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PART I

The scientific enterprise

I hold that in all cases of inductive inference we must invent hypotheses, until we fall upon some hypothesis which yields deductive results in accordance with experience. Such accordance renders the chosen hypothesis more or less probable, and we may then deduce, with some degree of likelihood, the nature of our future experience, on the assumption that no arbitrary change takes place in the conditions of nature.

William Jevons, *The Principles of Science: A Treatise on Logic and Scientific Method*

Pure logical thinking cannot yield us any knowledge of the empirical world; all knowledge of reality starts from experience and ends in it. Propositions arrived at by purely logical means are completely empty as regards reality. Because Galileo saw this, and particularly because he drummed it into the scientific world, he is the father of modern physics – indeed, of modern science altogether.

. . .

A complete system of theoretical physics is made up of concepts, fundamental laws which are supposed to be valid for those concepts and conclusions to be reached by logical deduction. It is these conclusions which must correspond with our separate experiences.

. . .

The structure of the system is the work of reason; the empirical contents and their mutual relations must find their representation in the conclusions of the theory. In the possibility of such a representation lie the sole value and justification of the whole system, and especially of the concepts and fundamental principles which underlie it . . . [T]hese latter are free inventions of the human intellect, which cannot be justified . . . *a priori*.

Albert Einstein, *On The Method of Theoretical Physics*

Science is not a system of certain, or well-established, statements; nor is it a system which steadily advances towards a state of finality. Our science is not knowledge (*epistēmē*): it can never claim to have attained truth, or even a substitute for it, such as probability.

. . .

We do not know: we can only guess.

. . .

The advance of science is not due to the fact that more and more perceptual experiences accumulate in the course of time. Nor is it due to the fact that we are making ever better use of our senses. Out of uninterpreted sense-experiences science cannot be distilled, no matter how industriously we gather and sort them. Bold ideas, unjustified anticipations, and speculative thought, are our only means for interpreting nature: our only organon, our only instrument, for grasping her. And we must hazard them to win our prize. Those among us who are unwilling to expose their ideas to the hazard of refutation do not take part in the scientific game.

Sir Karl Popper, *The Logic of Scientific Discovery*

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PART I The scientific enterprise

From impacts on our sensory surfaces, we in our collective and cumulative creativity down the generations have projected our systematic theory of the external world. Our system is proving successful in predicting subsequent sensory input. How have we done it?

. . .

Observation sentences are the link between language, scientific or not, and the real world that language is all about.

. . .

Traditional epistemology sought ground in sensory experience capable of implying our theories about the world, or at least of endowing those theories with some increment of probability. Sir Karl Popper has long stressed, to the contrary, that observation serves only to refute theory and not to support it.

. . .

Pure observation lends only negative evidence, by refuting an observation categorical that a proposed theory implies.

Willard Quine, *Pursuit of Truth*

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Ways of knowing

Since we hope to learn something about science and its operation and since science concerns itself with a certain type of knowledge and its attainment, let us begin with a brief consideration of how we arrive at knowledge. A common type of knowledge is that based on opinion or on the acceptance of another's authority. Most of our everyday knowledge used for dealing with the practicalities and necessities of life is gained in either of these fashions. Much of what one learns in the course of reading a book is taken as true simply because it has been presented on the printed page, although hopefully you will be more critical than that. Thus, we can merely have an opinion about a proposition and then decide to accept it as true or we can appeal to the authority of another, as 'Einstein says' or 'Aristotle says,' or to the authority of a text, as 'The Bible says,' or we can assert a fact to be 'obvious'. Consider the following example:

> We hold these truths to be self-evident, that all men are created equal; that they are endowed by their Creator with certain unalienable rights; that among these are life, liberty, and the pursuit of happiness. That, to secure these rights, governments are instituted among men, deriving their just powers from the consent of the governed; that, whenever any form of government becomes destructive of these ends, it is the right of the people to alter or to abolish it, and to institute a new government, laying its foundation on such principles, and organizing its powers in such form, as to them shall seem most likely to effect their safety and happiness.[1][†]

In writing the Declaration of Independence, Thomas Jefferson (1743–1826) did not adduce evidence for the correctness of these givens, but circumvented all argument on that point by stating them to be self-evident. While such may be a neat rhetorical ploy, it may or may not, depending upon your predilections, seem to offer a solid basis for the truth of the statement.

1.1 PHILOSOPHY

As with so much in our Western tradition of thought, we find some of the earliest systematic treatments of the nature of human knowledge among the discourses of Socrates (*c*. 470–399 B.C.), Plato (428/427–348/347 B.C.) and Aristotle (384–322 B.C.), those ancient Greeks who contributed so greatly to the philosophical foundations of Western culture. *Philosophy* in its etymological roots comes from two Greek words meaning friendly or loving (*φιλος*, pronounced philos) and knowledge

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[†] *Notes* begin on p. 378 and sources may be located via the *General References* (pp. 398–9) and the *Bibliography* (pp. 400 ff.)

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(σοφια, sophia). Originally, it connoted love of wisdom, a desire for fresh experience, or the pursuit of intellectual culture. It later came to denote the disciplined study of reality and of human nature. Socrates lived in Athens during the period of the Peloponnesian War between that city and Sparta. After the defeat of Athens by Sparta, the Athenian court of 500 citizens found Socrates guilty of impiety and of corrupting the minds of the young with his philosophical questioning that led them to deny the existence of the gods. For this he was condemned to die by drinking hemlock. Although Socrates wrote nothing himself, we know of his dialogues through the teaching of his most famous pupil, Plato. Born of a distinguished Athenian family, Plato founded the Academy in Athens in 387 B.C. This was in some ways the counterpart of a modern university. Plato's most outstanding student by far was Aristotle, a prodigious writer and thinker whom we shall meet again several times in these beginning chapters.

Plato distinguished between mere *opinion* and *science*. For him science was the ideal of human knowledge and was seen as necessarily true and unchanging. We might take, as a model of such a system of knowledge, axiomatic geometry, as later found in Euclid's *Elements* (about 300 B.C.). In his *Republic*, Plato discussed the ideal state and the philosopher kings fit to rule it. He tells us that these philosophers are to desire a knowledge of the truth and of reality, not just of superficialities. According to him, true knowledge must be real, stable and unchanging. It must be of unique, immutable objects (his *Forms*), whereas belief has to do with appearances; knowledge is infallible, while belief may be true or false. Plato distrusted the world of sense experience because of its constant change and posited the existence of another world of changeless forms accessible only to the intellect. In his conception these forms were the true reality and existed independently of the sensible world. Experience and sense data give us only an approximate picture of these forms. As an example, he would suppose that the concepts of mathematics (more particularly of plane geometry), such as a circle, line and triangle, exist only in the abstract and that knowledge of them is not gained through sense experience, since a true circle, line or triangle does not exist in the sense world. We cannot draw a mathematical point or line because these will have extension when produced by a pen or pencil. This was Plato's answer to the quest for the immutable amidst the change of the sensible world.

Although both Plato and Aristotle were realists in that they believed in the existence of an external world independent of the mind of the observer, we may briefly characterize their differences by saying that Plato posited a reality far removed from immediate sense experience (realism of ideas or of forms), while Aristotle assigned primary reality to the objects of sense experience (realism of natures or of substances). Aristotle believed that form and matter were intellectually distinguishable, but not in fact separable in the real world of experience. He taught that all genuine knowledge is gained through logical demonstration proceeding from true and necessary first principles that are abstracted from sense experience or observation. His treatise on natural (or material) bodies was titled *Physica* (*Physics*) since the Greek word φυσικα (physika) was originally derived from the adjective for

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'natural' (things) and, as used by Aristotle, had the meaning of natural science. It was in this sense that scientists were once referred to as natural philosophers. In his *Physics* he tells us that we must start from the things that are more knowable and obvious to us and proceed toward those that are clearer and more knowable by their nature.

> When the objects of an inquiry, in any department, have principles, conditions, or elements, it is through acquaintance with these that knowledge, that is to say scientific knowledge, is attained. For we do not think that we know a thing until we are acquainted with its primary conditions or first principles, and have carried our analysis as far as its simplest elements. Plainly therefore in the science of Nature, as in other branches of study, our first task will be to try to determine what relates to its principles.
>
> The natural way of doing this is to start from the things which are more knowable and obvious to us and proceed towards those which are clearer and more knowable by nature; for the same things are not 'knowable relatively to us' and 'knowable' without qualification. So in the present inquiry we must follow this method and advance from what is more obscure by nature, but clearer to us, towards what is more clear and more knowable by nature.
>
> Now what is to us plain and obvious at first is rather confused masses, the elements and principles of which become known to us later by analysis.[2]

Aristotle, unlike Plato (with his innate forms), holds that there is no such thing as innate (or inborn) knowledge. For Aristotle all knowledge must begin with input from the external world from which we may eventually generalize, abstract or induce the overarching schemes and unifying principles that please the mind and that produce in us a sense of finally having understood an area of knowledge or a collection of individual sense experiences.

1.2 LOGICAL DEDUCTION

Once we have arrived at these general principles (and we later discuss at length how this is done), we can then deduce further results from these by logical reasoning (that is, by valid inference). By *deduction* we mean the process of reasoning from the general to the particular, from a given premise or set of premises to necessary conclusions. A standard example of a deductive argument is that, given all men to be mortal and Socrates to be a man, it necessarily follows that Socrates is mortal. The syllogism, in its various forms, is one of the most basic and elementary tools used in logic. Aristotle sometimes uses the term *syllogism* loosely to mean a form of argument or discussion. He gave the definition: 'A syllogism is a discourse in which, certain things being stated, something other than what is stated follows of necessity from their being so.'[3] More precisely, 'syllogism' has a technical meaning as a structured form of arguing from two premises to a conclusion.

Although there are several forms of syllogisms and of deductive reasoning in general, we consider here only what are referred to as *hypothetical propositions* that will prove useful later. These statements are of the form 'If *p*, then *q*,' where *p* and *q* stand for two propositions. As a fanciful example consider the statement, 'If you are good, then I will give you a lollipop.' (Or, an instructor might say to a student, 'If

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you do well in my course, then I will give you an A for a final grade.') Once we accept this statement as binding, it necessarily follows that, provided you are good, I must give you the promised reward.[4] Let us now look at some possible outcomes of this reward–punishment scheme and see what we can logically conclude. If you are good, then, of course as already stated, you do get your lollipop. Suppose you do in fact get a lollipop. Does it necessarily follow that you were good? Of course not, since I could have given you a lollipop even if you were not good. The statement was not 'If and only if you are good, then I will give you a lollipop', but merely 'If you are good.' Finally, what follows if in fact you do not get a lollipop? You must not have been good since, if you had been good, you would certainly have received a lollipop.

In these hypothetical propositions, we refer to the *if* clause as the *antecedent* and the *then* clause as the *consequent*. Two important points are these: once the antecedent condition is fulfilled, the consequent always obtains; and, when the consequent does not occur, then the antecedent condition cannot have been fulfilled. That is, if we negate the consequent, then we must negate the antecedent. We introduce a shorthand or symbolic notation that can simplify the analysis of the structure of an argument. As before, let p and q denote propositions and $\sim p$ (non p) and $\sim q$ (non q) represent their negations. Finally, let the symbol $\Rightarrow$ stand for 'implies'. Hence we can state 'If p, then q' equally as well as $p \Rightarrow q$. The general logical rule that negating the consequent negates the antecedent becomes simply $\sim q \Rightarrow \sim p$.

Let us apply these results to the type of argument we meet in our study of physical theories. Suppose we take as given the statement (that we refine in Chapter 8) 'If Newton's law of gravitation governs a planet orbiting the sun, then the orbit of the planet is an ellipse.' We can make the following identification: p – 'Newton's law of gravitation governs a planet orbiting the sun' and q – 'The orbit of the planet is an ellipse.' The proposition itself is $p \Rightarrow q$. What if careful observation shows that the planetary orbit is not exactly an ellipse? In other words, we have established $\sim q$. Having negated the consequent, we must then negate the antecedent. That is, $\sim p$ follows so that Newton's law of gravitation does not govern the planet. As we shall see much later, one of the reasons that Newton's law of gravitation was replaced by Einstein's general theory of relativity is that a planetary orbit in fact departed slightly from elliptical shape.

Suppose, however, that (as seemed to be the case for a long time) the orbits of the planets were ellipses. Would this necessarily establish the validity of Newton's law of gravitation? Certainly not, since another agent could be responsible for keeping the planets in their orbits – say, angels beating with their wings against one side of the planets, as might be facetiously alleged some people believed at one time. Finally, if we know that Newton's law of gravitation is not correct ($\sim p$), does it follow that the planets do not go around the sun in elliptical orbits ($\sim q$)? No, it does not, since some other theory that is correct might yield the same result regarding elliptical orbits.

Let us summarize these important results as follows. Given the conditional statement (or hypothetical proposition) $p \Rightarrow q$, it necessarily follows that $\sim q \Rightarrow \sim p$, but it does not necessarily follow that $q \Rightarrow p$ or that $\sim p \Rightarrow \sim q$. Notice that there is a

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profound asymmetry between being able to prove an hypothesis and being able to disprove one. As a simple application of these general logical rules, criticize for yourself the following argument as to its logical validity. 'Because science, based on the belief in simple, objective laws of nature, has been so prodigiously successful for the past few centuries, we can necessarily conclude that these assumed laws of nature are correct and do exist as part of an external, objective reality.' We leave it to the reader both to identify properly propositions p and q, so that the basic argument can be put into the form $p \Rightarrow q$, and then to decide the validity of drawing the stated conclusion.

1.3 SELF-EVIDENT FIRST PRINCIPLES

So far we have given a few useful rules about logically valid relations between a given statement – what will sometimes be termed first principles – and consequences deducible from it. The critical question now is how we arrive at the truth of these givens (the antecedents). On this point let us examine the writing of René Descartes (1596–1650), the French mathematician and philosopher who is often considered the father of modern philosophy. Descartes was born in a rural area of France to a father who was a lawyer and judge in the province of Brittany. His early education (1604–1614) was by Jesuits at the Royal College in La Flèche. Descartes at an early age directed his studies and investigations to establishing an absolutely certain foundation for human knowledge. He spent most of his working years in Holland. In 1629, Descartes wrote his *Regulae* (*Rules for the Direction of the Mind*), although this was not published until after his death. He proposed that the method of mathematics could be generalized to science so that absolutely certain knowledge could be attained.

His plan was to start with self-evident propositions as his first principles. These first principles with which science was to begin were to be obtained through *intuition*, by which Descartes meant the direct apprehension of those truths that a clear and disciplined mind saw as certain. To these absolutely self-evident first principles one was then to apply logical deduction in order to obtain valid conclusions. Descartes' quest for certain knowledge was similar to Aristotle's in that both would begin with evident truths and then proceed from there by deduction. For Descartes the knowledge gained by intuition was even more secure than that obtained by deduction since intuition is immediate and simpler. A few quotations from the *Regulae* concerning these issues are given in Section 1.A at the end of this chapter.

In such a program Descartes saw an infallible means of adding to human knowledge:

> [I]f a man observe [these simple rules] accurately, he shall never assume what is false as true, and will never spend his mental efforts to no purpose, but will always gradually increase his knowledge and so arrive at a true understanding of all that does not surpass his powers.[5]

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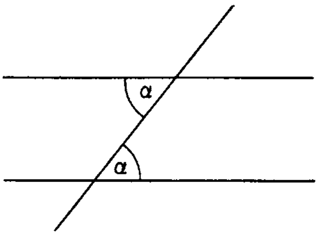

FIGURE 1.1 **Parallel lines cut by a third straight line**

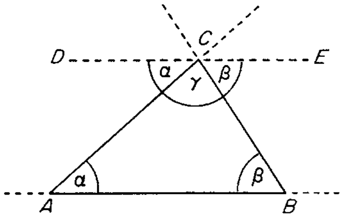

FIGURE 1.2 **Interior angles theorem for a triangle**

As a simple example of the type of argument Descartes had in mind, suppose we take as essentially a matter of definition the fact that a straight line subtends 180° and as an axiom (or postulate) that, when two parallel straight lines are cut by a third straight line, then the opposite interior angles (α of Figure 1.1) are equal. (This property can also be obtained from Euclid's famous parallelism axiom that through any point not on a straight line one and only one parallel to the original line can be drawn.) From this definition and this axiom let us now obtain the well-known result that the sum of the interior angles of a plane triangle is 180°. In Figure 1.2 we have drawn the line DE parallel to the base AB of triangle ABC. Using the property illustrated in Figure 1.1, we see that angle DCA equals α, while angle ECB equals β. Since $\alpha + \beta + \gamma = 180°$, we obtain the stated result.

It was this type of argument (or proof) from 'obvious' first principles that Descartes took as his model. Euclidean geometry with its self-evident axioms and scheme of logical deductions should lead to absolutely certain results. However, as we shall see in later chapters, it was found in the nineteenth century that non-Euclidean geometries could be constructed in which the parallel-line postulate is false. The problem with Descartes' scheme is that certain principles that appear to be self-evident to us may in fact be incorrect in the real world. That is, if the parallel-line axiom is accepted, then the stated result about the sum of the interior angles of a triangle does follow. However, mathematicians have discovered logical alternatives to Euclidean geometry. There are spaces in which a three-sided figure bounded by straight lines will have its interior angles sum to more or less than 180°. An example is a triangle drawn on the surface of a sphere. Without observation, we cannot be certain which of these geometries is that of the space we actually live in. This is the sense in which Albert Einstein (1879–1955) meant that logical thinking

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alone cannot give us knowledge of the real world. (See the quotations for Part I (*The scientific enterprise*).) We must very often appeal to sense experience to decide which general and logically possible principles are in fact respected by nature. All human knowledge is fallible. In his later work, such as *Discourse on Method* (1637), Descartes did retreat somewhat from this purely intuitive, deductive approach to physical laws. He continued to believe that the general principles of natural science could be demonstrated in this fashion, but admitted that these had to be combined with data from sense experience in order to derive the more specific laws of science. He also saw the need to do experiments to decide among these alternative laws. This was the germ of the scientific method as it has since come to be practiced.

In the mid-nineteenth century, the astronomer Sir John Herschel (1792–1871) believed in the existence of a straightforward and reliable procedure of beginning from unproblematic observational data and using deduction to gain certain knowledge:

> [O]ne preliminary step to make . . . is the absolute dismissal and clearing the mind of all prejudice . . . and the determination to stand and fall by the result of a direct appeal to facts in the first instance, and of strict logical deduction from them afterwards.[6]

While Descartes began with principles self-evident to the mind, whereas Herschel started with empirical evidence, each believed he had an unassailable foundation for knowledge.

1.4 RATIONALISTS VERSUS EMPIRICISTS

This basic difference in emphasis on reason or on experience recurs throughout the ages among philosophers. *Rationalists*, such as Descartes, rely mainly upon reason as the source of knowledge, while *empiricists*, such as John Herschel (cited above) or David Hume (1711–1776) whom we discuss in Chapter 3, rely more upon experience, through observation and experiment, as the basis of knowledge. This latter approach brings us to the problem of induction. By *induction* we mean a process of reasoning from particulars to the general, from the individual to the universal. For example, from the fact that all men of past ages who have ever existed have died, we might induce the general proposition that all men, including those still alive and even those yet to be born, are mortal. The question of how one goes from specific instances or observations to those general principles we need to begin a deductive argument is the subject of the next chapter.

We end this discussion by considering a quotation from the writings of the theoretical physicist Max Planck (1858–1947), one of the pioneers of modern physics and a founder of the quantum theory of light, for which he received the Nobel Prize in physics in 1918. Planck, like Aristotle, lays emphasis on the primacy of sense knowledge that has been essential for the eventual development of natural science. This is reflected in the following excerpt from *The Meaning and Limits of Exact Science.*

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> If we seek a foundation for the edifice of exact science which is capable of withstanding every criticism, we must first of all tone down our demands considerably. We must not expect to succeed at a stroke, by one single lucky idea, in hitting on an axiom of universal validity, to permit us to develop, with exact methods, a complete scientific structure. We must be satisfied initially to discover some form of truth which no skepticism can attack. In other words, we must set our sights not on what we would like to know, but first on what we do know with certainty.
>
> Now then, among all the facts that we do know and can report to each other, which is the one that is absolutely the most certain, the one that is not open even to the most minute doubt? This question admits of but one answer: 'That which we experience with our own body.' And since exact science deals with the exploration of the outside world, we may immediately go on to say: 'They are the impressions we receive in life from the outside world directly through our sense organs, the eyes, ears, etc.' If we see, hear or touch something, it is clearly a given fact which no skeptic can endanger.[7]

Even here, though, Planck attaches too much certitude to the reliability of what we observe with our senses. Not only can we misinterpret the stimuli that our senses send to the brain, as in many common varieties of optical illusions for instance, but there remains the more serious question of interpreting the data we gather from observation and experiment. There have been cases in the history of science in which skilled scientists of the hightest repute have 'seen' or 'verified', through observation and experiment, the prediction of some hypothesis, even though this prediction subsequently turned out not to correspond to reality and could not be reproduced by other observers. For example, Sir William Herschel (1738–1822), discoverer of the planet Uranus, the father of John Herschel and the most famous astronomer of the eighteenth century, was able with the powerful telescopes he manufactured to resolve into individual stars several nebulae that had previously appeared to be milky luminous patches in the sky. In the mid 1780s, he conjectured that all nebulae were composed of individual stars so that none were made of a luminous fluid. In 1790 he did observe a nebula that he was forced to interpret as a central star surrounded by a cloud of luminous fluid. In the interim period, however, Herschel claimed to resolve into individual stars both the Orion and Andromeda nebulae. In fact, though, Orion is a gaseous cloud containing a continuous distribution of matter, not just individual stars, while Andromeda is a galaxy of stars.

In more recent times, there was a dispute of several years' duration between the American Robert Millikan (1868–1953), who eventually received the 1923 Nobel Prize in physics for his observations of the electron as the fundamental and indivisible unit of negative electric charge, and Felix Ehrenhaft (1879–1952) of Vienna, who, along with his colleagues, obtained data that seemed to show the existence of electric charges much smaller than that of Millikan's electron.[8] Subsequent attempts by others to reproduce Ehrenhaft's results were unsuccessful, so that Millikan's view prevailed. It seems as though Ehrenhaft misinterpreted his data, perhaps largely because he believed that electrical charge should be continuously divisible. There have also been suggestions that Ehrenhaft was not always as careful as he ought to have been in his experiments. The point is not that either Herschel or Ehrenhaft was a dishonest man. Furthermore, especially in Herschel's case, one

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