discussed in section 1.4.

1.2 *The Products of Scientific Discovery*

1.2.1 What Do Scientists Discover When They Look At the World?

When ordinary mortals look at the world, they discover entities which exist in the world such at ordinary objects, properties, events, phenomena, causes and regularities. When the scientist investigates the world, the most important kinds of items he discovers are not entities in the world, but new concepts, ideas and scientific theories, which belong to the realm of his cognitive representation of the world. Epistemologically, the discovery of fruitful concepts and theories is more important than the discovery of entities existing in the material world, since theories enable science to make further discoveries of natural objects, events and phenomena. Thus, on the one hand, physicists discover new kinds of particles, such as, the electron or the neutrino, and on the other hand, concepts and ideas, such as the concept of spin or the idea of the field, or theories, such as quantum mechanics, which guide the physicists in discovering new particles and their properties.

Scientific theory is one of the distinguishing characteristics of modern science. In understanding its nature, we will increase our understanding of modern science. Therefore, my main concern in this section will be to elaborate on the nature of scientific theories as objects or products of scientific discovery and in particular, to distinguish them from laws of nature. Accordingly, as we will find out in the following chapters, the process of discovering or generating a theory is substantially different from other kinds of processes of discovery in science, in particular—from discovering empirical generalizations and regularities. In fact, the notion of discovery itself, which was inherited by science from ordinary experience, may not be suitable for describing the way scientists arrive at a theory or how they generate it.

Before we turn to theories, let us deal with less structured products of discovery: objects and events.

1.2.2 Objects and Events Contaminated by the Scientist's Intervention

The distinction between observational and theoretical terms or statements has a long history in twentieth-century philosophy of science. It is now widely agreed that all descriptive statements are "theory-laden" so that there are no purely observational statements. However, when we turn to discoveries, we may employ the following *methodological* definition: every object of discovery which can be discovered by observation, i.e. by the senses or by using observational instruments and methods, will be qualified as "observational" discovery. It is a matter of methodological decision or convention to determine what are the observational instruments.

In making an observational discovery, we have to rely on our system of categories or conceptual system through which we grasp the phenomena we observe. In the process of observation by the senses, i.e. in so-called direct observation, we process the raw data of observation using the conceptual and cognitive apparatus with which we are equipped. Our cognitive apparatus guides us in dividing our visual field into enduring objects and natural kinds. We also rely on some tacit assumptions and on inferences we make spontaneously and unawares. For example, when we observe an object, we assume that what we observe is more or less what is there; that the light coming from the object is not radically distorted or that no one painted it or sculptured it in order to deceive us. All these background presuppositions and beliefs would not make the observed object conjectural if we make the methodological decision to treat our cognitive apparatus as reliable and our innate or spontaneous presuppositions unquestionable. We would make this decision in order to retain the commonsensical notion of observation which in general does not deceive us in everyday experience. In fact, in ordinary experience we do not make any methodological decision such as this. Normally, we are not aware of our cognitive apparatus. Or, rather, we are not *focally aware* of it, to use Polanyi's expression (1958, 55-6). We may express it by saying that in the process of observation our cognitive apparatus is "invisible" or "*transparent.*"[3]

In "indirect" observation, which involves the usage of instruments, we rely not only on our innate (genetically and culturally determined) sensory and cognitive machinery; we also rely on established theories which govern the operation of the observational instruments and methods. In science, we rely also on established theories which supply us with the categories and concepts by which we describe the phenomena exposed by using the observational instruments. These theories are (provisionally) considered unquestionable. For example, when the particle physicist observes the products of collision experiments, he describes the phenomena using concepts, such as particle charge or spin, electrons and protons, which he treats as belonging to his observational vocabulary. Again, we may say that after the scientist acquired the skill of using his observational or experimental apparatus, he treats it as transparent. Or when a scientist relies on a set of theoretical presuppositions which he regards as unquestionable, we may say that these presuppostions are transparent.

Thus, the way we describe our object of observational discovery, depends on our cognitive apparatus, conceptual system and background knowledge. All this machinery determines what we observe. However, it does not uniquely determine what are the objects of *discovery* exposed by the act of observation. Indeed, we may observe a lot of things, none of which will be considered to be a discovery. And different observers may be making different discoveries by watching the same thing. Let us take the simplest kind of observational discovery. When we discover a black swan, the object of discovery seems to be an *individual* or an *object* in the world. Without entering now into questions related to the realism-antirealism debate, let us assume that there is an objective state of affairs which we encounter in our discovery. However, what we discover is not this objective state of affairs; our object of discovery is not identical with the state of affairs we encounter. It rather depends on our present beliefs, expectations and interests. If, for example, we have been believing that there are no black swans, we would be interested in the very *existence* of black swans. The product of discovery may then be the statement: "there exists a black swan." If we are interested in the fact that the black swan was discovered in a certain place and/or at a given time, we may be interested in the *event* observed, which is referred to by the statement: "there is a black swan at time t in place x." If so, then what is the object of discovery? Is it the particular swan observed swimming in an Australian lake? Is it the fact that it was black? Is it the fact that it was swimming? Is it the fact that it was swimming in a certain direction, at a certain speed, at a particular hour in the day, in particular weather conditions, at a particular distance from the shore, etc? Thus, given the same state of affairs, many discoveries may be made—in fact, an infinite number of different discoveries. *The object of discovery depends on both the state of affairs in the world and on the discoverer—on the discoverer's expectations, point of view and interests.*

It seems, therefore, that even if there is an objective state of affairs which is partially described by our conceptual system, the object of discovery is not a totally objective matter. Rather it is a certain aspect of reality, a certain facet of the state of affairs encountered. Thus, the object of discovery has both epistemological and ontological aspects; what we discover depends in part on what is there and in part, on our interests and on what we know or believe. Thus, when someone who does not have any prior beliefs about swans, or believes that there are black swans, observes a black swan, the observation of a black swan does not constitute a *discovery-for-him*. On the other hand, when someone who believes that all swans are white observes a black swan, the black swan constitutes a discovery-for-him which results in a refutation of one of his general beliefs. A discovery has the effect of adding something to the discoverer's system of beliefs or modifying it. Hence, even the simplest object of observational discovery is not something which exists out there in the external world independently of our state of knowledge, awaiting our discovery. When X discovers D, D is not determined only by the state of affairs in the world, but also on the cognitive state of X.

Yet, not everything which is observed and which is unexpected or interesting constitutes a scientific discovery; confirmation is part of the discovery process. If we refer to ordinary observational objects or events, there is an entrenched procedure of confirmation: the act of confirmation is carried out by repeating the observation. It seems, therefore, that a non-repeatable event cannot be an object of observational discovery. Indeed, "discoveries" such as the purported discovery of gravitational waves in the early seventies, are discarded by the scientific community since no one could repeat them (Collins 1975). Yet, a singular or unique event which is not repeatable can nevertheless be confirmed if it was independently observed by several qualified observers or if similar events were observed in the past. For example, astronomical events, such as a supernova are legitimate objects of observational discovery in science.

Thus, the following three factors contribute to the product of observational discovery: (1) A conceptual system or system of categories constitutes a precondition for making an observation. (2) A background knowledge and prior point of view (an expectation, a belief, a theory) determine what observational finding would be regarded as a discovery. (3) The act of confirmation determines whether the object is indeed a discovery. *All three factors "contaminate" the object of discovery with our cognitive intervention.* This is obvious for the first two factors. As we will see in the following chapters, the act of confirmation, too, is not an objective matter; it is not devoid of psychological and social components. Thus, even the most "naive" objects of scientific discovery, observational discoveries, are not objective entities in the world.

In science, the effect of factor (2), which determines which observational findings will be regarded as discoveries, is exhibited in the following way. The objects of observational discovery are objects and events, such as a new particle, species, chemical element and compound, star, galaxy, particle decay, chemical reaction or supernova. An object or an event are considered to be a discovery if it is unique of its kind or if only few of its kind have been discovered. A supernova belongs to the last category. What about a discovery of a new particle? The discoveries of the neutron, the π-meson and the neutrino were regarded by elementary particle physicists as genuine discoveries since the number of so-called elementary particles was relatively small at the time of these discoveries. However, since the1960s, when the number of particles increased, an observation of a new particle or resonance was not considered a discovery in its own sake. An observation of a new particle or state of matter was treated as a discovery if it confirmed or refuted a regularity or a theory. Thus, the discovery of the omega-minus particle in 1964 was an important discovery since it strongly confirmed the SU(3) symmetry of strongly interacting particles (hadrons). Thus, in a science which is in its theoretical phase, an observational discovery may be theory-laden in one more respect than an observational finding; an observational finding is a genuine discovery only if it leads to the confirmation of a not-yet established theory or law or to the refutation of an established theory or law.

In astronomy, the standard is different. A new star is considered to be a discovery, although many stars have been observed. Perhaps the reason for this is the same reason for considering a new biological species as a discovery. Every new species is unique; there is no law of nature or regularity which will enable us to predict the existence of a new species. The same thing can be said of stars; there is not a theory or a law of nature which can predict the existence of stars, as symmetry theories in particle physics or as the Periodic Table of elements predicts the existence of particles or elements, respectively. Discoveries of unique objects related to the history of humankind or life in general or to the history of our planet, have a special interest for their own sake. This is understandable since these sciences are not theory-dominated. Yet, even in theory-dominated sciences, there may be important discoveries of specific events or objects. Perhaps the most important scientific discovery ever, would be a discovery of a singular event: how our physical universe was formed (e.g. the "big-bang" event) or how life began. Moreover, the event or process by which life began would become even more thrilling had we shown that such an event is unique or that its probability is vanishingly small; no sane scientist would reject a research project which has high chances for leading to the discovery of this event even if it would be known in advance that it will not contribute a bit to our general knowledge. However, these kinds of singular events are non-observable and their discovery is heavily loaded with theoretical inference.

1.2.3 The Plasticity of Theories

We have seen that observational discoveries are contaminated by our cognitive intervention. However, when we come to scientific theories, the contribution of the discoverer's cognition to the object or product of discovery becomes much more significant. Theories are created by us, although not entirely by our free imagination; the process of creation is constrained by the empirical data and by the conceptual resources available to the scientist. Here the scientist and the artist are in the same boat. The sculptor, as well as the physicist, is restricted by his medium of creation.

The term *scientific theory* is employed in a variety of ways in the literature. Obviously, there is no a priori "right" definition of the term. I will propose a way to characterise this notion by distinguishing it from the notion of natural law, having in mind contemporary usages by scientists and by philosophers of science.

Laws of nature are specific kinds of regularities. The discovery of a regularity or an empirical generalization does not involve an introduction of new concepts which do not appear in the observational vocabulary. We make generalizations when we identify natural kinds which exhibit regular behavior or characteristics. The identification of natural kinds is a matter of both our experience and our natural endowment. Our cognitive apparatus guides us in the general pattern of concept formation and our experience in the specific field of investigation guides us in identifying the natural kinds in that field. Thus, regularities and empirical generalizations are contaminated by our cognitive intervention in the same manner as observational discoveries of singular events and objects are. And so, the above mentioned three intervening factors involved in observational discovery are also operative in this kind of discovery. The only difference is that the act of confirmation is different. It relies on inductive "inference." Induction cannot be justified by logical or "objective" standards, so we may treat it as another natural endowment which is part of our cognitive apparatus. Thus, the object or product of discovery is further contaminated by our belief in induction and in the uniformity of nature. If we still believe that we discover here an entity in the world, we may say that the object or product of our discovery is an invariable *relation* between properties in the world, for example, between the property of ravenhood and the property of blackhood. If we are realists we may regard relations as entities existing in the world, although in a more abstract sense than objects and events are.

Now, there is a difference between an empirical generalization, such as "all ravens are black," which seems to be "accidental," and a law of nature, such as the law of universal gravitation, which seems to be "universal." Both empirical generalizations and laws of nature embody invariable relations in the world. So what is the difference between them? Philosophers have tried to answer this longstanding question by looking at the logical form of law-statements, employing the machinery of "possible worlds." However, they have not yet found a satisfactory answer in this direction. This is one of the examples where philosophers unsuccessfully try to find answers to questions concerning science in a logicist direction. Perhaps the answer lies in the realm of the dynamics of scientific knowledge; perhaps it lies in the manner by which science progresses, rather than in the logical form of the law-statements.

When an empirical generalization is embedded in, or derived from, a strongly confirmed theory which holds over a wide range of phenomena, then we might treat it as a law of nature. Indeed, in such a case, we can explain why the generalization is not accidental; if the theory's postulates are true, then the generalization must be true. A unifying theory is confirmed by its wide range of successful predictions and explanations. So the theory gives the generalization a stronger confirmation; through the theory the truth of the empirical generalization is linked with the truth of other kinds of established phenomena. Sometimes an empirical generalization is so entrenched that it is treated as a law of nature even without being embedded in a theory. But then it is assumed that, eventually, a unifying theory will be found in which the generalization will be embedded.

A physical law, such as the law of universal gravitation, is an invariable relation between physical magnitudes, such as masses, distances and forces, which can be thought of as properties. There are other kinds of laws, which cannot be described as relations. For example, a conservation law, which states the constancy of a given magnitude, such as energy, or the second law of thermodynamics, amount to a restriction on possible processes, or to a limitation on the value of a given magnitude or property.

When we say, as it is customary to say, that a law "states" something, we do not mean that the law is a statement made by us. It plays an analogous role to a judicial law in preventing certain states of affairs to occur, or in specifying how properties or objects "should" behave. We represent the law by statements expressed, for example, by mathematical formulae. However, these formulae or statements *refer* to the law which is part of reality. A law of nature is not a proposition or a statement. The formula $F=kq_1q_2/r^2$ is not Coulomb's law, as is frequently stated (presumably as a shorthand) in textbooks. Rather, it is a law-statement which refers to Coulomb's law; the law is a relation between the physical magnitudes (properties) of the electric force between two interacting particles, their charges and the distance between them. In summary, a law of nature may be an invariable relation or a restriction on possible states of affairs or processes.

It is not within the scope of this book to deal with the ontological status of laws of nature—whether and in what sense they exist. However, in order to understand in what sense they differ from theories as objects of discovery, I will adopt the following mildly realistic view. I start from the assumption that objects, properties and events exist in the world. According to this view, laws of nature are invariable relations between properties or restriction on the existence of certain events or objects. That is, they do not exist in their own right in the sense objects and events exist in space and time (or in spacetime), but they correlate properties or dictate what objects or events cannot exist.

Thus, laws of nature are somehow related to entities which exist in the world, in the same fashion as properties are. We may view them as properties of higher order, or as restrictions on what can exist or happen in the world. If we have only two possibilities where to accommodate them, in our cognition or in the external world, then as realists we will choose the second possibility. This is still an intuitive view which is not fully analyzed. However, for the sake of distinguishing between laws and theories, I will not need more than this.

Theories are the most important targets of scientific discovery, at least in the physical sciences. What sort of entities are they? What sort of entity is Newtonian mechanics, the Darwinian theory of evolution or Maxwell's theory of electromagnetism? In order to answer this question, we have to find out what are the functions of theories in modern science. Among the functions attributed to a theory we can find the *explanation* and *prediction* of natural phenomena and laws of nature and the *unification* and *systematization* of our knowledge. Newtonian theory explains why planets are encircling the sun according to (a modified version of) Kepler's laws. It also provides a unification of diverse phenomena such as celestial and earthly motion. It seems, therefore, that theories fulfill epistemic functions. They stay closer to our cognition than to the objects and events which exist in the world. We would not say that Newton's or Darwin's theories exist in the world; rather they describe and explain what exists. Thus, if we do not wish to employ Popper's three-worlds machinery for accomodating theories and we have only the two above mentioned possibilities to categorize them, we would say that they are elements of *knowledge* rather than elements of reality; they are cognitive objects which *represent* reality.

When we discover a theory, we discover something which is related to external reality; for example, something which represents reality in our minds or something which helps us in comprehending reality. So what kind of entity is it? Is it just a description, a statement, or an explanatory instrument? Traditionally, philosophers of science viewed theory as a set of statements, or—simply—as a statement (which is the conjunction of all the theory's statements). This might distinguish between a law of nature and a theory, since a law of nature is not a statement. However, if we believe that a law of nature exists in the world, we would say that a law-statement refers to a law. We might, therefore, ask what the theory-statement refers to?

Some theories may be viewed as a system of *interrelated* law-statements. For example, Maxwell's theory of electromagnetism consists of Maxwell's equations which yield formulas and equations expressing laws of nature, the laws of electricity, magnetism and electromagnetism. Yet, the system of laws consists of something more than a mere collection of laws. Within the theory the laws are interrelated via Maxwell's equations. The theory thus serves as a unifying entity. This might be expressed by saying that the theory refers to relations of a second order: relations between laws which are themselves relations between physical magnitudes. If we admit relations to our ontology, there is no reason for rejecting relations of any specified order. Thus, in discovering a theory, we discover a set of relations between observable properties and measurable magnitudes.

Yet, it is doubtful that even Maxwell's theory just refers to nothing more than to a set of interconnected laws of nature. If we are not instrumentalists or anti-realists we would say that there are *ontological claims* made by the theory about the existence of some kind of entities, such as electromagnetic waves. And if one would argue that all these claims about waves can be reduced to relations, without committing oneself to the existence of anything else, we might take as another example the kinetic theory of gases, which deals with more tangible objects. This theory does not exclusively consist of a system of equations. It has clear ontological claims: the existence of molecules in motion etc. The theory's equations are derived from a model of molecules in motion. If we do not yield to the already bankrupt positivistic views of reducing everything in theory to the measurable and the observable, dismissing any ontological commitment, then we would say that the theory states the existence of particles and their properties and behavior.

This difference between law and theory is substantial. A law-statement does not state explicitly anything about the existence of any entities in the world. It just describes relations between entities which scientists have accepted as existing before the law was discovered. A theory, on the other hand, in many cases states the existence of *new* entities, such as electromagnetic waves, subatomic particles and forces, i.e. new with respect to our state of knowledge before the theory was discovered. More generally, the theory is constructed from new *ideas*, *concepts*, *models* and *analogies*. These may be qualified as *proto-theoretical* entities, which are also objects of discovery. In other words, the novelty of a theory is in the new proto-theoretical entities from which it is constructed, including the new entities it claims to exist. Thus, here the distinction between a law-statement and a theory-statement is not related to their form or their content but to their genesis.

In fact, the introduction of new entities, concepts, ideas, etc. is a necessary condition for the theory to be *explanatory*. Newtonian mechanics, for example, introduced the concept of mass. Indeed, one of the common principles of explanation is that explanation cannot be circular. Thus, a phenomenon is not explained by employing the same predicates used for describing the phenomenon. For example, "the sky is blue" would not be explained by "the sky consists of blue particles." This might apply to the explanation of laws of nature as well: Coulomb's law would not be explained, on pain of circularity, by the "theory": "all charged particles obey Coulomb law." Or, Boyle's law for an ideal gas in a container cannot be explained by the statement that every volume element of the gas in the container satisfies Boyle's law. Thus, the explanans should include something new—e.g., new kinds of objects, new properties, relations or structures—which do not appear in the explanandum. This principle is not mandatory in scientific explanation, since we encounter in science "bootstraps" kinds of explanation. However, if we restrict ourselves to atomistic explanations or to explanations by reduction, which constitute the majority of scientific explanations and perhaps the ideal model of scientific explanation, the principle must hold.

When I say that a theory introduces "new" concepts or entities, I mean new relative to our state of knowledge before the discovery of the theory was made. Hence, if we view the theory as a final product, independently of the epistemic circumstances in which it was discovered, no sense can be given to the "newness" of the entities referred to by the theory or of the concepts employed by it. The theory-statement in this case just employs a set of concepts, without making explicitly any ontological claim. In this respect a theory does not differ from the statement referring to a law of nature.

Thus, a substantial difference between the two would arise only if we view a theory from a historical or epistemic point of view. Only in a historical context can the theory be viewed as making explicit ontological claims. But then, a theory will be part of a historical process, transcending a mere statement. In saying that one of the distinctive features of a theory is the new entities it predicts, relative to the previous state of knowledge, we attribute to the theory an epistemic role of advancing knowledge. Therefore, we cannot view the theory in isolation from the historical process in which it emerged. Furthermore, in section 1.3, I will propose viewing the theory itself as a dynamic entity which brings about further discoveries after it was brought to life. According to this view, in discovering a theory, it is not just a static description, or a statement, which is discovered. Rather, it is a basic idea, model or picture which guides a research program.

We would expect, therefore, that the process of discovering a theory will differ from the process of discovering a regularity, for example. In discovering a theory, we discover a guiding tool for advancing knowledge. This means that the object of discovery in this case is neither something in the world nor a mere statement. A model or a picture cannot be fully described by a statement. It is not an entity which refers to something in the world. Rather it is a cognitive or epistemic object which helps us in *representing* the world or in *grasping* it in a *dynamic* fashion.

This view of theories can by no means be categorized as instrumentalism. If we were instrumentalists, viewing theories as instruments for organizing and predicting observational data, then the object of discovery would be a set of directions for deriving predictions, a superstructure for organizing the data, etc. The main difference between the view expounded above and the instrumentalist view is that according to the above view the theory as a cognitive tool is *mirroring reality*, whereas the instrumentalist view does not make such a claim.

From this point of view, the transition from the pretheoretical stage, when a science deals only with empirical generalizations, regularities and laws of nature, to the theoretical stage, is a radical transition. It does not involve a change in degree, such as the change embodied in the transition from a less general theory to a more general and abstract theory, as exemplified by the transition from the kinetic theory of ideal gases to the molecular theory of matter. It rather involves a category-change. *Discovering a regularity or a law of nature and discovering a theory are entirely different things.* In one case, we discover something in the world, in the other case—a cognitive object. One difference is that although discovering a regularity or a law of nature may require cognitive intervention and human ingenuity, a regularity or a law of nature is something we find in the world rather than create or invent. Proto-theoretical entities and a full-fledged theory, on the other hand, are our own creations or inventions. They are new tools for acquiring knowledge or new information channels through which we interact with the world. This categorial difference will be reflected in the process of discovery. At first sight, the difference seems to be so big that one may wonder why we subsume both kinds of processes under the same title of "scientific discovery."

Until now I have not distinguished between different stages in the development of a theory. It seems that even if a growing theory is not a statement, a mature theory comes close to being a statement. When a theory matures and becomes well established it is relegated to the unquestionable background knowledge of science. In its mature stage, the basic structure of the theory almost does not change over long periods of time. The theory is mainly applied for explanation and prediction, and is employed as a premise in scientific reasoning. It would be tempting to say that at this stage a theory *is* a statement, referring to a portion of reality. Namely, we may treat the mature *version* of the theory as what remains of the dynamic tool. Indeed, when people say that a theory is a (set of) statement(s), they have in mind a mature version of the theory. Thus, we may view the established version of the theory as an object of discovery, which may constitute a substantial advance over the initial version. As we will see when we discuss kinds of discovery processes, the process of discovering a theory may indeed be a prolonged dynamic process resulting in a mature version of a theory. Thus, in addition to the discovery of the initial version of a theory, there is another kind of discovery, which is a dynamic process in which the theory is adjusted to the data and further elaborated. For example, Bohr's discovery of the initial or "naive" version of the structure of the hydrogen atom was the major discovery. However, the mature version, including elliptical orbits, relativistic effects and spin, constituted a discovery in its own right.

Yet, even a mature theory need not, and perhaps should not, be seen as a static entity referring to some definite entities in the world. Classical mechanics, for example, the paradigm of scientific theory, gives a general description of the world—general equations which can be applied for describing different kinds of systems in the world. The application of the theory to a new kind of physical system is in many cases a creative task in its own right which does not involve mere computations. Here we should distinguish two kinds of application: the application of the theory to a general system, such as the physical pendulum or the planetary system, which results in a "model" for this general system, and the application of the theory to a concrete, specific, pendulum or planetary system. The structure referred to by this kind of "model" can be viewed as a generalized law of nature applying to a general kind of system.

The application of a theory to new systems is an essential part of the development of the theory proper. Indeed, the theory can be viewed as a theoretical core plus the range of general kinds of systems to which the theory applies. In the early stages of the theory development, the core is changing in order to adjust it to new kinds of systems. In the mature stage, the core may change only marginally, but the range of applications expands. Hence, we can say two things with respect to a mature theory. First, even in its mature stage, a theory is developing. Second, the mature theory is not a statement about reality. Rather it specifies general ways of treating different kinds of systems. Its domain of application expands and this is one of the major ways through which a theory grows. Only a "model" (in the above sense), describing a certain kind of system, functions as a statement referring to a general structure or to a generalized relation existing in the world.

In summary, the statement-view is not appropriate for describing the two major aspects of the growth of a theory as a dynamic entity. It is not appropriate for describing a developing theory which is changing in its basic structure. And it does not do justice to a mature theory extending its domain of application. *In both cases the theory serves as a guide for the growth of knowledge about the world rather than as a statement referring to something in the world.*

Due to the dynamical nature of scientific theories, the process of discovering them requires a high degree of creativity. Furthermore, the plasticity of theories makes them liable to creative changes and in particular to unintentional or serendipitous changes. As I will argue in Part II, scientific creativity is equated with unintentionality and serendipity. And this is what makes scientific progress an evolutionary phenomenon.

1.2.4 Explanations, Problems and Solutions

There are three additional kinds of products of discovery which deserve our attention, since they are related to the theoretical structure of science and to its evolutionary nature.

Explanations There are two kinds of scientific explanation: an explanation of the properties and structure of general systems, phenomena, regularities and laws of nature and the explanation of specific events and properties. The first kind of explanation is derived from the theory in conjunction with some assumptions regarding the structure or the dynamics of the explanandum. For example, a modified version of Kepler's laws was derived from Newton's theory of universal gravitation in conjunction with Kepler's model for the solar system. An example of the explanation of a phenomenon, i.e of a general kind of process or event, is the explanation of the phenomenon of tides which is provided by gravitational theory in conjunction with some assumptions about the initial condition of the system consisting of the earth, the sea and the moon.

In the second kind of explanation, the explanation is given by a law or a theory in conjunction with initial or boundary conditions, possibly in conjunction with auxiliary hypotheses or assumptions. This is the "deductive-nomological" kind of explanation treated by Carl Hempel (1965). However, the first kind of explanation is more common and more important in a theoretically advanced science. The advance from the phenomenological stage of empirical generalizations to a theory brings about the explanation of the phenomenological regularities by the theory.

To find an explanation is not the same as finding a cause. If we adopt the hypothetical realist view, a cause is an entity existing in the world. The cause of the tides is the moon moving in a particular trajectory. The cause of the pain I feel in my head is the object which hit it. Both causes are events, which exist in the world. However, the explanation of the phenomenon of the tides, or of a particular occurrence of a tide, is a human product. If we treat scientific explanation along the lines proposed by Hempel, for example, we have to find the theoretical premises and the statements describing the initial conditions, from which we can derive the explanandum. It may happen that we know all the premises from which such an explanation can be constructed, without being able to construct the explanation. Discovering an explanation involves finding the right ingredients, and the right combinations thereof, from our repertoire of theories, laws and facts, from which we can derive the explanandum. We encounter the same situation in puzzle-solving. Here the discovery is not made by looking at the world, but by looking at our representation of the world. In Chapter 6, I will discuss a theory which describes the process of discovery as consisting of quasi-random formation of combinations of "mental elements." The product of the process is a stable "configuration" which is finally selected. In the above mentioned process of discovering an explanation, the product of the process is, indeed, a "configuration" of mental elements, i.e. of ideas, theories, laws, facts, etc., which solves the problem.

Problems and Solutions A very general category of discoveries is a solution of a problem. When we resolve an inconsistency in a theory or between theories, or a disagreement between a theory and data or when we find an explanation for a puzzling event or when we explain a set of empirical generalizations by a general theory, we solve a problem. In general, when our scientific standards require a specified manner of explanation or understanding, we face a problem whenever we have not yet achieved the goal set up by these standards. Problems may arise in theoretical and pragmatic contexts.

However, an important kind of discovery is the discovery of a new problem. In many cases, the discovery of a solution of a given problem leads to the emergence of new problems. A discovery of a new problem may lead to a significant progress of science, sometimes more so than a discovery of a solution of a known problem; such a new problem may open up a whole new field of investigation. For example, the problem called "the ultraviolet catastrophe" in blackbody radiation was crucial for the discovery of quantum mechanics. Problem solving can be construed as an evolutionary phenomenon. We will turn to this point when we discuss the subject of serendipity and the evolution of science.

1.3 *The Kinds of Discovery Processes*

Let us divide processes of discovery into two main categories which may be termed *"exposure"* and *"generation."* Paradigm cases of discovery by exposure from everyday experience is when we discover the hidden content of a closed box by opening it, when we discover something in the darkness by throwing light upon it or when we infer the hidden cause of an event (discovering who is the murderer in a detective story). An example of generational discovery in everyday experience is when we discover the maximum tension which a rope can stand by hanging increasingly heavier weights on it. Or, when we discover how the color of the rope changes when we put it in a certain solution. Another example is when we discover the effects of growing some plants in a greenhouse. In all these experiments, the new effects discovered by us are in a sense created by us. However, the salient cases of generational discovery occur in science (actually, the above examples are on the border-line between ordinary experience and science), whereas in everyday experience exposure cases are more typical. In fact, generational discovery is one of the characteristics of modern science. In general, discovery by exposure does not create anything new in the world or in our representation of the world, whereas generational discovery, in a sense, perturbs the world, interferes with the natural course of events, creating new, or new kinds of, observational or theoretical entities. The sense in which generational discovery perturbs the world will be discussed in section 1.4. The distinction between exposure and generation will be essential to the evolutionary view of discovery: it is generational discovery which exhibits the characteristics of natural selection.

1.3.1 Exposure

Discovery by Observation Discovering a new object, event or a new observable property by looking or sensing, or by using observational tools and methods. Examples: The discovery of Jupiter's satellites by Galileo, using his telescope, or the discovery of the structure of a macromolecule, using an electron-microscope. Observation is by no means a passive act, since it involves looking at chosen directions, employing instruments and making inferences. However, it is not a generational process, since the act of observation does not create, or significantly effect, the object of discovery. We have to qualify this statement with regard to the observation of macroscopic systems. In quantum physics, observation does perturb the observed system.

Discovery by Searching Scanning a given portion of space looking for some prescribed event or object. Examples: Looking for oil resources by searching a given area. Scanning bubble-chamber photographs in order to discover certain events. Searching for a solution to a problem in a space of possible alternatives. This procedure is practiced in problem solving and in heuristic search in artificial intelligence. Search may be conducted where there is a finite number of possible hypotheses for explaining a given phenomenon. Here search means eliminating alternative hypotheses, the product of discovery being the remaining alternative. If there is a finite number of alternative hypotheses for the general cause of a phenomenon, this method is reduced to "inductive" inference, i.e. eliminative "induction"; if we come to the conclusion that there are n possible causes for a given general phenomenon, we may eliminate n-1 possibilities by conducting appropriate observations or experiments. The result will be the discovery of the cause of the phenomenon. In fact, eliminative "induction" of this kind, were the number of possible hypotheses is finite, is a deductive inference.

Calculation and Computation Mathematical calculation may lead to important discoveries in everyday life as well as in science. For example, by measuring the length of a metal rod at two different temperatures (L and L_0, at t and t_0), we can determine its coefficient of thermal expansion (α) by using the formula $L=L_0[1+\alpha(t-t_0)]$. If we have a table of thermal expansion coeficients for different metals, we can use this result to discover the chemical identity of the metal. This is an example of a procedure in which one starts from some premises which include certain mathematical formulas and the numerical results of some measurements and arrives at the result by substituting the numerical results in the formulas and carrying out the required mathematical operations. The mathematical formulas may be derived from a full-fledged theory or may be just rules of thumb. This procedure is a specific case of deductive inference when one starts with some premises and arrives at a logical conclusion by following the rules of inference.

Inference The question is why do we categorize calculation, and deductive inference in general, as a process of discovery by exposure rather than by generation? The reason is that the process of deductive inference leads to information which is already logically contained in, or necessarily implied by, the