J. Bernard Cohen

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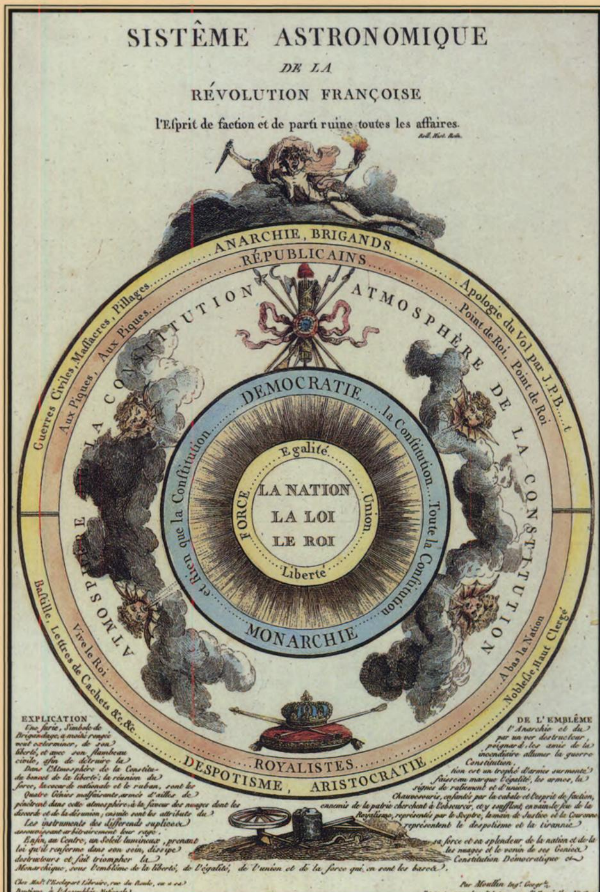

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Preface

R*evolution in Science* is a historical and analytic study of a concept through the course of four centuries. Such a complex topic, covering a broad range of events, individuals, and ideas, has seemed to require a number of approaches from different angles. The first of these is an analysis of the stages by which revolutions in science progress from the inception of a revolutionary idea to the acceptance and use of a new science by a sizable number of scientists. Whether a particular set of events in science does or does not constitute a revolution is necessarily a personal judgment, but I have developed a set of criteria—based on historical evidence—for the occurrence of a scientific revolution. These stages and criteria (outlined in chapters 2 and 3) constitute the analytic framework of the book.

I have used this framework to examine critically some of the major revolutions in science which have occurred during the four centuries modern science has existed. For each of those centuries, an introductory section on the political or social revolutions of that age and the images of revolution then current is presented, because I have found that occurrences of the word 'revolution' in the context of science have always reflected current theories concerning political and social revolution, as well as the awareness of actual revolutions that have taken place. Thus, the thinking about each revolution in science that I discuss is set against the background of social and political revolution.

A distinction must be made between the historical perception of revolution and the historian's perception. The former comprises the judgments made at the time of the revolution and during succeeding ages and are the objective facts or data of history; but the latter are present-day subjective judgments. Of course, in the case of each revolution discussed in this book, I have made a subjective historian's judgment. Yet in every example, I have stressed the historical evidence. In almost every case there is a confluence of the two; those revolutions that pass the test of historical evidence tend to be those that in the judgment of today's historians (and scientists) are also revolutions. But the comparison of historical evidence and the judgment of historians has also disclosed some fascinating anomalies.

In particular, the study of historical evidence shows that the concept of revolution in science, like the concept of revolution itself, is not and has not been static. For example, this book documents the changing views of scientists and historians on whether the progress of science is primarily gradual and incremental or is the result of a succession of revolutions. In addition to alterations in the general viewpoint toward revolutions in science, there have also been shifts of judgment concerning the revolutionary character of particular events. A case in point is the Copernican revolution. The notion that a revolution in astronomy attended the publication of Copernicus's *De Revolutionibus* in 1543 was a fanciful invention of eighteenth-century historians of astronomy; it was popularized to such an extent that the Copernican revolution became the paradigmatic revolution in science. But critical examination of the evidence by historians has shown that the revolution was not at all Copernican, but was at best Galilean and Keplerian.

The changing perspective of time has also produced radical alterations of the sense and significance of even great political revolutions. In *The Rights of Man* (1791), Thomas Paine explained how the American and French revolutions had introduced a new kind of revolutionary thinking into political science. Known primarily for his pamphleteering during the American Revolution—*Common Sense* and *The Crisis* are his most notable productions—Paine wrote *The Rights of Man* in reply to Edmund Burke's *Reflection on the Revolution in France* (1790). Paine's exposition of the new view of revolution resulting from the events in America and in France is a classic example of the way in which political concepts arise in relation to events and not mere theory:

> What we formerly called Revolutions were little more than a change of persons, or an alteration of the local circumstances. They rose and fell like things of course, and had nothing in their existence or their fate that could influence beyond the spot that produced them. But what we now see in the world, from the Revolutions of America and France, are a renovation of the natural order of things, a system of principles as universal as truth and the existence of man, and combining moral with political happiness and national prosperity.

Less than a half-century later, however, in 1835, Giuseppe Mazzini no longer considered the French Revolution to be a sound model for progressive political action. "The progress of France," he wrote (1907, 251) "depends upon its power to emancipate itself from the eighteenth century and the old Revolution." He argued that the French Revolution should be "considered, not as a programme, but as a summary: not as the initiative of a new age, but as the last formula of an expiring age." In the nineteenth century, and even in the twentieth, revolutionaries aimed to achieve what the French Revolution had failed to do, as may be seen clearly in the writings of Marx and Engels and many twentieth-century theorists of revolution.

English political history provides two clear-cut examples of the way in which the passage of time changes the way events may be perceived as revolutions. In other words, revolutions in science are not the only revolutions that undergo successive changes in their image as revolutions. The Glorious Revolution of 1688 was the paradigmatic political revolution for eighteenth-century historians and political theorists, but today it does not appear to have been very revolutionary. And the same is true for the American Revolution, often now called the Revolutionary War or the War of Independence. Contrariwise, the English Revolution of the mid-seventeenth century was not generally conceived to have been a revolution at all until some two hundred years later. This English Revolution was, according to some nineteenth- and twentieth-century commentators, an abortive social revolution rather than a political revolution like the Glorious Revolution. The concept of what constitutes a revolution also differs greatly from one age to the next, as

I began my book originally as an inquiry into the origins and successive uses of two concepts: the Scientific Revolution (of the sixteenth and seventeenth centuries) and revolution in science as a mode of scientific progress. I found that many historians, and even historians of science, believed that both of these concepts arose in our own days and that historians of science who used them were anachronistically attempting to force events of the past into a twentieth-century mold. The reader may well imagine my astonishment as my research began to produce examples of discussions of revolution in science from each of the past four centuries, and of references to the Scientific Revolution at least as long ago as the early nineteenth century. Because this material is not at all familiar to historians—and to scientists, philosophers, and sociologists—a large part of the book serves as a chronological record of these usages.

My first findings were presented in an article in the *Journal of the History of Ideas* (1976, 37: 257–288), which I had intended to expand into a small monograph. But as Thomas Mann (in the preface to his Joseph series) and many authors have said, "Fata sua habent libelli" ("Books have their own fate"). The overwhelming accumulation of evidence has led to this more ambitious book. Even it by no means exhausts my findings; I could easily have written a volume three or four times as large. References to revolution in science since World War I and the Russian Revolution could, alone, have been the subject of a monograph. Of necessity, I have given only some carefully selected samples that seem to me either to be typical of current expressions of opinion or to have special interest.

This work is part of a broad research program with a double aim. In part I am concerned with exploring and elucidating the creative process by which a practitioner in one discipline uses the ideas (concepts, methods, theories, tools) of another discipline. I gave an earnest of this investigation in my book *The Newtonian Revolution* (1980). There I stressed the doctrine of 'transformation of ideas' as a key ingredient in the revolutionary process. Here, however, I have restrained my use of this concept of transformation, so as not to put off readers primarily interested in the broad historical chronicle and the analysis of revolutions in science. I reserve for later study the further analysis of conceptual transformations in revolutions in science. The second goal of my research is to define and analyze the interactions between the natural and exact sciences and the social and behavioral sciences. This work combines historical and analytical studies. Its purpose is not only to identify and study in particular cases the general process of transformation that occurs whenever an idea from one discipline is used in another; additionally, I am concerned with analyzing the 'scientific' basis of the social sciences and examining how they have used the sciences to validate applications of their findings in matters of public policy. Although it is generally believed that ideas tend to flow from the natural and exact sciences to the social and behavioral sciences, there are many significant cases in which the influence has been in the other direction. The present book on revolutions is related to this theme because the concept and name 'revolution' arose in the sciences (astronomy and geometry) and then entered the discourse of political and social change, undergoing a significant initial transformation. As the book documents, this changing concept of revolution was then transferred back from the social sciences and the literature of political theory and action to discussions of scientific change. Thus the book explores an area of the relations between these two worlds of discourse.

The interactions between the concepts of political or social revolution and revolution in science are mentioned throughout this book, but I am fully aware that this topic merits a much more complete exploration. As early as the seventeenth century, even before the modern noncyclical concept of revolution had become universal, various authors sought to explain scientific advance by political analogies. There is also a countertheme, which I have mentioned but not explored, of the possible influence of science and of scientific revolutions on political revolutions. It is well known that Marx and more particularly Engels saw their revolutionary movement as 'scientific'. The terms 'scientific socialism' and 'scientific communism' occur frequently in the Marxian (especially the Soviet) literature, but I know of no critical assessment of the degree to which this use of 'scientific' depends on the use of science as commonly understood in national scientific communities.

Although the theme of change in the concept of scientific revolution is woven throughout this book and is indeed its major thread, many readers will find the case histories of particular revolutions to be of greatest interest. These case histories, which make up a large part of the book, describe some of the great revolutions that mark the development of modern science, and display in specific examples the stages of revolution which I have developed and the evidence for considering a particular series of events to be a revolution in science. These case histories also indicate how the recognition of revolution in the sciences has been (and is) conditioned by the image of political revolutions and by current revolutionary theory. A striking example occurs in relation

Finally, I have often referred to my findings in what may be too positive a manner. I am aware that in many cases the phrases 'so far as I know' or 'so far as my research has shown' should have been inserted. Are there earlier examples than I have found? I would be the last person to assume that my research has been exhaustive, a conclusion precluded by the nature of the topic. And so I hope that readers who have access to further information will inform me so that I can make corrections in any later editions.

Readers will naturally wish to know how this book is related to T. S. Kuhn's *Structure of Scientific Revolutions* and other writings. As many readers will be aware, Kuhn's work has been of fundamental importance in reorienting the thinking of scientists and historians of science, converting them to (or making them mindful of) the notion that revolutions are a regular feature of scientific change. Hence, Kuhn's writings constitute a major event in my history of the concept of revolutions in science. A major theme in Kuhn's analysis is that scientific changes of all kinds, including revolutions, are not the result of a contest of ideas, as Ernst Mach and others have supposed, but rather of scientists who accept or believe in ideas. I address this theme by analyzing four stages of development which I find to be characteristic of all revolutions in science. Finally, I accept Kuhn's general notion of revolutions as a shift in a set of scientific beliefs—in 'paradigms', to use that original term introduced in this context by Kuhn but later (unfortunately, in my opinion) abandoned by him when it was shown that he had used this term ambiguously and even in a number of quite different senses.

In my book I do not, however, discuss some particular features that Kuhn has assigned to the "structure of scientific revolutions." For example, I do not explore the theme (which I find to have too many exceptions to be useful) that revolutions in science are necessarily precipitated by crises. And it is the same for other details of his schema. Nor do I go into the question of Kuhn's changing distinctions among 'paradigm', 'exemplar', and 'disciplinary matrix'. It is an interesting fact of record that whereas Kuhn's schema has been subject to considerable discussion, criticism, and approval by historians of science, the latter (including Kuhn himself) have tended not to make use of a Kuhnian framework in their actual writings. Hence Kuhn's influence appears to be stronger among philosophers and sociologists of science (and scholars in wholly different areas such as political theory) than among scientists and practicing historians of science. An exception, however, must be made for historians of the recent revolution in the earth sciences. (For a first-rate—and good-naturedly irreverent—analytical presentation of Kuhn's system and the history of its reception by the community of historians of science, see Reingold 1980.)

Kuhn refers again and again to smaller revolutions and great revolutions. The latter are those generally accepted as revolutions in scientific discourse—those associated with Copernicus, Newton, Lavoisier, Darwin, and Einstein. But Kuhn's smaller revolutions may involve no more than a couple of dozen scientists replacing an accepted exemplar by a new one. In public discussions and writings Kuhn stresses the ubiquitous nature of these smaller revolutions. In my book, however, I have tended to concentrate on the larger or more visible revolutions. One of the reasons is that my formulation of an objective means of determining when a revolution occurs applies directly to revolutions in science which are more analogous with political revolutions.

Readers will discern, furthermore, that I am neither philosopher nor sociologist of science. As a historian, I have aimed more to produce a critical and analytical historical study than to debate the merits of Kuhn's system or the systems of other philosophers or sociologists of science. In short, my purpose and Kuhn's are not parallel but necessarily intersect. This book is not another discussion of Kuhn's "structure"; it is instead an attempt to examine the subject of revolution in science from a new and strictly historical viewpoint.

I have earlier quoted a Latin phrase used by Thomas Mann and others to indicate the well-known phenomenon that books tend to have a life of their own, that they develop by an internal logic of research and writing. Just as this book was going to press, however, I encountered the complete quotation of which this is an extract. Composed by Terentianus Maurus *(De litteris syllabis et metris Horatii,* line 1286), it reads in full: "Pro captu lectoris habent sua fata libelli." Who could possibly disagree that the fortunes of books depend on their reception by the reader? I hope that this book will find both critical and sympathetic readers, so that it may stimulate further research and thought. If this fascinating subject of revolutions can attract the attention of scholars, it will achieve the potential it so richly deserves.

I am grateful to many scholars—colleagues, friends, students—who, over the years, have either brought to my attention some examples of discussion of revolution in science during the past four centuries or

have answered queries. This company includes, among others, James Adler, Peter Buck, Lorraine J. Daston, Joy Harvey, Michael Heidelberger, Joseph Dauben, Stillman Drake, Henry Guerlac, Pierre Jacob, Gerard Jorland, Robert Proctor, Barbara Reeves, Joan Richards, Shirley Roe, and Frank Sulloway. A number of kind friends and scholarly colleagues helped me by giving one or more chapters a critical reading: Jed Z. Buchwald, Peter Galison, Owen Gingerich, John Heilbron, Gerald Holton, Ursula Marvin, Arthur Miller, and Noel Swerdlow. Additionally I have profited from the comments of three scholars who gave the penultimate version a complete reading: Joseph Dauben, Richard Kremer, and Roy Porter.

In the preparation of this book, I have depended heavily on the constant support of Julia Budenz, who has worked with me on every aspect of the research and the final text. It is difficult for me to imagine how I could have brought this long and complex book to completion without her help. Anne Miller Whitman, as ever, gave me the great benefit of her wisdom and insight. The contribution of these two old and dear friends, co-workers in many projects, was all the more significant in that this is the first work I have had to complete without the loving support and creative criticism of my wife Frances Davis.

During the early stages of research Kristie I. Macrakis served as research assistant. I am greatly indebted to three students who have helped me check and complete the text and references: Diane Q. Webb, Deborah Coon, and Kristin Peterson. The final assembling and checking of the bibliography was done by Bertha Adamson and Diana L. Barkan. Sarah Tracy prepared the index.

I especially record my debt to Arthur Rosenthal, director of Harvard University Press, who held out an encouraging 'carrot' at just the moment when my flagging spirit needed revival. It has been a constant joy to work with Susan Wallace, an editor of rare taste and discernment, whose critical judgment bettered the book at every stage.

Finally, I gratefully acknowledge the support of the Spencer Foundation in the preliminary stages of the research on which the book is based. The major support of my research during the years of exploring the topic of revolutions in science and of the larger subject which it forms in part came from the Alfred E. Sloan Foundation; it is difficult to imagine any foundation that could have been more considerate to its grantees.

I. Bernard Cohen

1

Introduction

Today we are apt to take it for granted that science and its associated technology progress through a series of revolutionary leaps—giant steps forward that give us an altogether new perspective on the natural world. But has revolution always been so familiar and acceptable a way to describe the advance of science? Could such innovative scientific thinkers as Kepler, Galileo, and Harvey conceive of their own work as being revolutionary in the sense that we use the word today? Did the contemporaries of Darwin, Freud, and Einstein see the theories of these scientists as creating a revolution, or did they prefer to view scientific progress in a less dramatic light? What effect have such social and political upheavals as the French Revolution and the rise of Marxism had on the way scientists, philosophers, and historians think about revolutions in science? For all of their emphasis on the great scientific revolutions of the past, surprisingly few scholars have addressed these sorts of questions—questions having to do with the historical development of the idea of revolution as a feature of scientific change. It was my own curiosity about these problems that led to the writing of this book.

The main body of the presentation deals with the chronological history and successive transformations of the concept of revolution in science in the seventeenth, eighteenth, nineteenth, and twentieth centuries—with illustrations taken from some major revolutions in each of these periods. These revolutions have been chosen either because of their intrinsic historical importance (as in the case of the Copernican, Newtonian, Darwinian, and Einsteinian revolutions) or because of their relevance in clarifying or exemplifying what I see as the central characteristics of all revolutions in science.

In declaring that certain historical episodes constitute revolutions in science, I have not relied solely on my own personal evaluations, or even on the consensus of qualified historians, but rather on historical evidence, both the judgments of contemporaneous observers and participants and the continuing tradition. For example, it is a historical fact that in the early 1700s Fontenelle said *expressis verbis* that the invention of the calculus was a revolution in mathematics, that in 1773 Lavoisier declared that his research program would lead to a revolution, that in 1859 Charles Darwin hailed Lyell's revolution in geology and predicted that the acceptance of his own ideas would produce a "considerable revolution in natural history." Contemporaneous documents show that the radical innovations of Lavoisier and Darwin and both relativity and quantum theory were very quickly acknowledged to be revolutions. Furthermore, almost all scientists and historians of science today agree with the opinion of the past that certain momentous restructurings of scientific thought were revolutions. Such a consensus, of course, does not make these events revolutions; we shall see in chapter 3 that additional tests can be applied to help us decide what is and what is not to be considered a revolution in science, and (in chapter 2) that distinct stages in the development of a revolutionary idea can indicate whether or not a true scientific revolution has occurred. These questions aside, there can be no debate concerning the overall historical record: it shows that for some three hundred years, ever since the first coming-of-age of modern science, great events in the development of science have been seen as revolutions in thought and practice. The main burden of this book is to delineate and to analyze those events and the interpretation of them as revolutions.

Defining 'Revolution in Science'

The problem of defining 'revolution', which plagues almost every discussion of political and social revolutions, has penetrated the literature on revolutions in science. I have not attempted in this book to display a strict definition of 'revolution' or of 'revolution in science', although I have discussed certain features of all revolutions in science: their stages of development, evidential tests for their occurrence, and transformations of ideas in the production of revolutionary innovations. While there would be little disagreement that the examples I have discussed in this book are to be considered revolutions—at least among all scholars who believe that scientific revolutions do occur—there would be no consensus concerning the exact defining characteristics that all of these revolutions have in common.[1] Discussions of what constitutes a revolution and how to define revolution are part of philosophy, however related to history. As a historian, and aware that I am not a philosopher, I have always very carefully held in check any temptation to ultracrepidate. In the Medawars' *Aristotle to Zoos: A Philosophical Dictionary of Biology* there is a discussion of definitions (1983, 66) which is very illuminating:

> In certain formal contexts—mathematical logic, for example, in which a definition is a rule for substituting one symbol for one or more others—definitions are crucially important, but in everyday life and in sciences such as biology their importance is highly exaggerated. It is simply not true that no discourse is possible unless all technical terms are precisely defined; if that were so, there would be no biology.

The life sciences differ in this regard from the exact sciences—mathematics, rational mechanics, theoretical physics and astronomy, and parts of chemistry—fields that have developed a long tradition in which definition has come to be of basic importance. But if exact definitions are not required of all sciences, then surely there is no ground for insisting that history of science must be like one portion of the sciences rather than the other.

It is a matter of record that the word 'revolution' first gained general currency as a technical term in the exact sciences, where it long had (and still has) a meaning very different from that of a sudden dramatic shift. Revolution means to return again, to go through a cyclical succession, as in the seasons of the year, or to ebb and flow, as in the motion of the tides. In the sciences, revolution thus implies a constancy within all change, an endless repetition, an end that is a beginning all over again. This is the meaning we have in mind in such a phrase as 'the revolutions of the planets in their orbits'. The expression 'scientific revolution' or 'revolution in science', however, conveys no such sense of continuity and permanence; rather, it implies a break in continuity, the establishment of a new order that has severed its links with the past, a sharply defined plane of cleavage between what is old and familiar and what is new and different. It is the historian's task to find out how and when an innocent scientific term that implies permanence and recurrence became transformed into an expression for radical change in political and socioeconomic affairs, and then to discover the way in which this altered concept was applied to science itself. This set of transformations embodies more than a mere shift in terminology. It suggests that there has been a profound conceptual change in our analysis of human and social action and in our image of the scientist and of scientific activity.

From the eighteenth century to our own, many scientists have written of their own scientific creations as revolutionary, but neither Copernicus nor Newton did so. Newton and his predecessors did not conceive of themselves as revolutionaries in part because their work was produced before the term 'revolution' had become generally applied to the sciences. But there is a deeper reason; we shall see that during the first century or so of modern science, many of the great creative scientists tended to think of themselves (and even to be viewed by their contemporaries) as revivers or rediscoverers of ancient knowledge, even as innovators who improved or extended knowledge, but not as revolutionaries in the sense in which we would commonly use this expression today.

Early in the eighteenth century, soon after Fontenelle recognized that there had been a revolution in mathematics, Newton's *Principia* was seen to constitute a revolution in physics, and before long Robert Symmer was proclaiming that he had made a revolution in the science of electricity. These events occurred when revolution in the political sense had a benign connotation, before the French Revolution had reached such extremes in the Terror that 'revolution' became a frightening word rather than an expression of rapid progress. Joseph Priestley, who suffered political persecution for his espousal of the French Revolution and who emigrated to the United States in 1794, shows us how the attitude toward revolution changed by the end of the eighteenth century. In a letter to Robert R. Livingston, statesman and inventor, who worked with Robert Fulton on the development of the steamboat, Priestley congratulated his correspondent on his "most valuable discovery relating to the fabrication of *paper*" (Schofield 1966, 300). "If you can succeed in bleaching it," Priestley wrote, "you will produce a complete revolution in the whole manufacture." The date was 1799, and Priestley — mindful of the generally negative feeling about revolutions — hastened to add a note of regret that Livingston's innovation must not "be called a *revolution* in these times. That alone would discredit it, tho ever so useful. It is not, however, the less acceptable to me."

The publication of *The Communist Manifesto* in the middle of the nineteenth century, the revolutions of 1848, and the formation of the first 'International', with its plans for world-wide revolution, conveyed anew a sense of violence associated with rapid change. Because these negative aspects of revolution were in the forefront of the thoughts of most people living in the 1850s, it is a little surprising to find English and Irish scientists like Darwin and Hamilton categorizing their respective reconstructions of science as revolutionary in the old benign sense, as if the new political urgencies had no significance for the image of scientific change. On the Continent, the reactions of scientists were markedly different.

In the twentieth century, the stark drama of the Russian Revolution and the specter of a possibly imminent world communism caused some scientists and nonscientists to be aghast at the alleged 'bolshevism' of such radical physics as Einsteinian relativity. Closer to our own time, the doctrines of Mao and the Chinese Revolution with its attendant 'cultural revolution' have in their turn affected the concept and image of revolutionary activity.

Comparison of Political and Scientific Revolutions

Political theories and events that involve rapid change in the social structure have had a pervasive influence on concepts of scientific revolution since the seventeenth century. Therefore we might profitably ask which specific features of political revolutions (and theories about them) have been incorporated into the concept of scientific revolution that most of us recognize today, and which other ones have proved to be inapplicable. A comparison of the two types of revolution reveals a closer degree of concordance than might at first be imagined. (A historical perspective on the comparisons of political and scientific revolutions is provided in §1.1., below.)

One of the features that all political revolutions have in common is the element of 'newness,' as Hannah Arendt (1965) has insisted. "The modern concept of revolution," she writes, is "inextricably bound up with models for world meteorology. That is, Galileo's telescopic observations changed the data in a way that required an abandonment of traditional theories and the acceptance of a new one, but they did not fundamentally affect the way in which theories are related to experiential data. By contrast, the introduction of probability produced a new kind of theory—and, in fact, a new kind of science—in which the traditional basis of a one-one cause-and-effect is replaced by a statistical foundation. It is the same for the computer, which has also altered the form of scientific theories, in that logically linked propositions and formal mathematical statements have been replaced by complex computer models.

In addition to newness, another feature that revolutions in science share with political and social revolutions is the phenomenon of conversion (discussed in chapter 29). One example will suffice to indicate the revolutionary zeal of the scientific convert. In 1596, in the original preface to *The Secret of the Universe* (1981, 63), Kepler described the stages of his conversion to the Copernican astronomy, a topic which he enlarged upon in the first two chapters. He believed that God had shown him how and why the Copernican system was put together, why there were six planets and "not twenty or a hundred," and why the planets were situated in their respective orbits with the speeds that they there exhibited. His solution was later expressed in what we now call Kepler's third (or harmonic) law, but in 1596 he undertook to prove that God, in creating the universe and regulating the order of the cosmos, had in view "the five regular bodies of geometry, known since the days of Pythagoras and Plato." He later wrote that he owed the Copernican heliostatic system "this duty: that since I have attested it as true in my deepest soul, and since I contemplate its beauty with incredible and ravishing delight, I should also publicly defend it to my readers with all the force at my command."

The comparisons one can make between political and scientific revolutions transcend such inner factors as zeal. For example, every political revolution has as its main feature a series of acts of physical violence related to the takeover of the institutional loci of power. Chalmers Johnson (1964, 6) states categorically that radical changes "not initiated by violent alteration of the system are instances of some other form of social change." Although one might not ordinarily think of a scientific revolution as involving physical violence, many of the great revolutions in science have exhibited a pattern of action similar to the physical overthrow of a government. In a scientific revolution, there is apt to be a series of acts whereby control is gained of the scientific press, the educational system, and the seats of power — in scientific academies and laboratories or on major scientific committees which make policy and apportion resources. One can see this very dramatically in the Lysenko revolution in the Soviet Union, in the course of which the forces of orthodox (Western) genetics were routed. Lysenko and his followers gained control of the genetics section of the Soviet Academy of Sciences and the system of agricultural experiment stations. They rewrote the textbooks to accommodate their new unorthodox ideas and reordered the whole system of teaching and practice of genetics. These revolutionaries drove from their posts all geneticists and even academicians who refused to hew to the new revolutionary line. The leading geneticist of the Soviet Union, N. I. Vavilov, brother of the president of the Soviet Academy of Sciences, dropped out of sight; in fact, at the time of his death in 1943, there was no official obituary telling the date and details of his last years and ultimate death in a concentration camp.

In Nazi Germany in the 1930s, not only were Jews removed from their jobs but the party approved a revolutionary movement to purge German science of the taint of 'non-Aryan' or overly theoretical thinking. Two of the leaders of this movement were Nobel Prize-winning physicists, Philipp Lenard and Johannes Stark. Under Hitler, Stark attempted to reorganize and expand German physics, but he was opposed by brave and decent men, led by Max von Laue, Max Planck, Arnold Sommerfeld, and Werner Heisenberg, whom Stark called "white Jews in science," the "viceroys of the Einsteinian spirit" (see Hermann 1975, 615). Lenard, an old friend and colleague of Stark, was a super-patriot who believed that a "disarmed nation" was a "dishonorable nation" (Hermann 1973, 182). In 1920, at the annual conference of German scientists and doctors, Lenard got into a public debate with Einstein, which was marked by Lenard's "sharp malicious attacks" and "an unconcealed anti-Semitic bias." As early as 1924, Lenard ended his academic lectures on physics with praise for Adolf Hitler as the "true philosopher with a clear mind." He became Hitler's chief authority in physics and published four volumes on experimental physics called *Deutsche Physik* (1936–37), or *German Physics,* which he defined as "Aryan physics" or "physics of the Nordic man." He said that "science . . . is racially determined, determined by blood." The 'Deutsche Physik' group, despite their official Nazi backing, never gained full control of German physics in the way that Lysenko and his followers did in the field of genetics in the Soviet Union. Only a few colleagues came to join Stark and Lenard, and their "efforts remained, despite the support of the Third Reich, fruitless" (Hermann 1973, 182; Beyerchen 1972).

Scientific change through a political kind of power is not limited to twentieth-century totalitarianism in the Soviet Union and Nazi Germany, however. We may see an early example in the various stages by which the Cartesian forces gained intellectual and institutional control of science in France (Sutton 1982). The revolutionary Cartesians fought for power with the forces of orthodoxy—represented by the Jesuits and their schools, the Church and its University of Paris, and the Aristotelians—on every imaginable level. They gained entrée into the influential salons and eventually attracted followers from among the intellectuals. Before long, Cartesians were in control of the schools (the *lycées* and the Jesuit *collèges*) and the universities. Cartesians came to have a strong voice in the Paris Academy of Sciences, where the 'permanent secretary' was Fontenelle, a staunch Cartesian and author of a major work on the Cartesian cosmological system of vortices ('tourbillons'). In the late seventeenth century the general textbook of Jacques Rohault, a noted follower of Descartes, replaced the traditional works and became the standard source of scientific knowledge; it was printed again and again and translated into a number of languages.

When the new revolutionary science of Isaac Newton was set forth in 1687, it was obvious that the real enemies to be routed were not the Aristotelians and scholastics but the Cartesians and their physical cosmology based on vortices. Newton showed, in the conclusion to book 2 of his *Principia,* that the Cartesian hypothesis "is completely in conflict with the phenomena of astronomy" and leads to a "confusion rather than an understanding of the celestial motions." But it was not enough to confute the Cartesians and others; an active campaign had to be mounted on a number of fronts simultaneously. First, there was a definite courting of the forces of the State, initiated when Newton dedicated the first edition of his *Principia* to the Royal Society and its patron, King James II. Edmund Halley, knowing of the King's interest in naval affairs, wrote for him a special account of the portion of the *Principia* dealing with the tides (see Cohen and Schofield 1978, §5). Because the church was such a powerful force in all intellectual matters, the Newtonians wanted control of the new Boyle Lectures (founded under the terms of the will of the chemist and natural philosopher Robert Boyle), which consisted of eight sermons in London churches on the evidences of Christianity (see Guerlac and Jacob 1969). These at once became a major vehicle for expounding the Newtonian science.

The Newtonians followed the path taken by Rohault and introduced popular lectures on the new science, extensively using demonstrations in order to make the subject matter more palatable and easier to understand. The pioneers were William Whiston and J. T. Desaguliers. Newton used his personal influence to replace the scholastic and Cartesian teachers at the major universities with orthodox Newtonians. Before long there was a powerful Newtonian network, comprising Colin Maclaurin in Edinburgh, Roger Cotes in Cambridge, David Gregory in Oxford, and others. To gain control of textbooks, the Newtonian Samuel Clarke added critical notes to his translation of Rohault's book on natural philosophy. This was the same Clarke who spoke for Newton in the famous debate with Leibniz. Eventually Rohault's treatise became the major work for teaching the Newtonian natural philosophy under the guise of a revised Cartesianism. Other Newtonians wrote original textbooks. And finally, when Newton went to London to become head of the Mint, he was elected president of the Royal Society, a position he used to make sure that this institution became a party to the struggle to establish the Newtonian philosophy and to guarantee Newton's priority over Leibniz in the quarrel over the invention of the calculus.[4]

These examples, for the most part, have been taken from successful or partially successful revolutions. But there is, additionally, the category of revolutions that fail. Prominent failures from the realm of politics are the revolutions of 1848 and the abortive Russian revolution of 1905. Scientists and historians of science generally do not talk about failed revolutions. That is, they tend to designate by the name 'revolution' only those movements in science that actually succeed (see chapter 2). No one has as yet written a history of scientific failures. Here, then, is one aspect of revolution in which science notably differs from political and social action.

A final point of difference between political or social revolutions and scientific revolutions is the goal. In one sense, both types of revolution have a specific, narrowly defined goal. For instance, the goal of the Newtonian revolution was to produce a new system of rational mechanics on the basis of which one could retrodict and predict the phenomena observed on earth and in the heavens. It was postulated on concepts of mass, space, time, force, and inertia, and it embraced the concept of universal gravity. This appears similar to the goal of producing a society in which, for example, there may be equality of economic opportunity, political liberty, a system of parliamentary or representative government, and so on. But the real difference is that in most political and social revolutions the goal is alleged to be immediately attainable. For instance, it was certainly the goal of the Russian Revolution to establish a communist state or a classless society. The achievement of this aim was never thought to be simply a prelude to an unending series of political and social revolutions; once the ideal state was achieved, no subsequent revolutions would be necessary. But developments of science, particularly after the revolutionary period of the seventeenth and the eighteenth centuries, have led us to expect that science will provide a series of continual revolutions without end. There is no final particular goal which, once achieved, means that no more revolutions will occur. The Newtonians, for example, were well aware of additional areas in which a scientific revolution was necessary: chemistry, optics, heat, and physiology. And even in terrestrial and celestial dynamics there was still the unsolved problem of the moon's motion under the joint action of the sun and the earth. In science a successful revolution establishes a revolutionary program for future revolutions, whereas a political or social revolution (at least ideally) has a finite program that the revolutionaries hope to achieve.

Revolutionary Science and Society

The scientific revolutionary has a quite different role in society from that of the political or social revolutionary. The social or political radical threatens the established social order or political system by plotting or preaching its overthrow, developing a theory that might be put into practice and that would produce a social or political revolution, or even participating in a revolutionary movement. Thus the social or political radical appears as an immediate or potential danger to our way of life, our mode of government, our value system, and may even seem to put in jeopardy our family system, our homes, our possessions, and our jobs. These considerations obviously apply to the 'haves' more simply than the 'have-nots', but even have-nots may eschew the revolutionary movement in the hope of making it within the established system and becoming haves (even if on a small scale). The scientific radical,[5] on the other hand, threatens directly the current structure of knowledge or the alteration of classical physics had no ideological component, although every physicist from then on was aware that the subject had changed in a very fundamental way.[6] And it is the same for quantum mechanics, "one of the most fundamental scientific revolutions in the history of the theory of matter" (Popper 1975, 90). Physicists have long been puzzled by the fact that the revolution of quantum mechanics has had no ideological component, that Heisenberg's uncertainty principle has never laid hold of the public imagination as relativity had done a few years earlier. And it is noteworthy that—at least as of now—no tremendous ideological component has been associated with the great revolution in molecular biology in our own days.[7]

A second kind of societal hostility to scientific revolution arises—properly speaking—from a reaction to the results or applications of science rather than to the science itself. Because so many rapid advances in both civilian and military technology are sparked by new science or by scientific revolutions, there has been a growing tendency to consider science and technology as one, and even to hold science responsible for the effects of technology. This phenomenon is not wholly new. When, during the Great Depression, a too-rapid rate of science-based innovation was deemed responsible for what was called technological unemployment, there was a call for a "moratorium on science." We have seen objections raised to the enormous costs of the space program in our own day, especially by those who would rather see public moneys spent for improving the conditions of our cities or for achieving other socially beneficent goals and not for revolutionizing our knowledge of the solar system and the rest of the universe. And many people have expressed an obvious deep concern about weapons whose technology is based on the latest discoveries in the biological as well as the physical sciences. Men and women of good will all around us decry the effects of pollution and other aspects of the deterioration of the environment and—rightly or wrongly—attribute such evils to science as the mainspring of technological innovation. And so many believe that the revolutions by which science advances are not necessarily benevolent and do not imply real progress for the 'condition of man'.

Apart from considerations of this sort, within the scientific community itself there is a general belief that each revolution in science is a step forward. Of course, some die-hards will always struggle against any major innovation that destroys existing concepts, theories, and general beliefs. Every great revolution in science has engendered an opposition among some scientists; the degree and extent of the antagonism may even be taken as a measure of the profundity of the revolutionary changes. Furthermore, every scientist has a vested interest in the preservation of the status quo to the extent that he does not want the skills and expert knowledge which he has acquired at great cost in time and learning energy to become obsolete.[8] But despite this natural resistance to change, there is no organized conservative party within the scientific system—as is found in the sociopolitical system—that seeks to keep things as they are and to suppress revolutionary movements within the sciences. One will always find radicals and conservatives (even individual counterrevolutionaries) within the sciences, and there will always be those who prefer old-fashioned methods and styles to new ones. But I believe that all scientists would agree with the reply, reported by the late Paul Sears, to a colleague in the humanities who said, "I suppose you will think I am old-fashioned, but I don't think that germs have anything to do with disease." The response was, "No! I don't think you are old-fashioned; I think you are just ignorant."

Because the scientific revolutionary produces an innovation within the sciences that primarily affects other scientists, the radical new science does not need to be comprehensible to nonscientists. It may be beyond the understanding of many other scientists, even most other scientists, especially those in areas other than the specialty to which the innovation pertains. This was certainly the case for Einstein's theory of relativity, the alleged general nonintelligibility of which was enshrined in the popular saying that only eight (or twelve) people understood it. But its nonintelligibility to the public affected neither the acceptance of relativity by the scientific community nor the general lay opinion that Einstein was a genius and that his incomprehensible and revolutionary theory was one of the great intellectual creations of the twentieth century.

Works of art, music, or literature, on the other hand, are not intended primarily (and certainly not exclusively) for the eyes and ears of only other artists, musicians, or writers, in the sense that science is primarily addressed only to other scientists. Literature is meant to be read, art to be seen, and music to be heard by the public. Furthermore, artists, musicians, and writers depend in large measure for their livelihood on the fees and royalties that come from an appreciative audience. This condition all but automatically goes against the true revolutionary in creative areas in which mass tastes may determine canons of acceptability. There are, of course, exceptions, such as Stravinsky and Picasso. In art especially, a kind of mass 'radical chic' seems to have enabled

Picasso to achieve a popular success that by far exceeds the public's comprehension of his oeuvre. No doubt, in the 1920s, James Joyce was read, understood, and fully appreciated by as large a number of writers and critics as there were scientists who truly understood Einstein's general relativity. But Einstein's results were accepted and used by many scientists despite their inability to comprehend the theory fully in all its aspects, or despite their inability to read Einstein's writings with ease or complete understanding. In Joyce's case, on the other hand, there was only a *succès d'estime;* the greater part of the reading public and the writing profession did not adopt and make use of Joyce's radical innovations because of their inability to read and understand *Finnegan's Wake* (called "Work in Progress" when being published serially in the journal *Transition*) and because to have adopted the new style would have separated writers from their readers and so have hindered rather than advanced their professional stature.

It is a curious paradox that conservative societies (and all highly organized and institutionalized societies must be essentially conservative in the sense of being self-preserving) not only tolerate revolutionary activity in the sciences to a degree that is simply not the case for any other form of intellectual or artistic creative effort, but even encourage it. Whereas a man or woman with extremely radical political, social, or economic views may encounter barriers (especially in relation to employment) that impede ordinary career development, and may even—as a dissident—encounter the restraining force of the law or the state, the scientist is especially honored when his or her most radical ideas succeed. Science is an exceptional enterprise in that revolutionary activity has been institutionalized; the system not only recognizes originality and assigns great value to it (as R. K. Merton has taught us) but bestows large cash prizes and social rewards on the successful revolutionary. In art or letters or music an extreme radical is denoted a member of the avant-garde and his or her audiences may be few in number; there are no rewards or prizes or honors for revolutionaries in these creative areas comparable to those in the sciences. It is notable, moreover, that whereas Nobel Prizes are regularly awarded to scientists whose contributions have been radical and truly revolutionary, no such awards in literature have been made to innovative writers of similar radical or revolutionary stature—August Strindberg, Henrik Ibsen, Marcel Proust, James Joyce, or Virginia Woolf.[9]

A major reason why society is usually willing to support and to reward revolutionary science, even an extreme form of ordinarily incomprehensible science, is the constant expectation of practical benefits: healthier and longer lives, better transportation and communication, new and improved manmade fibers, more efficient agriculture and manufacturing processes, greater conveniences for daily life, better instruments for national defense, and so on. The experience of the last half-century has vividly demonstrated again and again that the more innovative and revolutionary the science, the more profound and far-reaching the practical applications.

Predicting Scientific Revolutions

Although every scientist is aware of impending revolutions, no clear universal sign tells even the most astute observer the area of science in which the next revolution will occur or what form it will take. The most brilliant scientists are not able to predict exactly the kind of revolution they themselves will be making. (This is in direct contrast to the political and social revolutionary, who has a program worked out in advance and can, accordingly, direct his revolutionary activity toward a carefully defined goal.)

A major reason why there is no way of predicting precisely where the next revolution will occur, or what it will consist of, is that the sciences are 'arts' to one another. An unpredictable revolutionary innovation in one area may provide the means for effecting a revolutionary breakthrough in some other area. Because revolutionary advances in one science are apt to depend on revolutions in yet other sciences, the unpredictability rapidly increases exponentially. An example is the rise of molecular biology, notably the enodation of the structure of DNA, which required the use of a technique developed in physics—x-ray crystallography. Since the most rapid changes in technology are apt to come from unpredictable revolutions in the basic sciences, there is also an exponentially rising uncertainty in technological forecasting, notably about coming revolutions in the technological sphere. Computer scientists keep alive the story of the great expert in the nascent specialty of computers who, in the late 1940s or early 50s, is said to have predicted that some six or seven computers would satisfy the future needs of the United States, with a few more for Europe. The number would prove to be small, even for the machines of the giant type then in existence. The anonymous forecaster could hardly have guessed the series of revolutions (such as the one in solid-state physics) that would wholly alter the size, nature, and function of computers in the future.[10]

Revolutions in science are inevitable, in that they cannot be prevented, at least as long as science continues to exist, although they may have to await the arrival of a particular revolutionary genius to ignite the fuse. And scientists, as I have said, do not want the revolutions to be prevented. But the pace of such revolutions, or their frequency of occurrence, may be slowed down or speeded up. That is, the tempo of scientific advance can be accelerated and more areas for revolutionary scientific activity can be opened up by such factors as large-scale financial support, which provides additional manpower for research and enables costly apparatus to be built or obtained. Enormous sums of money are required to mount field work and expeditions, to make observations, to establish better communications within the scientific community, and to give creative men and women in the sciences time to reflect (that is, by relieving them of excessive teaching or administrative obligations). The availability of funds for jobs and training fellowships attracts young men and women with creative potential into science. Contrariwise, a paucity of funds not only limits the possibilities of purchasing and constructing instruments of research and making expeditions but also limits travel and easy communication, the nerve system of scientific intelligence that is so necessary to progress. Even more important, the lack of funds reduces the number of jobs and fellowships and narrows the net of recruiting for the coming generation of scientists. Such a shrinking of manpower directly decreases the rate of scientific revolutions by making smaller the likelihood that a revolutionary genius will be in the right place at the right time.

Changing Concepts of Revolution in Science

Today it is a commonplace to speak of the Scientific Revolution, the Copernican revolution, the Darwinian revolution, the computer revolution, the communications revolution, and so on. Almost every advance in science and technology in recent years is described as a revolution in the daily press. To some extent we can attribute this to a cheapening of our verbal currency, but in part it is a reflection of the simple fact that so many revolutions in science have occurred and continue to occur. As I was writing this chapter, a glance at a single shelf in

Congress of the History of Science (Edinburgh, 1977), one out of every six papers in section 11 on philosophy, methodology, and history dealt with aspects of revolution.

In the vast and ever-growing literature on scientific revolutions, containing studies and analyses of almost every conceivable aspect of the subject, the history of the concept is hardly mentioned. An exception is Lewis Feuer's book on *Einstein and the Generations of Science* (1974, 241–252), where some examples are given of the use of revolution in relation to science, chiefly in the late nineteenth and the twentieth centuries. The disregard for this topic on the part of historians of science would be all the more surprising were it not for the fact that historians of science have been generally notorious for neglecting the history of their own discipline and profession (see Thackray and Merton 1972; Thackray 1980).[13]

The purpose of this book is to fill that gap in the literature — to trace the many transformations, throughout four centuries, in the way scientists, philosophers, and historians have conceived of scientific change. In many cases scholars who have used the term 'revolution' may have had in mind nothing other than a historical metaphor for a great change, a truly significant invention. Such usage may be impressionistic and idiosyncratic; I doubt whether scholars have always had in mind the analogy with a particular political or social revolution when referring to a revolution in science. But we will examine many instances in which theories of social and political revolutions have strongly affected scholars' changing concepts of revolution in the sciences. And we will see how these concepts have been further influenced by the actual occurrence of social and political revolutions in the scholars' lifetimes.

For example, the image of revolutionary science in many parts of the world was affected by an abhorrence of bolshevism which grew out of the Russian Revolution of 1917. In the eighteenth century Lavoisier could compare his revolution in chemistry to the political revolution going on in France, which at that stage was a benign alteration of the absolute monarchy of the Bourbons; but the comparison would soon lose this meaning when the revolutionary excesses developed into the Terror, in which Lavoisier himself lost his life on the guillotine. A British historian living in the late eighteenth century, contemplating the Glorious Revolution and even the American Revolution, might very well consider revolutions benign, having the effect of restoring certain natural rights to Englishmen. Yet such a historian could legitimately hold the French Revolution, with its greater social violence and more complete destruction of the established order, to be a pernicious evil. This is hardly a theoretical case, since it is an accurate description of the opinions of Edmund Burke.

A final example of changes wrought by time in the concept of revolution is provided by a current view that the Scientific Revolution may have lasted for a century, or even for three centuries, from 1500 to 1800 (Hall 1954). Not only would this make the Scientific Revolution the longest-lasting revolution in recorded history, but it would imply a wholly different concept of revolution from the models of the Glorious Revolution or the American and French revolutions. That is, current views on the Scientific Revolution consciously or unconsciously invoke a concept of revolution that apparently is not derived by abstracting a set of supposed principles and practices of political and social revolutions and transferring them intact to the consideration of the growth of science.

Whether a given view of scientific change is influenced by social and political theories and events or whether it is influenced by other external considerations, we can safely say that it is always influenced by scientific developments themselves—the actual theories, inventions, or formulations that dramatically alter scientists' thinking about their field and the practice of their profession from day to day. We cannot fully understand the view of scientific change of a historian, philosopher, or scientist from any era without being aware of the nature of the scientific innovations to which he has been witness. Only then can we fully appreciate the ways in which the interpretation of those events has been affected by attitudes and events within the larger society. For this reason, a significant portion of this book concentrates on specific scientific developments—tracing the stages whereby a theory is conceived, discussed, opposed, transformed, and ultimately recognized for the revolutionary new perspective on nature that it makes possible. In short, this book treats not only of the concept of revolution but displays some of the major features of the actual revolutions in science to which the idea of revolution was applied and which exemplify the types of revolution in science in different centuries.[14]

2

The Stages of Revolutions in Science

The past decade has witnessed the rise of a variety of analyses of revolutions in science, or of the ways in which science advances, produced by historians and philosophers of science, among them Feyerabend, Kuhn, Lakatos, Laudan, Popper, Shapere, Toulmin, and myself. A vast literature has come into being, much of it a series of arguments about the internal consistency, the universal applicability, or the general usefulness of one or the other of these analyses. A major part of the debate has centered on the ideas of T. S. Kuhn. It is not necessary to agree with Kuhn in every detail in order to appreciate the real worth of his presentation, based originally on the notion of a 'paradigm' (1962; 1970; 1974; 1977), a set of shared methods, standards, modes of explanation, or theories, or a body of shared knowledge. Kuhn sees a revolution in science as a shift from one such paradigm to another, caused—he believes—by a crisis in the state of science that makes a new paradigm necessary. The activity of scientists within one accepted paradigm is called "normal science" and usually consists of "puzzle solving," that is, adding to the accepted stock of knowledge. Such normal science continues until anomalies turn up which eventually cause a crisis, followed by a revolution producing a new paradigm.

There have been serious problems in applying this scheme. One was that the term 'paradigm' was used by Kuhn in a number of different senses (Masterman 1970; Kuhn 1970);[1] another, that all revolutions do not necessarily arise from a crisis; yet another, that the whole scheme seems to work out better for the physical sciences than the biological sciences (Mayr 1976; Greene 1971). But Kuhn's analysis has the solid merit of reminding us that the occurrence of revolutions is a regular feature of scientific change and that a revolution in science has a major social component—the acceptance of a new paradigm by the scientific community. Kuhn has made the notable contribution of shifting the discussion from conflicts among scientific ideas to conflicts among the scientists or groups of scientists who hold those ideas. Additionally, he has stressed certain features of revolutions, such as the occurrence of anomalies that lead to a condition of crisis that in turn precipitates the revolution, the incompatibility between the old and new paradigms (which inhibits meaningful dialogue across the paradigm barrier), the existence of minirevolutions between major revolutions, and much else.

My own research differs from Kuhn's primarily in that I have been exploring the ways in which participating observers and contemporaneous analysts have viewed revolutionary changes in science during the four centuries in which modern science has existed. This line of enquiry sees the concept of revolution as a complex, historically changing entity — affected in turn by revolutionary theory and events in the realm of politics—rather than as a single and simple idea of how scientific change comes about. I have also tried, wherever possible, to juxtapose contemporaneous views of revolutions with the interpretation of later historians and scientists, including those of our own time. I have identified revolutions in science not so much by their fit into a fixed taxonomic scheme as by tests of historical evidence (see chapter 3). A basic step is to examine the mode of genesis and development of revolution-making ideas in science, in the way that I have done for Newton's revolutionary innovations in my book *The Newtonian Revolution* (1980). Another is to examine the fine structure of revolutions in science, as I have done here, taking the genesis of the new ideas or theories or systems (or paradigms) as a starting point, next tracing their public presentation and dissemination, and finally making precise the stages of acceptance by the scientific community that lead to a recognized revolution.

How can we know that a revolution has occurred? There are two types of criteria: one arises from logical analysis in terms of a strict definition, the other from historical analysis. Many of the major revolutions in science turn out to be revolutions on both counts: the Newtonian, Darwinian, Einsteinian revolutions, the Chemical Revolution, and the recent revolutions in molecular biology and the earth sciences. They all pass the tests for revolutions in science that I give in chapter 3. In the present chapter, my aim is to examine the successive stages that I have found to form a characteristic sequence in all revolutions in science and the role of participating observers and contemporaneous analysts in documenting the occurrence of such revolutions. I take it as given that revolutions do occur in the sciences, although I am aware that there are disbelievers and that among believers there is no consensus concerning which events in the development of science constitute revolutions.

From Intellectual Revolution to Revolution on Paper

In the course of studying a large number of revolutions, I have found four major and clearly distinguishable and successive stages in all revolutions in science. The first stage I call the 'intellectual revolution', the 'revolution-in-itself'. This revolution occurs whenever a scientist (or a group of scientists) devises a radical solution to some major problem or problems, finds a new method of using information (sometimes extending the range of information far beyond existing boundaries), sets forth a new framework for knowledge into which existing information can be put in a wholly new way (thus leading to predictions of a kind that no one would have expected), introduces a set of concepts that change the character of existing knowledge, or proposes a revolutionary new theory. In short, this first stage of revolution is what one or more scientists are always found to accomplish at the beginning of all revolutions in science. It consists of an individual or group creative act that is usually independent of interactions with the community of other scientists. It is complete in itself. Of course such an innovation arises from the matrix of existing science and is generally a fundamental transformation of current scientific ideas. Furthermore, it tends to be closely related to certain canons of the received philosophy and modes and standards of the science of the time. But the creative act that expresses itself the articles and books that might then have convinced his contemporaries and revolutionized mathematics were never composed.

The career of René Descartes (1596–1650) illustrates another delay in a revolution's advance to the public paper stage. In 1633 he put aside the manuscript of *The World,* a radical text on cosmogony that contains the first complete statement of the general law of inertia. He had just learned of the condemnation of Galileo and of the Copernican doctrines of astronomy, and he did not see how he could publish *The World,* with its Copernican cosmology. He even suppressed the physiological part of the book *Treatise on Man* because he did not see how to disengage this discussion of the life sciences from its Copernican foundation. In this case, the effect was not wholly and permanently to confine the Cartesian revolution to privacy, since both the cosmological and physiological parts of *The World* were published soon after Descartes's death. Furthermore, Descartes went on to write and publish another work, his *Principles of Philosophy,* in which the laws of inertia and some of his cosmogonic ideas were set forth; but the revolution was for a time robbed of a powerful instrument.

From Revolution on Paper to Revolution in Science

Even after publication, no revolution in science will occur until a sufficient number of other scientists become convinced of the theories or findings and begin to do their science in the revolutionary new way. At that time, what had been merely a public communication of an intellectual achievement on the part of a scientist or group of scientists becomes a scientific revolution. This is the fourth or final stage of every revolution in science.[4]

The history of science records the fate of many revolutionary ideas that never got beyond the public paper stage. Mesmerism is a good example. Mesmer proposed a revolutionary system of medical 'science' which was related to his practice of therapy. Although he won a large following among laymen (Darnton 1974) and converted some doctors, Mesmer's concepts and methods were ultimately rejected by the medical and scientific establishment, who found in them no scientific merit. They could not verify the existence of the Mesmeric 'fluid' of animal magnetism.

In our own century, a number of revolutionary areas of 'phenomena' have been similarly rejected when scientific critics could find no real basis for their existence. Among these are the N-rays, discovered in France in 1903. These rays attracted great attention among the scientific community, and their discoverer, René-Prosper Blondlot, achieved great fame and notoriety. But eventually it was shown that N-rays existed only in the mind of their discoverer and of other scientists whose will to believe evidently produced a temporary suspension of their normal scientific disbelief (Rosmorduc 1972; Nye 1980). And it is the same for the mitogenetic radiation discovered in the 1920s in the Soviet Union, comprising rays supposedly given off by growing plants and other living things. They could be transmitted through quartz but not glass. Hundreds of papers were published on this exciting and revolutionary new subject on the borderland of plant physiology and radiation physics. But eventually, careful experiments showed that these rays were nonexistent. In yet another failed revolution of this kind, Paul Kammerer announced in Vienna that he had demonstrated the inheritance of acquired characters. In 1926 his specimens of the mating toad, which presumably were his proof that acquired characters can be inherited, proved to have been doctored by the subcutaneous injection of India ink.

These examples (with the possible exception of Kammerer and his doctored specimens; see Koestler 1971) illustrate how both self-delusion and the excitement of a crowd of followers can lead from a revolution on paper to what may almost become a revolution in science. To some degree these fall within the category of 'fringe' or even 'pathological' science (Langmuir 1968; Rostand 1960), but a failed revolution in science need not be of this sort—although it is often difficult to separate what is extremely radical from what is pathological. Langmuir explained that almost always "there is no dishonesty involved." Scientists are "tricked into false results by a lack of understanding about what human beings can do to themselves in the way of being led astray by subjective effects, wishful thinking or threshhold interactions."

Two abortive revolutions illustrate the difficulty of this problem: one is Velikovsky's radical cosmological physics, the other is polywater. Immanuel Velikovsky attempted to revolutionize physical science with a radical set of ideas concerning the way the solar system came into its present state. One part of his revolutionary theory was that only a few thousand years ago Venus made repeated collisions with the earth and Mars, initiating events recorded in the Bible and other early chronicles; Venus was then a comet. Needless to say Velikovsky's ideas contradicted basic laws of dynamics and gravity. Velikovsky proposed that electrical and magnetic forces overwhelmed the action of gravity on the close encounter of planets. Though widely disseminated, especially in the public press, Velikovsky's radical ideas were not accepted by the scientific community. In fact, they gained serious consideration and even aroused great forces of opposition. In 1973, a debate was held at a meeting of the American Association for the Advancement of Science. Five scientists (Carl Sagan among them) attacked the theory of the collision of planets; only Velikovsky himself defended it (see Goldsmith 1977; Sagan 1979). In a review of this episode in the *New York Times* on 2 December 1979, two weeks after Velikovsky's death, Robert Jastrow listed three predictions of Velikovsky that had been verified and seven major ones that were directly contradicted. He lamented that "the facts" were not "otherwise," since "nothing could be more exciting than to witness a revolution of scientific thought in our own lifetime.""Unfortunately," he concluded, "the evidence does not support this possibility."

Polywater, first known as 'anomalous water', was discovered in 1961 by a Russian chemist working in a small provincial technical institute; the research was almost at once taken over by Boris V. Derjaguin, a well-known Russian physical chemist working at the head of a large group in a prestigious institute of the Soviet Academy of Sciences (see Franks 1981). Produced from ordinary water, this fluid differed from water as we know it in almost all its properties. It had a different boiling point and freezing point. In an article in the leading scientific journal in America, *Science*, on 27 June 1969, spectroscopic evidence was presented to support the judgment that the properties of this substance "are no longer anomalous but rather those of a newly found substance—polymeric water or polywater." The polymerization required a "previously unrecognized type of bonding for a system containing only hydrogen and oxygen atoms." At first, this discovery was not taken seriously by Western scientists, but before long research on polywater began in England and then on a large scale in America, accompanied by many conferences and supported by millions of dollars from the Department of Defense. As a referee for a research proposal wrote to the United States Air Force Office of Scientific Research (Franks 1981, 186), "All of chemistry, including that part of great relevance to the Air Force, will be revolutionized by this type of work." The eminent British crystallographer J. D. Bernal hailed polywater as "the most important physical-chemical discovery of this century" (ibid., p. 49).

Before long there was an avalanche of research papers on polywater published in reputable scientific journals; in November 1970 Derjaguin published an account of this "superdense water" in the prestigious *Scientific American.* Speculations arose on the implications of the new discovery. A professor from Pennsylvania issued a warning, printed in the widely read and authoritative British journal *Nature* (1969, *224:* 198), that if "the polymer phase [of water] can grow at the expense of normal water under any conditions found in the environment," all life on earth would become extinct. "The polymerization of Earth's water would turn her into a reasonable facsimile of Venus." Utmost caution was required, he concluded, because "once the polymer nuclei become dispersed in the soil it will be too late to do anything."

Of course there were skeptics, many of them quite vocal. They advised the Air Force, the Office of Naval Research, and the National Science Foundation not to associate themselves by financial support with polywater research, lest they eventually look ridiculous. In a letter to *Science* (1970, *168:* 1397), entitled "'Polywater' is Hard to Swallow," Joel H. Hildebrand, dean of American physical chemists, expressed the doubts of many members of the scientific community that polywater existed. Eventually it was shown that the properties of polywater came from (Franks 1981, 136) "different types and levels of contamination." An editorial in *Nature* sounded a melancholy note: "The failure of several experimenters to pursue with all the vigour at their command the possibility that contamination might account for most of their observations is nothing to be proud of."

The story of polywater is of special interest in the analysis of revolutions in science, not so much because it is a revolution that failed but because of the way it initially succeeded. Most failed revolutions in science are revolutions that never get beyond the state that I have called a revolution on paper. That is, they do not generate enough support among the scientific community to begin restructuring scientific theory to the extent of constituting a revolution. Other such revolutions fail because they are contradicted by experimental findings. Many others simply do not pass the primary test of being useful. In the case of polywater, however, the revolution was—at least for a time—almost, if not quite, a proper revolution in science. A large number of believers produced and published a considerable amount of research on the subject, much of it sponsored by major prestigious sources of financial support; these publications on the properties of the new substance proliferated in major scientific journals. In one sense, polywater can perhaps be described better as a discovery requiring a revolution (or a revolutionary discovery) than as a proper revolution — in the sense that a revolution would have been required in order to explain how this anomalous polymerization is produced in water. But if polywater represents a revolution in science rather than something that was only revolution-making, then one is tempted to say that for several years the revolution all but succeeded, despite the heavy skepticism of a considerable portion of the scientific community. Such skepticism and even downright hostility is, however, a normal feature of the early stages of any revolution in science.

In the end there was no polywater revolution because of the stern test of experiment that eventually required the abandonment of belief in this polymer of water. One can understand why many scientists must have overcome their fundamental skepticism and joined those doing research on polywater, since there is always a great desire to be active on the forefront of science, to be part of the team working on what is new and challenging. These researchers could not have been engaged in a conspiracy to defraud their fellow scientists, but rather must have suffered a massive self-deception, perhaps from too strong a desire to achieve positive results (see Ziman 1970). The history of this mass delusion is a subject worthy of exploration by those studying the sociology and psychology of science and the nature of revolutions in science. The rise and fall of polywater show how men and women actually behave in the laboratory, under the stress of today's extremely competitive scientific system: their behavior does not always conform to the ideal search for abstract truth that has long been the classical image.

The desire to be an active part of a revolutionary movement is often in conflict with the natural reluctance of any scientist to jettison the set of accepted ideas on which he has made his way in the profession. New and revolutionary systems of science tend to be resisted rather than welcomed with open arms, because every successful scientist has a vested intellectual, social, and even financial interest in maintaining the status quo (see Barber 1961). If every revolutionary new idea were welcomed with open arms, utter chaos would be the result.

The rigid and brutal insistence on demonstration which is part of the resistance to change in science actually is a source of strength and stability. Many attempted or proposed revolutions simply do not pass the test. Their predictions may not be verified, the experiential base may prove to be wrong or inadequate, or the theory itself may be shown to have a flaw. If there are no real advantages to a proposed new theory

Scientists tend to ignore proposed fundamental revisions of accepted science that come from outside the ranks of the established profession. No doubt, the initial hostility to Velikovsky and his ideas was strongly tinctured by the fact that Velikovsky himself was not a recognized member of the scientific establishment—he was not on the staff of a university, a research institute, or an industrial laboratory; he was an outsider, an amateur. Further, he sinned against orthodox procedure by having the first presentation of his ideas appear in a popular article in *Harper's Magazine* rather than a sober scientific journal. But in the end, the major reason for the rejection of Velikovsky's ideas was that they were wrong, or else that they were so inexact and nonquantitative that they could not really be tested by experiment and observation.

The case was much the same a little over a hundred years ago, in the 1870s, when J. H. van't Hoff published his revolutionary ideas on the asymmetrical carbon atom. Most chemists then were hostile and did not even give serious consideration to this proposed revision of orthodox chemical theory. One of these critics, the great German organic chemist Hermann Kolbe, downgraded van't Hoff's ideas in part because he was only a member "of the Veterinary School at Utrecht." Instead of pursuing sound and "exact chemical research," for which he has "no taste," Kolbe wrote, van't Hoff "has thought it more convenient to mount Pegasus (obviously loaned by the Veterinary School) and to proclaim . . . how during his bold flight to the summit of the chemical Parnassus, the atoms appeared to him to have grouped themselves throughout universal space" (Kolbe 1874, 477; see Snelders 1974, 3). In part, the opposition to van't Hoff's ideas arose also from the fact that he had written of atoms and molecules as if they had physical reality, in direct opposition to the views of most organic chemists, who were willing to use the concept of atom and molecule but were skeptical as to their actuality. Today van't Hoff's revolutionary ideas on the asymmetrical carbon atom are considered to be at the foundation of stereochemistry.

Given these many obstacles in the path to a revolution in science, it is somewhat surprising that any new theory or finding succeeds. In fact, many revolutionary ideas do not survive in a form that would be recognized and accepted by their first proponents; instead, they become transformed in the hands of later revolutionaries. To take an example, the system of the world that was fully elaborated by Copernicus in his *De Revolutionibus* in 1543 had no fundamental impact on astronomy until after 1609, when Kepler published his own radical reconstruction of

Copernican astronomy. From that time on we can begin to discern a revolution in astronomy, culminating in the work of Newton. But this revolution was not merely the Copernican revolution delayed by half a century. Rather, the new astronomy was in a real sense not Copernican at all (though it is often still called 'the Copernican revolution'). Kepler's reconstruction essentially rejected almost all of Copernicus's postulates and methods; what remained was primarily the central idea that the sun is immobile, while the earth moves in an annual circumsolar orbit and has a daily rotation. But this concept was not original with Copernicus, as he was well aware; it came from his ancient predecessor, Aristarchus of Samos.

This same phenomenon of transformation is apparent in the history of continental drift. Here again we have an apparent time-lag between Wegener's revolutionary announcement in the pre-World War I years and the ultimate acceptance of the revolution in the 1960s. But whereas Wegener imagined that the continents had moved in the manner of barges pushing or being pushed apart in the sea, thus making their way through the earth's crust, the eventual revolution was based on the concept of sea-floor spreading, which forces large sections of the earth's crust (plates) to move by a process of accretion at one boundary and disintegration at another. Because these plates may encompass continental land masses, their motion causes a separation of the continents. In this revolution, as in the example of Copernicus, what remains of Wegener's theory is primarily the idea that the continents are not orientated with respect to one another today in the same way they were when the earth was formed.

Scientific revolutions that fail are usually doomed to obscurity. When a political or social revolution (such as the revolutions of 1848 and the abortive Russian revolution of 1905) fails, it may nevertheless be a significant event, serving as an index of political or social conditions and problems that merit the serious attention of historians (Langer 1969; Stearns 1974; Ulam 1981). Some of the goals of failed political revolutions may still be achieved to a limited degree in the post-revolutionary period. But historians of science generally ignore revolutionary failures, unless they are examples of 'pathological' science. Perhaps this is because much of the history of science has been written by scientists themselves, who are more interested in the successive and progressive stages of truth than in the ups and downs of history, with its mixtures of truth and error.

3

Evidence for the Occurrence of Revolutions in Science

A discussion of revolutions in science cannot completely avoid a pair of related questions: (1) What *is* a revolution? (2) How can we tell whether or not a revolution has occurred? At first glance, it may seem that these are not wholly distinct, especially if it is believed that all sound definitions must have an 'operational' component. Yet it turns out to be possible to have a working test for the occurrence of revolutions in science, even without a clear-cut definition.

Kuhn's characterization (1962) of a revolution in science as a shift in "paradigms" (to use his original language) that arises when a series of "anomalies" has produced a "crisis" helps us in our attempt to formulate a definition and test. But we face a triple problem in trying to make precise the three notions of anomaly, crisis, and paradigm. Additionally, there is the problem (already mentioned) that not all revolutions in science exactly fit Kuhn's schema.

I have no easy answer to the definitional question of what constitutes a revolution. I repeat that what is of historical significance is that during the four centuries or so in which modern science has existed, scientists and observers of science have tended to call certain events revolutions. These include conceptual changes of a fundamental kind, radical alterations in the standard or accepted norm of explanation, new postulates or axioms, new forms of acceptable knowledge, and new theories that embrace some or all of these features and others. The Newtonian revolution entailed the radical concept of a gravitational force of attraction and achieved the goal of expressing and developing the principles of natural philosophy in mathematical terms; the Cartesian revolution was posited on the 'mechanical philosophy'—the explanation of all phenomena in terms of matter and motion; the kinetic-molecular theory of gases and radioactivity introduced explanations based on probability, while quantum theory denied simple nonprobabilistic causality; the theory of evolution denied the fixity of species and introduced a science that did not permit the prediction of single events; relativity not only sounded the death knell of absolute time and space, but radically altered the apparently simple concept of simultaneity; the Harveyan revolution set forth the idea of a continuous circulation of the blood from the heart out through the arteries and back into the heart through the veins and rejected the ancient and well-established doctrine that blood merely ebbs and flows in the veins, that it is continually being generated in the liver. In all such cases, an event occurred that has been (and is now) generally called a revolution. This is a historical fact, whether we like the word 'revolution' or not, whether we are or are not able to produce a definition that fits all these examples and others.

Since my purpose here is primarily to learn about revolutions that have been acknowledged as having occurred, and not to analyze a concept in abstraction, my method of study has been to examine the ways in which revolutions in science have been perceived. And this leads at once to a series of four tests that may be universally applied to all major scientific events that have occurred during the past four centuries. The basis of these tests is purely historical and factual. It consists, in its first part, of the testimony of witnesses: the judgment of scientists and nonscientists of that time. Among such witnesses I would include philosophers, political scientists, people active in political affairs, social scientists, journalists, literary figures, and even educated laymen. Both Newton and Leibniz were still alive and working on the development of the calculus when Fontenelle recorded his contemporaneous impression that their creation had produced a revolution in mathematics. Within a decade of Newton's death, Clairaut hailed Newton's *Principia* as the "epoch" of a revolution in the science of mechanics. Lavoisier's radical reform of chemistry was seen to be a revolution in chemistry by many of the scientists of his day. A number of Darwin's contemporaries wrote of the theory of evolution as a revolution in biology. To many earth scientists of the 1920s and 30s it was obvious that Wegener's ideas concerning the motion of continents were revolution-making, long before continental drift had changed its status from revolution on paper to revolution in science. These revolutions all pass the first test—the testimony of contemporaneous witnesses.

In three of the above examples, the scientist chiefly responsible for the revolution (Lavoisier, Darwin, Wegener) said expressly that his own work would create a revolution. This concurrence gives added strength to the testimony of other witnesses. It is obvious, however, that one should not make too much of the lack of such special testimony, since most scientists are usually too modest or too restrained by the conventions of the scientific enterprise to make such judgments about their own creations.[1] On the other hand, I would not put much trust in a later historical judgment that a revolution in science had actually occurred if there were no witnesses to testify to the event (such as a Mendelian or Babbagian revolution in science in the nineteenth century).

A scientist may believe he is making or has made a revolution even though later events show that such a revolution never occurred. Two examples are Symmer's theory of electricity and Marat's theory of optics. And as we saw in chapter 2, there are many examples of revolutionary movements in science that simply do not go on to develop into full-scale revolutions—Mesmerism, N-rays, and polywater, to name only a few. And so we need additional tests to supplement the testimony of witnesses.

A second test is an examination of the later documentary history of the subject in which the revolution is said to have occurred. A study of the treatises and textbooks of astronomy written between 1543 and 1609 does not show the adoption of Copernicus's ideas or methods. Hence this test indicates the nonexistence in those years of a Copernican revolution. By contrast, most of the mathematical writings of the eighteenth century—whether treatises, articles, or textbooks—are written in terms of the new calculus (whether the Leibnizian or the Newtonian algorithm), thus giving confirmatory evidence to Fontenelle's statement that the invention of the calculus was the epoch of a revolution in mathematics. Similarly, we have evidence of the Newtonian revolution if we compare and contrast post-1687 mathematical astronomy (with its the community of geologists and geophysicists) during the 1920s and 30s — thus passing the first test: the contemporaneous opinion of scientists. Furthermore, Wegener himself was fully aware of the revolutionary character of his new idea. When in the 1960s and 70s a new version of continental drift, based on the idea of plate tectonics, came to be part of the belief of earth scientists, they tended to speak of this change as a revolution. The literature of the earth sciences documents the dramatic changes that have occurred in this subject, consistent with a revolution. So continental drift passes the second and fourth tests. Finally, in the third test, we may note that historians have produced works in which the rise and acceptance of the ideas of continental drift have been described in terms of a revolution in science. A number of the discussions of continental drift, by both historians and scientists, even invoke the ideas of Kuhn and present the subject in terms of paradigm and paradigm-shift. Since, in this example, all our tests concur, can there be any doubt that a revolution has taken place? The theory of continental drift passes all tests for being a revolution.

For me, the testimony of contemporaneous witnesses weighs very strongly. Unlike later judgments, which are reflections less on the events of the revolution than on the revolution's long-term effects or on the postrevolutionary history of the science, these evaluations provide a direct insight into what was going on. There is a real significance, for example, to the fact that Charles Darwin not only believed his new ideas would create a revolution but actually said so in the conclusion to the *Origin of Species* in 1859. His prediction of a "considerable revolution in natural history" is a rare instance when a scientist was so bold as to make such a declaration in print — in this case, in the major publication announcing the discovery.[2] Darwin's judgment was echoed by a number of his correspondents. The statements by Lavoisier and Darwin about the revolution implicit in their own ideas are reinforced by the corroborative judgment of their contemporaries and are sustained by the evaluations of later historians and scientists. But self-evaluation may be unreliable. Few scientists or historians have ever heard of Robert Symmer and those who have would hardly agree with his own opinion that his contribution to electricity was "revolutionary." And our judgment is even stronger that Jean-Paul Marat, despite his self-evaluation, never did create a revolution in science.

Very few scientists appear to have described their own work in terms of revolution. Some fifteen years of research on this subject, aided by the contributions of many students and friends and the fruits of the investigation of several research assistants, have uncovered only some dozen or so instances of a scientist who said explicitly that his contribution was revolutionary or revolution-making or part of a revolution. These are, in chronological order, Robert Symmer, J.-P. Marat, A.-L. Lavoisier, Justus von Liebig, William Rowan Hamilton, Charles Darwin, Rudolf Virchow, Georg Cantor, Albert Einstein, Hermann Minkowski, Max von Laue, Alfred Wegener, Arthur H. Compton, Ernest Everett Just, James D. Watson, and Benoit Mandelbrot.[3]

Of course, there have been others who have said dramatically that they have produced a new science (Tartaglia, Galileo) or a new astronomy (Kepler) or a "new way of philosophizing" (Gilbert). We would not expect to find many explicit references to a revolution in science prior to the late 1600s. Of the three eighteenth-century scientists who claimed to be producing a revolution, only Lavoisier succeeded in eliciting the same judgment of his work from his contemporaries and from later historians and scientists.

Evidence from contemporaneous observers or participants concerning a revolution in science is subject to certain obvious uncertainties. The survival of evidence from an earlier period may be a matter of chance; even if it exists in some physical form (published reports or diaries, notes, correspondence, and so on), it might not be known to historians today. So the lack of contemporaneous documents stating explicitly that a revolution has occurred (or is about to occur) cannot always be used as positive proof of the nonoccurrence of a revolution. In other words, such contemporaneous evidence is one of the sufficient conditions for our judgment that a revolution has occurred, but is not always a necessary condition.

Information arising from the period under discussion may be extraordinarily valuable. A case in point is the annual report of the president of the Linnean Society of London for 1858, the year in which Darwin and Wallace published their first joint communication on the evolution of species by natural selection. The president said that the past year had not been noted for one of those revolutions that change the face of a science. Are we to assume that he was merely insensitive to the revolutionary implications of evolution? Not necessarily. As we shall see, his report shows that he believed revolutions occur in science, and that he supposed the time was ripe for a significant revolution in the life sciences. His statement thus proves that the great Darwinian revolution was not produced merely by the enunciation of bold ideas concerning evolution and natural selection. For a revolution to occur, there was needed the careful and complete body of documentary evidence and the fully worked-up theory that Darwin provided in his book a year later. The Darwinian revolution was not produced by the mere statement of radical ideas but by an interplay between an overwhelming mass of factual data and theoretical inferences on a high level.

Admittedly, these four criteria are in the end somewhat subjective. And obviously they do not cover every possible contingency. But at the very least they do provide the conditions sufficient for our judgment that a revolution has occurred, which may be buttressed by further research and critical reflection.

Historical Perspective on 'Revolution' and 'Revolution in Science'

II

4

Transformations in the Concept of Revolution

A political revolution is commonly conceived to be a change that is sudden, radical, and complete, often accompanied by violence or at least the exercise of force. Such a fundamental change has a dramatic character that usually enables observers to discern that a revolution is taking place or has just done so. The classic revolutions of early modern times—the American and the French revolutions—were notable for their alteration of the system of political organization, more drastic for the French than for the American Revolution. In both cases, the government or the ruler was renounced and overthrown and a new form of government was substituted for the old one by the action of the people being governed or their representatives. To some extent this had also been true of the Glorious Revolution.

In the nineteenth century, revolution and revolutionary activities began to transcend such purely political considerations as the form of government, and came to embrace fundamental socioeconomic policies. The word 'revolution' eventually came to connote not merely events leading to radical political or socioeconomic changes, but the activities (either unsuccessful or not as yet successful) intended to effect such changes. Thus in 1848, Marx and Engels set forth in *The Communist Manifesto* a blueprint for a revolution and a call for "a Communist Revolution." A year later, Marx announced among the "auguries of the year 1849" (1971, 44): "revolutionary uprising of the French working class, and world war."

From the eighteenth century onward, a revolution was more than an armed uprising, more than a defiance of established authority, more than a revolt or active renunciation of allegiance or subjection to a government. That is, a revolution transcended acts of revolt or rebellion that would not necessarily produce a new form of government or a new socioeconomic system.

A shift from one ruling house to another or a dynastic change was no longer deemed to be a revolution. Generally, a mere opposition to authority, especially if open and armed, has tended to be called a rebellion—this is especially the case when the act of rising up against authority has proved to be unsuccessful in either the short or the long term. For example, what we know today as the American Civil War was formerly called The War of Secession or The Rebellion, and a Confederate soldier was colloquially referred to by Northerners as Johnny Reb. (The rebel yell was the name given to the prolonged high-pitched scream or shout of the Confederate soldiers.) The events associated with the English Civil War—the military encounters between Cavaliers and Roundheads, the execution of Charles I, and the establishment of the Commonwealth—were referred to by the seventeenth-century historian and chronicler Clarendon as "The Rebellion and Civil Wars in England."

The history of the concept of revolution cannot be separated from the history of the ways in which the word itself has been used. This history has a number of closely related themes that are relevant to the subject of revolution in science. First: the origins of the word itself in late Latin, as a substantive deriving from the verb 're-volvere' as 'to roll back' and hence also 'to unroll', 'to read over', 'to repeat', and 'to think over'; whence the further meanings of 'to return', 'to recur'. Second: the employment of the substantive 'revolutio' as a technical term in astronomy (and in mathematics), beginning in the Latin Middle Ages. Third: the gradual introduction of 'revolution' in a political sense, to signify a cyclical process or an ebb and flow, implying a return to some antecedent condition, and eventually to indicate an 'overturning'. Fourth: the association of 'revolution' with the process of overturning in the realm of political affairs, and the subsequent separation of the sense of an 'overturning' from the cyclical connotations of 'revolution'; at the same time the word 'revolution' came into use to indicate a more than ordinarily significant event. Of considerable importance in the development of thinking about revolutions was the rather early recognition that a revolution had occurred in England (the Glorious Revolution in 1688) and that a revolution was going on in the sciences. By the beginning of the eighteenth century, revolutions (in a sense very much like that which we would use today) were thought to occur not only in relation to the state but also in the realm of intellectual and cultural affairs, specifically in the growth of science; there was an awareness that by the time of Newton a revolution had occurred in science. This period is notable for the recognition by at least three different scientists that their individual research could lead (or was leading) to a revolution in science.

In the last quarter of the eighteenth century, the American and French revolutions gave a factual demonstration that revolutions are part of a continuing political and social process, and at the same time Lavoisier announced a new revolution in science: the Chemical Revolution. By this time it had also become generally agreed that there had been a Copernican revolution as well as a Newtonian revolution, plus a succession of minor revolutions in the sciences.

During the nineteenth and twentieth centuries the name 'revolution' was applied to a series of social and political revolutionary events, unsuccessful as well as successful ones. A body of revolutionary theory was also developed, accompanied by the formation of a revolutionary movement dedicated to putting the theory into practice through the activities of organized groups of committed revolutionaries. Above all there arose the concept of 'permanent' (or continuing or ongoing) revolution, rather than a revolution consisting of a series of events closely packed within a relatively short interval of time. In the twentieth century, a succession of major and minor revolutions has made everyone keenly aware of revolutions as a regular feature of political, social, and economic change, and today they have been generally accepted as an equally regular feature of scientific change.

Revolution in Antiquity

Students of political theory trace a history of the analysis of revolutions going back at least as far as the philosophers Plato and Aristotle and the historians Herodotus and Thucydides. Although a number of events in ancient times might be called revolutions, the Greeks did not have a single agreed-upon word to describe them. Greek philosophers and historians tended to use a number of different words for what we would call revolutionary uprisings and changes. Hence, "though the Greeks had their fill of revolution they had no single word for it" (Hatto 1949, 498). In short, 'revolution' was not a clear and fully developed concept in the sense that we have known it since 1789. Arthur Hatto, who has made the fundamental study of the early history of the word and concept, has pointed out that Plato's 'revolution' is more properly an evolution, to the degree that "his ideal state tends to deteriorate into a timocracy and a timocracy into an oligarchy and so on through democracy into tyranny" (ibid.). Apparently Plato himself did not actually complete the cycle and conceive that this sequence of events would be repeated again and again, which would require that tyranny give way once again to an ideal state. That step was taken by Polybius, who alleged that he was making a summary of what Plato had said. It was Polybius and not Plato who conceived that kingship passes "into tyranny, tyranny into aristocracy, aristocracy into oligarchy, oligarchy into democracy"; then "democracy into mob-rule and mob-rule into that state of nature which . . . must inevitably produce kingship and a new cycle" (p. 499). In Polybius' own words, "Such is the cycle of political revolutions, the course appointed by nature in which constitutions change, disappear and finally return to the point from which they started." This cyclical view was expressed by Polybius (*Hist.* VI, 9, x) in the word 'anakyklosis' (from the stem 'kyklos', circle or wheel, the root of our word 'cycle') as in the turning of a wheel; "the force behind its turning is Fortune" (or 'tyche').

Book 5 of Aristotle's *Politics* is a discussion of revolutions, including a refutation and rejection of the cyclical theory of revolutions (V, 12, vii). Aristotle's 'regular term' for 'revolution' is 'metabole kai stasis' (change with uprising); if there is no violence, the 'metabole' is used by itself. Hatto (p. 500) concludes that the Greeks obviously had a sense of the concept of revolution and had experienced revolutions. But although a word could always be found to express this concept, or some phase of it, the Greek writers "did not always choose the same word and sometimes chose two or more." Perhaps the reason may be that although they experienced many revolutions and near-revolutions or proto-revolutions, the Greeks were not witness to a "classic revolution" in the sense that Europe was "in *the* Revolution of 1789" (ibid.).

In later Latin, the noun 'revolutio' had the sense of 'conversio' in classical Latin. Two instances may be cited from the fifth century: Martianus Capella (9.22) writes of "the courses of sidereal revolution [sidereae revolutionis excursus]," and Augustine (*City of God* 22.12) describes metempsychosis as many "revolutions through different bodies [per diversa corpora revolutiones]."

The Middle Ages and the Renaissance

The Middle Ages were not witness to revolutions in the sense of a dramatic and complete overturning of the political and social hierarchical system, although changes in government were sometimes brought about by revolts or forced removals of dynastic rulers. The Peasants' Revolt in England in 1381 had many features of an incipient revolution, including "the burning of manors, destruction of records of tenures, game parks, etc., assassination of landlords and lawyers, and a march (100,000 [?] men) . . . on London," where "lawyers and officials were murdered, their houses sacked, the Savoy (John of Gaunt's palace) burned" (Langer 1968, 290). But this was not a revolution in the present sense of the word because it did not have an organized program, did not even envisage the end of the monarchy or the abolition of the aristocracy, and was limited, insofar as there was a program at all, to the correction of particular grievances or excesses. Some scholars (Rosenstock 1931, 95; Hatto 1949, 502) have said that the beginnings of the now-current usage of 'revolution' can be seen in the early Italian Renaissance, for example, in the fourteenth-century *Cronica* of Matteo Villani (4.89 = Villani 1848, *5*: 390), who wrote about "la subita revoluzione fatta per i cittadini di Siena" ("the sudden revolution made by the citizens of Siena") in 1355. Here, apparently, was a political event that was produced by men and that did not occur as a result of forces beyond human control, but, as Hatto warns us, we must be careful not to make too much of this single revolution that allegedly resulted from man's actions, since in another passage (4.82 = *5*: 384) Villani refers to this very same event in terms of "le novità fatte nella città di Siena" (the changes made in the city of Sienna), and he also uses 'rivoluzione' (9.34 = *6*: 223) and "revoluzioni" (5.19 = *5*: 413) for general political unrest.

Scholars have found a few other early examples of use of the term 'rivoluzione', but it was not in general circulation as either a political primary astronomical and astrological signification, well beyond simple mathematical and physical exemplifications.[4] A revolution could be any periodic (or quasi-periodic) occurrence, and eventually any group of phenomena that go through an ordered set of stages—a cycle (in the sense of 'coming full circle'). Even the rise and fall of civilizations, or of culture, as a kind of tidal ebb and flow, was called a revolution. All of these senses are obviously linked to the primary astronomical meaning.

A similar word is 'rotation', with which 'revolution' is sometimes confused. Today we like to make a clear distinction between the turning of a body on its axis (rotation) and the motion in a circuit, as along a closed path or orbit (revolution); we thus speak of the daily rotation of the earth about its axis and the annual revolution of the earth in its orbit about the sun. But as late as the end of the seventeenth century, these two words were apt to be used interchangeably, as they are in Newton's *Principia* (1687). 'Rotate' comes from the Latin verb 'rotare' (to turn, or to swing around); the Latin noun 'rota' means wheel (and hence also chariot) and can even have the figurative sense of alternation or fickleness. This word 'rota' survives in current English usage to denote a fixed order of rotation of individuals or of duties, or even a roll or list of persons. A late Latin noun 'rotatio' has given us our word 'rotation'.

In the fortune-telling 'tarocchi' (or tarot cards) of the late Middle Ages and Renaissance, as in those of today, a major card is the 'rota di fortuna' or Fortune's Wheel. The fate of men was supposed to be determined by this wheel or 'rota' and its rotation. There would thus be two major sources of 'turning' that were believed to affect or even determine the course of men's lives and of the state: the rotation or turning or spinning of Fortune's Wheel and the revolution of the celestial spheres. Possibly, the rise of the word 'revolution' may be associated with Fortune's Wheel as well as with the celestial spheres (this notion has been advanced by Henry Guerlac). Evidence for this association could be found in the frequency of the occurrence in a political context of 'revolution' or 'rivoluzione' in association with Fortune's Wheel or the 'rota di fortuna'. In Dante, 'revoluzione' occurs in the *Convivio* as a term for the circular motions of the heavens; but there he does not invoke the image of the 'rota di fortuna'. Although the turning of a wheel is cyclical, there is no implication that the wheel will end up at the end of the spin at the same place where it began. Hence the sense of return or going back or completing a cycle is not necessarily implied by Fortune's Wheel in the same sense that is true of the revolutions of the celestial spheres.

There is abundant evidence of a widespread belief during the late Middle Ages and Renaissance that the affairs of state were controlled by the planets in their revolutions. Eugen Rosenstock-Huessy (Rosenstock 1931, 86–87; cf. Hatto 1949, 511) turned up a sixteenth-century example from Germany, in which events of human history are linked with planets in relation to zodiacal signs "in the first revolution" ("in der ersten Revolution"). Villani (Hatto 1949, 510) has an entry for the year 1362, in which astrology provides the exact hour when the Florentines should set out against the Pisans. Both Kepler and Galileo cast horoscopes for the rulers as part of their professional employment. Kepler (1937, *4*: 67; cf. Griewank 1973, 144) held that the occurrence of comets was associated with prolonged evils that cause sufferings "not only because of the departure of a potentate and the consequent change in government [nicht eben durch Abgang eines Potentatens und darauf erfolgende Neuerung im Regimen]." In a letter of 1606 Kepler (1937, *15*: 295–296) criticized superficial astrological predictions about human history made "on the basis of the revolution of the universe [ex revolutione mundi]." There is pictorial evidence that the royal power and the basis of monarchical government of both Queen Elizabeth and Louis XIV were associated with astrology (see figures 1, 2, and 3).

Anyone who lived in the Renaissance, or in the sixteenth or seventeenth century, would at once associate the word 'revolution' with the idea of the unrolling of the great wheel of time. The notion of the wheel of time and its revolutions was not only used as a purely intellectual metaphor but was exemplified in definite physical images and objects. For instance, on the clock towers of Renaissance buildings everyone could see the continual revolution of the hand to mark the passage of time.[5] (There was only one hand, to mark the hours.) Another image of the passing of time would be the daily apparent motion in revolution of the celestial sphere with sun, stars, and moon. The wheel of time could also invoke the image of the motion of the sun in its annual apparent orbit among the fixed stars. The daily revolution (which we today call rotation) of the celestial sphere brings with it the change from morn to noon to evening to night and marks a twenty-four-hour cycle of days. The revolution of the sun in its orbit during the course of a year brings with it a change in the rising and setting point of the sun, the relative length of hours of daylight and darkness, and the seasons.

The significant quality of these revolutions is not merely that they are cyclical or repeat a succession of phenomena in the sense that the word 'revolution' itself means to roll back, but rather that during the course

Figure 1. The traditional finite geocentric universe. A diagram published in Petrus Apianus's *Cosmographia* (Antwerp, 1539). At the center is the immobile earth (with its water and the spheres of air and fire), surrounded by spheres of the seven traditional 'planets': the moon, Mercury, Venus, the sun, Mars, Jupiter, and Saturn. Then come the sphere of the firmament or fixed stars, the ninth crystalline sphere, and the tenth sphere of the prime mover. Surrounding all is the EMPYREAL HEAVEN, ABODE OF GOD AND OF ALL THE ELECT. (Courtesy of Houghton Library, Harvard University.)

Figure 2. Political power and royal virtue linked with the revolutions of the celestial spheres in John Case's *Sphaera Civitatis* (Oxford, 1588), an "Aristotelian treatise on political moral philosophy," according to Frances Yates, *Astraea* (London, 1975, 64–65). As is partially explained in the facing poem and amply clear in the diagram itself, IMMOVABLE JUSTICE is shown as the immovable earth in the center. The inner spheres are those of the seven planets of the civic universe, with ABUNDANCE as the moon, ELOQUENCE as Mercury, CLEMENCY as Venus, RELIGION as the sun, FORTITUDE as Mars, PRUDENCE as Jupiter, and MAJESTY as Saturn. The sphere of the fixed stars consists of the *Star Chamber, Nobles, Lords, Counsellors,* while the outermost sphere is ELIZABETH BY THE GRACE OF GOD QUEEN OF ENGLAND, FRANCE, AND IRELAND, DEFENDER OF THE FAITH. Queen Elizabeth, therefore, as representative of the Deity, is the "prime mover" of the "Sphere of the State." (Reproduced by permission of The Huntington Library, San Marino, California.)

of each of these revolutions of time there are dramatic and significant changes. What could be more different than day and night or winter and summer! They are as different as birth, life in a mature state, death, decay, eventual resurrection—the cycle of life on earth and life everlasting. The cyclical revolution of astronomical time comprises a sequence of changes so dramatic that they were quite properly defined by the word mutation, which was used by Montaigne and other writers of the Renaissance to signify a great change, similar to what we would call a revolution. Until the seventeenth century, a revolution was a sequence of events, a cycle, an ebb and flow in the tides of human affairs and the fate of nations, or a return (more or less) to some antecedent state, while the individual occurrences or particular events in the sequence were apt to be called mutations. But even if a great event or change was not necessarily part of a regular sequence, it could be described in terms of revolution because it occurred in time and came into being with the unrolling of the great wheel of time. A revolution could also be an event that altered the normal course of history, one that—so to speak—nudged forward the wheel of time with a slight acceleration, an event that marked an epoch (or 'epoca'), the beginning of an epoch. In the sixteenth and seventeenth centuries, and even in the eighteenth, great changes are called revolutions in ways that reflect the background of thinking about astrological causes, the Wheel of Fortune, the ebb and flow or cyclical aspect of events, and the unrolling of the wheel of time.[6]

What is perhaps of the greatest interest in this emergence of 'revolution' is that it implied a determining of events beyond human will and human forces—whether by astrological causes or simply by the laws of cyclical succession, which come from the revolution of the wheel of time. Thus human events and the course of history would follow the same inexorable and fixed schedules as the motions of the stars, sun, moon, and planets, alterable by the direct intervention of God, much as in the occurrence of a miracle. Possibly a revolution could arise by man's intervention, transcending or momentarily replacing the inexorable sequence determined by the revolutions of the stars.

The Seventeenth Century

Out of this set of usages and implications, there gradually emerged the concept of revolution as a noncyclical event of enormous change. In this development we must keep in mind that in the sixteenth and early

—as a 1649 *Manifestation* of the Levellers put it (Aylmer 1975, 153)—of the principles of the "[Voluntary] Community [which existed] amongst the primitive Christians." As late as the American Revolution, the word 'revolution' still had decided overtones of return, in this case a return to the principles of the Bill of Rights (1689), which had been denied Englishmen in the American Colonies.

In the sixteenth and seventeenth centuries, and even in the eighteenth, it is not always easy (and sometimes not even possible) to tell which sense of 'revolution' a particular author may have in mind: a definite return (a cyclical phenomenon or an ebb and flow), or an event of major proportions (which may entail the establishment of something new), or merely an event in a sequence. For instance, in 1603, in John Florio's translation of Montaigne's *Essays* there occurs (p. 74) a modern-sounding passage: "In viewing these intestine and civill broiles of ours, who doth not exclaime, that this worldes vast-frame is neere vnto a dissolution, and that the day of judgement is ready to fall on vs? never remembring that many worse revolutions have been seene. . . . ?" In isolation this sounds much like a comment made in the post-1789 sense, and it is thus interpreted by Vernon F. Snow (1962, 169), but the presence of the modifiers "many worse" suggests that Florio had in mind nothing more than events in earlier cycles or perhaps merely earlier events; this interpretation is supported by the fact—not noticed by Snow—that Florio's "revolutions" renders Montaigne's "choses" (1595, "97" = 88; 1906, 204). To indicate events which are like those that we would call 'revolutions', Montaigne used the expression 'mutation d'estat', from the Latin 'commutatio rei publicae'.

The cyclical sense certainly predominates in another example brought forward by Snow (and also involving a translation to which he does not make reference). The 1614 edition of Camden's *Remaines* includes a chapter on "Apparell" which is not contained in the first edition of 1605. Towards the end of this chapter (p. 237) Camden says: "They which mislike most our present vanity herein, let them remember that of *Tacitus.* All things runne round, and as the seasons of the yeare, so mens maners have their revolutions." This obviously includes a rendering of what Tacitus says in a similar context and with similar meaning, though without, of course, the word 'revolution' (*Annals* 3.55.5): "Nisi forte rebus cunctis inest quidam velut orbis, ut quem ad modum temporum vices, ita morum vertantur . . . "

A striking instance of the cyclical use of the word 'revolution' in relation to human affairs and life occurs in the famous grave scene in

Hamlet (5.1.98). Shakespeare has Hamlet talk to the skull turned up by the clown: "Here's fine revolution, an we had the trick to see't. Did those bones cost no more the breeding, but to play at loggats with 'em? Mine ache to think on't . . . " Has Shakespeare (as suggested by Snow 1962, 168) equated "*revolution* with a restoration to one's former status, or a return to a previous point in the life-death cycle"? That is, is there here the idea of an ebb and flow, a sense of that 'reversal of fortune' to which some authors refer? It was in this vein that Molière wrote of "all the revolutions to which inhuman fortune can expose us" (*Psyché,* lines 611–612).

During the first part of the seventeenth century, the general or non-scientific use of the word 'revolution' most often implied some cyclical or quasi-cyclical phenomenon, somewhat similar to the astronomical meaning. Thus in a dictionary of 1611, 'revolution' was defined only as "a full compassing, rounding, turning backe to its first place, or point; the acommplishment of a circular course." But revolution was also coming to mean a great event, a change. We may perhaps see how these two senses of the word 'revolution' occur together, in the following extract from a letter written in 1646 by James Howell: "I think God Almighty hath a quarrel lately with all Mankind . . . for within these twelve years there have the strangest Revolutions and horridest Things happen'd not only in *Europe,* but all the World over, that have befallen mankind, I dare boldly say, since *Adam* fell, in so short a revolution of time." In the phrase "so short a revolution of time" Howell (1890, *1* : 512) has used the word in the traditional and literal sense; but in "the strangest Revolutions" he may or may not have had in mind the political events of those turbulent days.[7]

The sixteenth century knew no major or large-scale revolutions in the social and political realms in any sense in which we use the word today. There were thus no political or social events of the sixteenth century or of the early seventeenth century that could serve as concrete examples of revolutionary theory, or that could provide examples or conceptual models for revolutions (in the sense of a drastic and even sudden secular change) in the areas of human creative effort. But by the middle of the seventeenth century the development of the theory and concept of revolution was given a tincture of reality by political upheavals, notably the Glorious Revolution of 1688—the first recognized political revolution of modern times. (On the Reformation, see §4.1.)

The historical significance of the Glorious Revolution (see below) is somewhat obscured today by considerations of the series of events that occurred a few decades earlier, in the mid-seventeenth century, and which today are sometimes known collectively as the English Revolution—a name that is far from being in universal usage among historians, many of whom do not consider these events to have been a revolution at all. There is further confusion arising from the fact that a historian such as Acton (1906, 219) refers to the later Glorious Revolution as the English Revolution. This English Revolution is almost never defined, even by those historians who believe that a revolution occurred. A central feature is a constitutional and religious upheaval punctuated by dramatic events: the Civil War (1642–1646), the trial and execution of King Charles I (1649), the interregnum of the Commonwealth and Protectorate under Oliver Cromwell. Samuel Rawsun Gardiner, an eminent constitutional historian of the nineteenth century, saw this episode as "the Puritan Revolution 1625–1660,"[8] and so titled his great documentary history (1906); but in his text (for example, pp. x, xi) he referred to "the English Revolution." Although this English Revolution was marked by violence (civil war, regicide) and temporarily produced a change in the outward form of government (commonwealth rather than monarchy), no basic political or social changes "of lasting value" occurred. Even the fundamental issue of the king's divine right versus the power of Parliament (with real sovereignty based on the electorate) was not fully resolved until the Glorious Revolution.

The name Puritan Revolution, put forth by Gardiner (1886, and other works), was based on the plain fact that the opposition to the king was primarily Puritan, but the issues were economic as well as religious (the anti-royal party comprised many of the rising class of merchants and artisans who wanted to have a greater role in government and to effect a lessening of the restrictions imposed by government on finance and commerce). Within the Puritan movement, there were true revolutionaries, of whom a most extreme sect were called the Levellers (a pejorative expression applied to them because of their beliefs in democracy and equality). The Levellers were twice defeated by Cromwell and "the 'revolution' which *they* wanted never took place" (Aylmer 1975, 9). They wanted to abolish monopolies and special privileges (but not private property), to establish universal "male household suffrage" but not "unqualified manhood suffrage" (p. 50). Their aim was to revolutionize the mode of government by extreme parliamentary reforms, election of local magistrates and other officials, rotation in office, and decentralization of government plus a severe limitation of its powers, together with the abolition of the monarchy and the House of Lords.

Christopher Hill, the most important writer on the English Revolution in our day, asserts in *The Century of Revolution* (1972, ch. 11, pp. 165 ff.) that "a great revolution took place" during "the decades 1640–60 . . . comparable in many respects with the French Revolution of 1789." It was a "great revolution" because "absolute monarchy on the French model was never again possible." The "instruments of despotism, Star Chamber and High Commission, were abolished forever" and "Parliamentary control of taxation was established." But here again Hill asserts that this "was a very incomplete revolution," that "between 1640 and 1660 there had been two revolutions, of which only one was successful." Hill also insists that there had been a "great revolution in human thought"—a "general realisation . . . that solutions to political problems might be reached by discussion and argument," that "questions of utility and expediency were more important than theology or history," and that "neither antiquarian research nor searching the Scriptures was the best way to bring peace, order, and prosperity to the commonwealth." This being so, we would agree with Hill that it constituted "so great an intellectual revolution that it is difficult for us to conceive how men thought before it was made." In this same work, Hill sums up the effects of the decades from 1640 to 1660 by making a contrast between "the Puritan revolution" which "was defeated" and "the revolution in thought [which] could not be unmade." The latter included "the revolution in science led by the men who were to form the Royal Society after the Restoration" and "the revolution in prose which the same Royal Society was to consecrate."

This so-called English Revolution was not generally called a revolution until the nineteenth century; in its own century it was referred to as "The Great Rebellion" and "The Civil War." The nineteenth-century historian and statesman François Guizot produced a very influential six-volume *Histoire de la révolution d'Angleterre* (1826–56), in which he drew parallels between the French and English revolutions (both marked by regicide) and expressed his great admiration for the relative moderation of English revolutionism. This work particularly aroused the ire of Karl Marx, who wrote a major essay attacking Guizot in 1850. Marx and Engels discussed the English Revolution (and also the Glorious Revolution) in many writings. By the twentieth century, many books on English history referred to the English (or Puritan) Revolution along with the Glorious Revolution.[9]

William and Mary, destroyed that right in practice. Within a year, in 1689, certain rights and privileges of Englishmen were spelled out in a series of 'articles' comprising the Declaration of Right, the instrument setting forth the conditions that had to be accepted by William and Mary in order to be King and Queen. They could not be elevated to the throne unless they accepted the declared limitations of the royal power. When William and Mary simultaneously accepted the Crown and the Declaration of Right, they formally agreed to a contract which has not needed fundamental alteration for three centuries. England had "acquired the outline of a Constitution" which has worked and worked well. But we must note that the Declaration of Right "introduced no new principle of law, not even Toleration for Dissenters or irremovability of Judges, though there was entire agreement on the immediate necessity of those two reforms" (Trevelyan 1939, 150).

Today the revolutionary aspects of the Glorious Revolution may seem minimal, especially in contrast to the French and Russian revolutions. But in the succeeding century, men of as different political views as the conservative David Hume and the radical Joseph Priestley were as one with respect to the significance of the principle that a monarch rules by and with the consent of the governed. According to Priestley (1826, 286–7),

> the most important period in our history is that of the revolution under king William. Then it was that our constitution, after many fluctuations, and frequent struggles for power by the different members of it (several of them attended with vast effusion of blood), was finally settled. A revolution so remarkable, and attended with such happy consequences, had perhaps no parallel in the history of the world, till the still more remarkable revolutions that have lately taken place in America and France. This it was, as Mr. Hume says, that cut off all pretensions to power founded on hereditary right; when a prince was chosen who received the crown on express conditions, and found his authority established on the same bottom with the privileges of the people.

For most Englishmen this had been a beneficent revolution. No doubt the Glorious Revolution thus contributed to the intellectual linking of revolutions with the idea of progress.

The contrasting progressive and conservative aspects of the Glorious Revolution were presented in a dramatic way in an essay by Lord Acton found, expressed in a forceful way, in Thomas Hobbes's history of the Long Parliament (1969, 204): "I have seen in this revolution a circular motion of the sovereign power through two usurpers, father and son, from the late King" to his son. It "moved from King Charles I. to the Long Parliament; from thence to the Rump; from the Rump to Oliver Cromwell; and then back again from Richard Cromwell to the Rump; thence to the Long Parliament; and thence to King Charles II., where long may it remain." Another kind of cycle, the revolution of stars, was invoked by the Earl of Clarendon in a "Speech about Disbanding the Army," September 13, 1660: "The *Astrologers* have made us a fair excuse, and truly I hope a true one; all the motions [!] of these last twenty Years have been unnatural, and have proceeded from the evil Influence of a malignant Star; and let us not too much despise the Influence of the Stars. And the same *Astrologers* assure us, that the Malignity of that Star is expired; The good *Genius* of this kingdom is become superiour and hath mastered that Malignity, and our own good old Stars govern us again" (*State Tracts,* 1692, 3).

I do not know when the revolution of 1688 was first called 'glorious', but in that year John Evelyn wrote to Samuel Pepys to ask how "I may serve you in this prodigious Revolution."[10] A text of the following year mentions "this great revolution." As early as 1695, the word 'revolutioneer' was being applied to a supporter of the revolutionary settlement of 1688. A volume of *State Tracts* (1692) from 1660 to 1669 was stated to have the purpose "to shew the necessity, and clear the legality of the late Revolution." The opening decades of the eighteenth century also produced a number of references to the revolution of 1688; in Dr. Johnson's *Dictionary of the English Language* (1755), the third definition of 'revolution' reads: "change in the state of a government or country. It is used among us . . . for the change produced by the admission of king William and queen Mary."

Conservative Catholic opinion in France did not view the revolution settlement as a beneficent or glorious event. Rather, there was seen to be a cycle, a parallelism between the execution of Charles I and the flight of James II, both having been Catholic monarchs who lost their thrones, both having been replaced by Protestants: Cromwell and William of Orange. There was a quite natural fear that a similar cycle would unfold its revolution in France. A main theme of *The History of the Revolutions in England,* written by the French Jesuit P. J. d'Orléans, is that there was no inexorability in these events. As he says in dedicating the book to Louis XIV (translated in 1711 into English and reissued in a second edition in 1722), "It was no Failure in Your Majesty, that the last of [the revolutions of England] . . . was not prevented." Had Louis's "Advice been followed," and his "Succours accepted of, the King of *England* had been still on his Throne."

French Protestants, however, took new hope from the revolution of 1688. At the end of that year Pierre Jurieu, in one of his *Lettres pastorales, adressées aux fidèles de France qui gémissent sous la captivité de Babylone,* expressed his Protestant hope that this "great and surprising revolution will doubtless lead to others which will be not less considerable" (quoted in Goulemot 1975) than the revolutionary succession of William and Mary. Jurieu could find hope that "the tyranny of the anti-Christ [that is, Louis XIV] will fall without bloodshed, fire, and sword." In 1691, in a discussion of the execution of Charles I and the rise of Cromwell, the Catholic Raguenet invoked the image of "those idle and uneasy souls who are disgusted with a constantly even life and who delight in revolutions; in a word all those who hoped to gain some advantage in change or in general confusion entered with pleasure into this Cabal and spared nothing to make it succeed."

The Spread of a Concept

Jean-Marie Goulemot, in his *Discours, révolutions, et histoire* (1975), has shown that in the last decade of the seventeenth century the word and concept of 'revolution' was used rather extensively in France in relation to the English revolution of 1688, not considered in any way 'glorious' but rather as a Protestant threat to the established monarchy. In particular, Goulemot has traced the revolutionary idea during the closing years of the seventeenth century and opening years of the eighteenth in literature (tragic drama and romantic fiction) and in historical writing. The wealth of example he has found, showing the growing popular currency of the concept and term 'revolution', helps to explain the introduction during these years of the idea that there are 'revolutions' in mathematics and the sciences.[11] Unfortunately, this extraordinary book, while developing at great length the author's theme concerning the ideas of revolution in the seventeenth century, does not make a constant and consistently clear distinction between the seventeenth-century view and his own interpretation, strongly and admittedly influenced by the political events of the 1950s, 60s, and 70s. This is especially the case with respect to the actual occurrence of the word 'revolution', as opposed to some kind of idea of revolution (as seen by a twentieth-century thinker) in the works under analysis. And even in the examples given, there is not always a really careful attempt to discover whether 'revolution' in its actual occurrences means a cyclical phenomenon or a single event of major proportions.

Nevertheless, the number of instances in which 'revolution' does occur provides convincing evidence of the growing currency of this word and of the concept of radical change it carries.[12] An example is Fénelon's *Aventures de Télémaque* (published in April 1699); the "éditions commentées," published in 1719 and afterwards, "connect numerous episodes of the romance with the death of Charles I, the restoration of Charles II, the dictatorship of Cromwell, and the fall of James II" (see Goulemot 1975). Fénelon has his characters discuss "the revolts" and "the cause of the revolts" (particularly "the ambition and the restlessness of the great personages in the state"). There are three "fictional revolutions," each occurring in a monarchy in which a prince has become a tyrant; in two of them the tyrant is killed, but in a third he is exiled. As Goulemot observes, in two cases there is an uprising ('révolte'), in which the people rise up in order to gain their liberty, but they do not get rid of the monarchy and establish a republic. They chose a new king by legitimacy of succession or by elective vote; hence, it has been said that this kind of "revolution is not at all the creation of a new order, nor even a radical modification of the mode of exercising sovereignty, but a return to the old political order which tyranny has perverted." Fénelon says, "There is only a sudden and violent revolution that can bring back into its natural path this overflowing power" (quoted in Goulemot 1975). In 1697 Le Noble gave a Jacobite view of the revolution in England in a novel entitled *Milord Courtenay, ou Histoire secrette des premières amours d'Elisabeth d'Angleterre,* in which he wrote: "England is a perpetual Theatre of revolutions, in an instant the calm is changed into the most furious tempest, and this tempest changes in a moment into calm." In many late-seventeenth-century French novels, which turn out to be "oeuvres historico-galantes," revolutions abound. Thus, in *Abra Mulé, ou l'histoire du détrônement de Mahomet V,* Le Noble tells the story of "the revolution that occurred in the Ottoman Empire in the month of November 1687, by the deposing of Sultan Mahomet and by the elevation of his brother Soliman to the throne."

The new usage of 'revolution' as a transfer of an astronomical concept to the world of political affairs and even to conditions of life is illustrated by a seventeenth-century French-Latin dictionary by François Pomey. His *Royal Dictionary* (3rd ed., Lyon, 1691) has two separate entries for 'revolution'. First the technical sense, the traditional motion of circularity and the going around of the heavenly bodies: "*tour, cours des Astres.* Astrorum circumactus, circuitus, circuitio, conversio." But there is a second entry for 'revolution', devoted to political change, change in general, and even the advance of time and the vicissitude of fortune: "*changement d'état.* Publicae rei commutatio, conversio, mutatio. Temporum varietas, fortunaeque vicissitudo."

The spread of the new sense of revolution is seen in a book by John Ovington, *A Voyage to Suratt, in the Year 1689* (London, 1696). Of the four appendixes, the first was announced as "The History of a Late Revolution in the Kingdom of *Golconda.*" The revolution in question appears to have been a change in government in which a puppet king rather peacefully became a true monarch by taking power from his ministers. In the introduction, Ovington describes how he set sail from Gravesend on "*April* the 11th, 1689, the Memorable Day whereon their Majesties, King *William* and Queen *Mary* were Crown'd." The ship was sent to the East Indies, he says, "as an Advice-Ship of that wonderful Revolution, whereby their Sacred Majesties were peaceably setled in the Throne, and had been receiv'd with the Universal Joy of all the Nation." Ovington also used the word 'revolution' in an implied sense of a return when he talks of the "Rebellion of Cha-Egber against his Father" (new ed., Oxford, 1929, pp. 108–109). He "daily waits for some favourable Revolution," Ovington says, "when he may return to *India* again, whither he hopes to be recall'd by his Father's death."

In this new age of revolution, an earlier work on the English Revolution had a new relevance. Anthony Ascham's *Of the Confusions and Revolutions of Governments* (London, 1649; for which see Zagorin 1954, ch. 5) was an enlarged version of a work published in 1648. He used the phrase "confusions and revolutions" in a general, rather than a specific sense, but what made his book seem important after the Glorious Revolution was his political discussions of lawful and unlawful monarchical powers.

We may conclude this discussion with a presentation of the use of 'revolution' by Thomas Hobbes and John Locke.[13] Hobbes was perfectly familiar with the traditional scientific sense of the word 'revolution' and he used this expression in his writings on geometry and on natural philosophy. He wrote of "a contrary revolution," "epicycles," and of revolutions in the sense of completed circular motions. In his study of "the civil wars of England," or *Behemoth* (pt. 4, concl.), Hobbes

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The Scientific Revolution: The First Recognition of Revolution in Science

A number of historians—among them Roger B. Merriman (1938), H. R. Trevor-Roper (1959), E. Hobsbawm (1954), and J. M. Goulemot (1975)—have called attention to the almost simultaneous occurrence of revolts, uprisings, or revolutions in different parts of Europe in the middle of the seventeenth century—in England, France, the Netherlands, Catalonia, Portugal, Naples, and elsewhere. This was obviously a time of crisis and instability, and it would almost seem that there was a general revolution, of which the geographically separate events were but individual manifestations. That there was a "general crisis," as Trevor-Roper put it, was apparent to sensitive men of that day. In a sermon preached before the House of Commons on 25 January 1643, Jeremiah Whittaker declared that "these days are days of shaking," and the "shaking is universal: the Palatinate, Bohemia, Germania, Catalonia, Portugal, Ireland, England" (see Trevor-Roper 1959, 31, 62 n.1).

The seventeenth century was also the time of the Scientific Revolution. The first Civil War in England, in 1642, began just four years after iment. Some otherwise incomprehensible manuscript notes of Galileo were found by Stillman Drake (1978) to be a set of actual experiments that led him to the discovery of these laws.

This example shows us how novel and revolutionary it was to discover principles by experiment combined with mathematical analysis, to set scientific laws in the context of experience, and to test the validity of knowledge by making an experimental test. Traditionally, knowledge had been based on faith and insight, on reason and revelation. The new science discarded all of these as ways of understanding nature and set up experience—experiment and critical observation—as the foundation and ultimate test of knowledge. The consequences were as revolutionary as the doctrine itself. For not only did the new method found knowledge on a wholly new basis, but it implied that men and women no longer had to believe what was said by eminent authorities; they could put any statement and theory to the test of controlled experience. What counted, therefore, in the new science of the seventeenth century was not the qualifications or learning of any author or reporter but rather his veracity in reporting, his true understanding of the method of science, and his skill in experiment and observation. The simplest and humblest student could now test (and even show the errors in) the theory or laws put forth by the greatest scientist. Knowledge thus took on a democratic rather than a hierarchical character and no longer depended so much on the insight of a chosen few as on the application of a proper method, accessible to anyone with sufficient wit to grasp the new principles of experiment and observation and the way to draw proper conclusions from the data. It is not surprising, therefore, that so much attention should be given during the Scientific Revolution to codifiers of the method—men like Bacon, Descartes, Galileo, Harvey, and Newton, who wrote about the way to proceed in scientific inquiry.

The scientists of the seventeenth century and of the late sixteenth century were fully aware of the newness of their approach in directly appealing to nature. This approach is apparent in the books on plants and animals of the late sixteenth century. Not only do they show a new sense of realism derived from the use of perspective, but they state explicitly that the illustrations were made from living specimens. Thus, Fuchs's herbal of 1542 has a plate showing the artist and the woodcutter working from a plant held in front of them. In Vesalius's great book on *The Construction [or Fabric] of the Human Body* (1543), a plate shows all the tools necessary to make dissections. The message is plain: "Do it yourself." Vesalius not only wanted his student-readers to duplicate his results and confirm his findings, and then to go on to add to our knowledge; he was also making it evident that his revolutionary book was based on experiential and testable facts.

This sixteenth-century fascination with nature was evident in the response of men and women to the discovery of new worlds, especially North and South America. What was of interest was not just the land forms and geological deposits but the forms of life, plant and animal. Were these animals spared the Noachian flood and so different from the animals of Europe? Or were they separate and special post-diluvian creations? Both questions were disturbing because they seemed to have answers that ran counter to Scripture. And the question of the men and women native to the New World was more disturbing still.

In the opening decade of the seventeenth century, when Galileo's telescope made known for the first time what the heavens are like, the excitement was worldwide. Marjorie Nicolson has chronicled for us the eagerness with which people all over Europe waited for each new revelation of Galileo's telescope and the way in which his discoveries quickly took their place in the images used by poets. A masque of 1620 by Ben Jonson entitled *Newes from the New World* is not about America but about the heavens, the moon in particular, containing mention of the telescope—in keeping with Galileo's name for the account of his discoveries, *The Message of the Stars,* or *The Messenger* (both are suitable translations of the Latin *Sidereus Nuncius*). As an announcement of novelty, Jonson's work is the humorous equivalent of Monardes's description of the medicinal flora of America called *Joyfull Newes out of the Newe Founde Worlde.* Here was a symbolic beginning of the revolutionary newness of the sciences. For Galileo announced not only new facts, new information, but he speedily concluded that the new data of telescopic observations falsified the Ptolemaic system (which it did) and proved the Copernican (which it did not).[1]

Many of the seminal books of the Scientific Revolution bear the word 'new' in their titles. Kepler published (1609) a *New Astronomy,* based on physical principles. Galileo's last book (1638) bears the title *Two New Sciences;* though this may not have been the title he chose, he does introduce the third book, on motion, by stating that he had discovered many new things worthy of note. Tartaglia called his work a *New Science* (1537). An account of revolutionary experiments made with the newly invented vacuum pump was called *New Experiments Made at Magdeburg* (1672) by von Guericke. Boyle used the word 'new' in the titles of many of his books. In 1600 William Gilbert published a work significantly entitled *On the Magnet . . . a New Physiology, Demonstrated by Many Arguments and Experiments.* He dedicated this "nature-knowledge" which is almost "entirely new and unheard-of" to "you alone, true philosophizers, honest men, who seek knowledge not from books only but from things themselves." Gilbert was aware that only a small company as yet were devoted to "this new sort of Philosophizing."

The Scientific Revolution, which produced a new kind of knowledge and a new method of obtaining it, also produced new institutions for the advancement, recording, and dissemination of that knowledge. These were societies or academies of like-minded scientists (and some others who were just interested in science) who met to do experiments in concert, to see performances and tests of experiments done elsewhere, to hear reports on scientific work done by members, and to learn what was going on in other scientific groups and in other countries. The emergence of a scientific community is one of the distinguishing marks of the Scientific Revolution. By the 1660s permanent national academies arose in France and England, and both had official journals for the publication of research done by their members.

The example of Isaac Newton shows how significant election to such membership could be. In 1671 Isaac Barrow (Newton's predecessor as Lucasian Professor) took an example of Newton's newly invented reflecting telescope to London to show to the Royal Society. Newton's invention was "applauded" and Newton was shortly afterwards elected a Fellow of the Royal Society. Pleased at being so recognized by his fellow scientists in London, Newton wrote then to ask when the Society met so that he could present a report on his experiments on light and color, the ones that were the basis of the invention of the new telescope. With the pride of youth, writing to the secretary of the society that had reached out to make him a member, Newton said that his discovery was "the oddest" detection yet made in the operations of nature. Newton's eagerness to share his discovery at once with his new associates in science is in such marked contrast to his later reluctance to print (or to have printed) any of his findings that it gives us an indication of how significant formal admission to the established scientific community can be to a scientist.

Newton's paper on light and colors carried a number of firsts: the first scientific publication of Isaac Newton; the first or founding paper in the physics of colors; the first major scientific discovery to be published as an article in a scientific journal. And it is remarkable, furthermore, because it describes Newton's experiments and the theoretical conclusions he drew from them without expounding a system of cosmology or a doctrine of theology; it is science, pure and simple, as we have understood that term ever since.

A revolutionary feature of the emerging scientific community was the establishment of a formal information network. In part, this was accomplished by personal visits and correspondence, but chiefly by scientific journals and reports. The short-lived Galilean Accademia del Cimento (Academy of Experiment) published the result of its labors in a volume of *Saggi* (1667) in Italian. These were made available in English in 1684, in a volume that had a symbolic frontispiece showing how the Italian academy had handed on its tradition to the Royal Society of London. The *Philosophical Transactions* of the Royal Society contained articles in English and Latin. Soon there appeared volumes intended for Continental readers which translated the English articles into Latin. The summary volumes, or abridgements, of the *Philosophical Transactions* were wholly in English but were rapidly translated into French, while the findings of the French Academy of Sciences were made available in English. A surprising number of the great works of science in the seventeenth century were not published in Latin, as is often supposed, but in the vernacular languages. Some examples are Galileo's *Dialogue Concerning the Two Chief World Systems* (Italian, 1632; Engl. trans. 1661; Latin trans. 1635), Descartes's *Geometry* (French, 1637; Latin trans. 1649, 1659), and Newton's *Opticks* (Engl. 1704; Latin trans. 1706). Other examples are Descartes's *Dioptrique* (1637), Huygens's *Traité de la lumière* (1690), and Hooke's *Micrographia, or Some Physiological Descriptions of Minute Bodies* (1665).

We can see the information network in operation through the extensive correspondence of Henry Oldenburg, the inaugural Secretary of the Royal Society. In 1668 Oldenburg wrote a letter to Huygens, who was in Paris, expressing the desire of the Society to have him communicate to them "what he had discovered on the subject of motion," even though he "did not yet think fit to print [it]." He was asked whether he "would impart to them his theory of it, together with such experiments, as he grounded his theory upon." Huygens agreed, "not doubting but the society would secure to him the honour of that discovery, by giving it place in their Register-book, as coming from him." A few months later, Huygens's text was sent over and studied, in part by Christopher Wren. Then "several experiments were tried" as a means of testing Huygens's theory and also Wren's, but the apparatus did not work perfectly, and the experiments were ordered to be performed again at a science was empirically based, its principles could be embodied in real devices. Functioning machines embodying or based on new principles provide tangible evidence of the truth of the principles.

All of these revolutionary features aside, what did the Scientific Revolution actually achieve in the way of basic scientific advance? We have already seen that abstract laws of motion were replaced by Galileo's laws of freely falling bodies. Furthermore, free fall—a type of accelerated motion—could be combined with uniform horizontal motion to yield, as Galileo showed, the parabolic path of projectiles. The seventeenth century also saw the beginnings of the science of magnetism. Kepler found the three laws of planetary motion that bear his name and devised the modern heliocentric system of the universe that we often call Copernican. Newton not only founded the science of colors but produced a mathematical system that simultaneously embraced the new terrestrial and celestial physics. His principle of universal gravity accounted for Kepler's laws and the laws of falling bodies and could explain the occurrence of tides in the sea and the shape of the earth. It even set the ground for the successful prediction of a comet some four or five decades ahead. In the simplicity of its explanations and in the depth and scale of its applications, Newtonian physics was without a doubt a revolutionary force.

But the physical sciences were not the only ones that saw a revolution in our understanding of nature. The life sciences were also active, culminating in Harvey's discovery of the circulation of the blood, which revolutionized physiology. Here, as in the science of motion, the revolution had definite nonarguable aspects of falsification. Just as the prediction of Aristotelians (if not of Aristotle himself) that heavy bodies fall in air more swiftly than light bodies in proportion to their weight is demonstrably false—as is easily seen by making the experiment—likewise, Galen was simply incorrect in saying that the blood ebbs and flows in the veins and can ooze from one side of the heart to the other through pores in the septum, or inner wall, of the heart.

Contemporaneous Views on Revolution in Science

Although it was hard to deny the tremendous progress science had made in the sixteenth and seventeenth centuries, some observers nevertheless preferred to think of the advances as improvements rather than as revolutions, and there were some who denied that such truly great the discovery of the circulation of the blood would inaugurate a 'revolution in medicine'. The verb Magiotti used was 'rivolgere' ("bastante a rivolger tutta la medicina"), which means 'to turn', 'to turn over' (as in 'to turn over in one's mind'), and sometimes 'to overturn'. But in order to make sure that his readers got the message, he explained what he meant by the use of this word, since at that time it was not a common occurrence for discoveries to have such an overturning (that is, revolutionary) effect on a science. And so Magiotti compared its effects with two major breakthroughs in technology: gunpowder and the magnetic compass. This pair of technological innovations along with printing from movable type were said by Bacon to have produced the most radical changes in the modern world. (Bacon, we may observe, also did not have at hand the word 'revolution', nor the concept that this word implies in its current sense.) Magiotti was saying in effect that this new phenomenon of turning a subject of science upside down, for which there was no name or clear concept and which was not as yet a well-established kind of event, was like those extraordinary inventions that had changed the nature of world trade, exploration, and warfare. Further, in order to make his point effectively, Magiotti compared Harvey's discovery with what was in 1637 the single most dramatic and most subversively revolutionary discovery as yet made in any branch of science: the new phenomena of the heavens revealed by Galileo who demonstrated with a mighty blow that the Ptolemaic system was false and that for thousands of years astronomers had written about the heavens without any true conception of what the heavenly bodies were like. Equally, Harvey had shown that the Galenic system was false and that therefore the whole medical system based upon Galenic physiology would have to be replaced. And so Magiotti said that the effect of the discovery of the circulation of the blood was to be compared to "the invention of the telescope," which has turned "astronomy upside down." In this case, Magiotti did not use the verb 'rivolgere' (as he had done a moment earlier), but rather 'rivoltare', which means not only 'to revolt' but also 'to turn upside down' and 'to turn inside out', and so 'to turn over', 'to overthrow'.

The word 'revolution' was actually coupled with Harvey's discovery in an essay written later in the seventeenth century by Sir William Temple. We can also see the first stages in the emergence of the modern concept of revolution in the ways in which the author used this word. In the essay, entitled "Of Health and Long Life" and probably written before 1686 (see Woodbridge 1940, 212), Temple referred to the establishment of the ancient systems of medicine by Hippocrates and Galen, the attempts of Paracelsus "to overthrow the whole scheme of Galen" and his introduction of "the use of chymical medicines," and then discussed Harvey and the circulation of the blood. This sequence of events Temple (1821, *1*: 73) called "great changes or revolutions in the physical empire," that is, in the empire of 'physic' or medicine. The word 'empire' suggests that Temple was not referring here to the new sense of a single dramatic event but rather to the traditional use of the word 'revolution' in the phrase 'revolutions of empires'. And this is all the more likely in that Temple elsewhere ("Heroic Virtue," 1821, *1*: 104) invoked the image of revolution of empires as an unfolding or sequence of events. Furthermore, Temple himself did not really believe in a Harveyan revolution and said that the doctrine of the circulation "was expected to bring in great and general innovations into the whole practice of physic," but actually "has had no such effect."

In his *Ancient and Modern Learning* (1690 [1963], 71) Temple generally came out in favor of the ancients, arguing that the older books were best, that—in the words of Alfonso el Sabio—the only things in life worth pursuing are "old wood to burn, old wine to drink, old friends to converse with, and old books to read." He asked, "What are the sciences wherein we pretend to excel?" For 1500 years there have been no new philosophers of note, "unless Des Cartes and Hobbs should pretend to it." In astronomy he found "nothing new . . . to vie with the ancients, unless it be the Copernican system, nor in physic, unless Harvey's circulation of the blood." But Temple had no doubt that even "if they are true,""these two great discoveries have made no change in the conclusions of astronomy, nor in the practice of physic." So, although these discoveries have been the source "of much honour to the authors," they have been "of little use to the world. (pp. 56–57, 71)."

The subject of a revolution in medicine also appears in Fontenelle's *Nouveaux dialogues des morts,* issued in 1683, which contains a dialogue between the Alexandrian physician and physiologist Erasistratus and William Harvey (called Hervé). Erasistratus opens the dialogue with a summary of the marvels ('choses merveilleuses') reported by Harvey: the blood circulates in the body, the veins carry the blood from the extremities to the heart, and the blood then leaves the heart and enters the arteries which take it toward the extremities. He admits how wrong were the doctors of antiquity who thought the blood had only a very slow movement from the heart to the extremities of the body and he records how grateful the world is to Harvey for "having abolished that old error." But in the ensuing dialogue, Erasistratus admits that the moderns are better scientists than the ancients and that they have a better knowledge of nature; yet he avows that they are "not better doctors," since the doctors of antiquity cured sick people just as well as the doctors of the newer age.

Harvey counters with the observation that ignorance of the blood's circulation had been responsible for the death of many patients. "What," replies Erasistratus, "you believe your new discoveries to be truly useful?" When Harvey answers affirmatively, Erasistratus asks him why there are now as large a number of the dead coming to the Elysian Fields as formerly. "Oh!" says Harvey, "if they die, it's their fault, not that of the doctors." Harvey ends his reply on an optimistic note for the future, when the world will have had "the leisure to make useful application of discoveries made only recently," since "very great effects" will be seen with the passage of time. In the English translation by John Hughes (Fontenelle 1708), Erasistratus's acerb comment is that there will be "no such Revolutions, take my Word for it." That is, man early attained "a certain Measure of useful Knowledge," to which some small additions have been made, but which can never be surpassed. Fontenelle ends the dialogue on a pessimistic note: that whatever scientists may discover about the human body will be in vain, since "Nature will not be baffled" and men will continue to die at the appointed time.

This dialogue is of extraordinary interest in the present context. First of all, Fontenelle compares a discovery like Harvey's ("to find out a new Conduit in Man's Body") with that of an astronomer discovering a "new Star in the Heavens"—both are of little or no practical use. Second, Fontenelle, despite his rather strict adherence to the Cartesian philosophy, takes direct issue with Descartes's boast in his *Discourse on Method* that sponsored medical research would produce an indefinite prolongation of the life-span. Finally, we would note that Fontenelle's assertion (through Erasistratus) that there will be no revolutions in medicine is the direct antithesis of Fontenelle's own recognition of the occurrence of a revolution in mathematics. In this case, the denial of a possible revolution may be taken as an index of the general rejection of Harvey's great discovery by French doctors (see Roger 1971, 13, 169). Despite Descartes's own warm espousal of the circulation of the blood, Fontenelle could not conceive that this was a discovery of any great consequence for medicine. In fact, Fontenelle does not seem to have

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How did "revolution," a term from the physical sciences, become transformed into an expression for radical change in political and socioeconomic affairs, and then become appropriated once again to the sciences? How have political revolutions and intellectual forces modified our image of the scientist and scientific activity? Spanning five centuries and virtually all of scientific endeavor, *Revolution in Science* traces the changes in both scientific revolutions and human perceptions of them, weaving together physics, mathematics, behaviorism, Freud, Darwinism, atomic physics, and even plate tectonics into the larger fabric of intellectual history. Cohen seeks to uncover nothing less than the nature of all scientific revolutions, the stages by which they occur, their time scale, specific criteria for determining whether or not there has been a revolution, and creative factors in producing a revolutionary new idea. His book is one of the most impressive surveys of the history of science ever undertaken.

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