KÁROLY SIMONYI

A CULTURAL HISTORY OF PHYSICS

Translated by David Kramer

CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business
AN A K PETERS BOOK

Originally published in Hungarian as *A fizika kultûrtörténete*, Fourth Edition, Akadémiai Kiadó, Budapest, 1998, and published in German as *Kulturgeschichte der Physik*, Third Edition, Verlag Harri Deutsch, Frankfurt am Main, 2001. First Hungarian edition 1978.

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

Printed in the United States of America on acid-free paper
Version Date: 20111110

International Standard Book Number: 978-1-56881-329-5 (Hardback)

Library of Congress Cataloging-in-Publication Data

Simonyi, Károly.
[Fizika kultúrtörténete. English]
A cultural history of physics / Károly Simonyi ; translated by David Kramer.
p. cm.
Includes bibliographical references and index.
ISBN 978-1-56881-329-5 (alk. paper)
1. Physics--History. I. Title.

QC7.S55313 2010
530.09--dc22 2010009407

Visit the Taylor & Francis Web site at
http://www.taylorandfrancis.com

and the CRC Press Web site at
http://www.crcpress.com

Contents

Chapter 2: The Stewards of the Heritage

Chapter 3: Demolition and the Construction of a New Foundation

Foreword by Charles Simonyi

An exceptional book such as this could have been created only under exceptional circumstances. My father was a working physicist and a beloved university professor who taught a whole generation of Hungarian electrical engineers. His textbooks on the foundations of electrical engineering have been translated into many languages. Yet, in the politically charged atmosphere of the 1960s in Hungary, his quasi-apolitical personal conduct, based on the age-old virtues of hard work, good character, and charity, was interpreted as political defiance that could not be countenanced by the state. Hence, he progressively lost his directorship at the Physics Research Institute, his post as department head, and finally his teaching position altogether. I was still a minor when I left the country—and my parents—in search of a better life. It was understood by all that my doing so—a political act in a totalitarian era—would make my father's situation even more difficult.

Besides being a scientist, my father was a great humanist, not only in terms of his concern for his fellow man but also in the sense of a scholar of the humanities: he was extremely well read in the classics as well as in contemporary literature and history. The break in his career at midlife did not drive him to despair; his humanism instead commanded him to work on the subject he had perhaps always wanted to work on: the history of the interplay of science and the humanities. His first notes became a lecture series, first given off campus, in the evenings at the invitation of student organizations. Much later, when I was able to return to Hungary, I was privileged to listen to one of these lectures, still filled to more than capacity with students and young intellectuals, hearing my father convey the excitement and wonder of scientific development—how difficult it was to make progress in science, not simply because of ignorance but because the arguments were complex and the evidence was often ambiguous, and how the scientists gained courage or were otherwise influenced by the humanities. The success of these lectures gave rise to the present book that he continued to revise and extend almost until his death in 2001.

All history books that treat the modern period face a problem: when should the discussion close? My father prided himself on keeping the book up-to-date as it progressed through five Hungarian editions and three German editions. Now, nearly a decade after his death, we edited the story down to what was firmly settled by the year 2000, and asked the noted and brilliant physicist Ed Witten to write an epilogue bringing us up to date with the current scientific outlook, as opposed to the already stale speculations made in the recent past.

The English edition of the book was a dream for my father that he was unfortunately unable to realize due to the costs and the difficulties of supervising the translation. I was very fortunate in having found an experienced and courageous publisher, A K Peters (now part of CRC Press, a Taylor and Francis Group), who was willing and able to undertake the task. The translation was based on the third German edition, but being cognizant of the dangers involved in a second-generation translation of a translation, we carefully compared the results with the original Hungarian text and, wherever necessary, the more direct and conversational tenor of the original was restored.

The goal of the English edition is to be a "world book"—not just for the US and for other English-speaking countries but for all nations. Just as in the Middle Ages when Latin was the language of international scholarship, now we have a true world language of great expressive power, beauty, and flexibility, namely English, and it is our earnest hope that this translation will be enjoyed by everyone interested in the subject regardless of their native language.

Special thanks are due to Alice and Klaus Peters for the direction of this multifaceted project, from the typographic design to the supervision of the translation, editing, and production. The base translation was done by David Kramer. The text was reviewed by Robert Schiller and Alex Farba DeLeon. Charlotte Henderson did the final copy editing, including that of the mathematical formulas. Others involved in the project were Camber Agrelius, Sarah Chow, Julie Nicolazzo, and Sandra Rush.

This republishing of my father's main work would not have been possible without the support of the family: my mother, Zsuzsa, my brother, Tamas, and my wife, Lisa. Special help from Ildikó Csurgay with the illustrations is gratefully acknowledged.

Finally, I am tremendously grateful for Prof. Edward Witten of the Institute for Advanced Study for contributing the epilogue.

Preface

Today, the history of science is a discipline in its own right, with its own subject matter and methodology, its own journals, and its own university chairs. And, of course, it has its own professional practitioners, a group that the author of this book does not belong to. His profession is teaching and research in physics and he has simply taken delight in the history of his subject, a delight that he wishes to share with others. The reader may therefore take those parts of this book that deal with physics and technology to be authentic—to the extent that any book can be regarded as such—while the interpretation of the historical and philosophical background bears some of the stamp of the subjective and, to a certain, perhaps permissible degree, that of dilettantism.

This book has been written for a broad audience. The author hopes that the non-specialist reader will be able to follow the presentation—to be sure not without a certain measure of intellectual effort—and at the same time that the professional physicist will also find it of value. Such a twofold goal should not be attained at the cost of compromise: the level of discourse cannot just be set somewhere between that of the educated member of the general public and the professional physicist. Rather, it was the author's intention to set apart, wherever possible—if necessary by typography—the more easily assimilated portions from those requiring specialized knowledge. These latter segments appear in the present book in a smaller typeface, and they may be skipped by someone reading the main text, without loss of continuity. Yet, these technical passages can be also useful for the general reader, for the formulas and illustrations there—even from a cursory examination—should help to fend off false impressions. For example, one feels Greek literature and art to be of importance not only for their time, but for all time, since they have something of value to say to us even today. On the other hand, with regard to the greats of ancient science, we might consider it to be self-evident that they were largely prisoners of their time, and that today the knowledge of a schoolchild may well exceed that of a learned man of antiquity, Archimedes, for instance. Perhaps we would say the same about the ancient artists if we were unable to marvel at the sculptures of Praxiteles and Myron of Eleutherae, in the originals or copies, or if we could not read Homer at home, or see the plays of Euripides at the theater. If we would immerse ourselves as thoroughly in the ideas of Archimedes—to stay with the above example—we would see that to reconstruct them requires, even of the scientifically educated, a significant intellectual effort and that doing so can give one great intellectual delight. The reader may therefore look upon the technical passages as the analogues of the indispensable illustrations or quotations in works on the history of art or literature.

This book is, therefore, a work for the public understanding of science, and it may also serve as a textbook for college students. It has been the author's intention that to these two goals a third should be added, and he is fully aware of the danger that in attempting too many tasks he might succeed satisfactorily in none of them. This third goal is to be a primer in the history of physics because it contains almost as much in the way of quotations as it does of main text. In order to separate the quotations as little as possible from the text and to interrupt it no more than necessary, the quotations—printed on shaded background—are in most cases presented in side notes to the text that they accompany, or on occasion are inserted directly into the main flow of the book.

Biographical information that could not be organically integrated into the main text, as well as additional facts that require no special commentary, can be found in the extended figure captions. Thus there is a fourth use to which this book can be put, namely, as a sort of encyclopedia.

The color plates should serve—or so the author has intended—apart from their decorative and informational functions, to provide in their coordinated entirety a skeleton for the book or—more generally—for the cultural history of physics.

The author of a book such as this one must—if only from the scope of the project—rely on a host of other books. Some of the books listed in the bibliography have served as inspirational sources, others offer the reader introductory material, and still others provide a more wide-ranging view. The author has tried to indicate the origins of his ideas and to give proper credit for the figures and quotations, referring where possible to original sources. The figures have been taken—again, wherever possible—from first editions, primarily those to be found in Hungarian libraries.

Finally, the author would like to thank all those who participated in the creation of this book. First of all, his thanks are due to his assistant Ildikó Csurgay, who participated in preparing the manuscript for publication and in solving a number of technical and stylistic problems.

The author's thanks go also to the following Hungarian libraries for their help in locating ancient works and for permission to make photocopies to be used in the present book: the Library of the Technical University, Budapest; the Budapest University Library; the National Széchényi Library; the main library of the Benedictine Abbey in Pannonhalma; the Székesfehérvár diocesan library; the Memorial Library of the University for Heavy Industry, Miskolc; and the Library of the Hungarian Academy of Sciences, Budapest.

The author would also like to thank the following museums and institutions, which made illustrative material in their collections available without charge: CERN, Geneva; the Zwettl collegiate church; the Museum of the City of Paris; the Museum of Versailles; the Naples Museum, the Herzog August Library, Wolfenbüttel; and the Berlin State Museums.

The author thanks the Urania publishing company, in Leipzig, the publisher Akadémiai Kiadó, in Budapest, Harry Deutsch publishers, and in particular Bernd Müller, for a pleasant and sympathetic collaboration. Also to be mentioned are the valuable comments of Dr. Martin Franke as well as those of Dr. Otto Haiman, which were of great use in the final formulation of the text.

The last part of Chapter 5 was read critically by Professor András Patkós, and we have adopted many of his suggestions, some of them directly into the text. I thus owe him a special measure of thanks.

In addition to the collaborators mentioned above, I thank my son Tamás, who reviewed the Arabic texts and helped with editorial work. I thank as well my son Charles for his generous support, both material and emotional.

The author has striven to recognize all those to whom he owes thanks, especially for comments and suggestions, and to do so as precisely as possible. He is aware that he has been unable to realize these intentions completely. Finally, the author thanks his wife, who offered tireless assistance in preparing the manuscript, in bibliographic work, and in discussions of stylistic and pedagogical questions.

Károly Simonyi, 2000

INTRODUCTION

0.1 The History of Physics and Its Relevance to Our Lives Today

In today's industrialized societies, it has become possible for an ever-increasing number of individuals to pursue a life free of want. For this achievement we may thank the ever larger number of specialists working in very narrow fields of endeavor. Individuals yearn for a general overview of the cultural values created by the whole of humanity; or if not, we would like to awaken such desire in them. But is it possible to arouse in specialists—the "cultural barbarians"—an enthusiasm for art or literature? And conversely, can those versed in the humanities be convinced that discoveries in the various branches of science constitute an integral part of universal human culture? Or to put it in more general terms, employing a notion made popular in the twentieth century by C. P. Snow (1905–1980), is it possible to bridge the gap between the "two cultures," that is, between the humanities and the natural sciences? (See Figure 0.1 and Quotation 0.1.) Are today's citizens capable of making such a synthesis, and is it even possible or useful for a society to set such a goal? After all, the capacity of the individual to absorb knowledge is very limited; moreover, is it not the mark of truly great specialists that their work within their professional fields represents a calling, a life's work, a complete source of satisfaction and self-fulfillment?

In this context, what does the history of physics offer us? For physicists, the triumphs in the history of their science could stand as points of reference, as criteria for measuring the value of significant accomplishments in other cultural domains, while those with a more humanistic education or inclination could find in the history of the natural sciences, and in particular that of physics, those elements—research methods, principles of establishing the validity of results, and of course the results themselves—that in the course of history have become significant milestones of universal human culture, indeed often serving as a cultural driving force. In any case, one thing should be stated plainly: *Human culture is a single, unified whole, and it is only for us, the consumers of culture, that the problem arises how its significant elements are to be selected, appropriated, and transmitted* (see Quotations 0.2–0.4). Yet we must also note that paradoxically, the greatest creative personalities, both artists and scientists, of necessity operate as laws unto themselves, which often means that they are completely one-sided in their views.

There is much to be found in the history of physics that can make instruction at all levels, from elementary school to university, interesting, indeed exciting: There are amusing anecdotes, to be sure, but also tales of tragic conflicts, entertaining accounts of historical events, and the birth pangs of the clarification of concepts and methods—which has a philosophical aspect as well. All of this is highly suited to awaken interest in the student and provide valuable educational experiences. Moreover, the history of physics abounds in examples of lofty ideals and guidelines for ethical behavior.

On the other hand, we might ask what, in contrast to general expectation, is *not* to be expected from instruction in the history of physics? There is much talk in the contemporary pedagogical literature about education for independent, "critical," thinking. In scientific education attempts are often made to achieve this goal not by presenting students with the laws of nature as established fact or the opinion of

▲ **Figure 0.1** A scientist with the ecstasy of a saint or of an artist. This image of a Greek scholar in a medieval cathedral stands as a symbol of the unity of human culture (statue of Ptolemy in the Ulm cathedral, sculpted in 1470 by Jörg Syrlin).

Quotation 0.1

I believe the intellectual life of the whole of western society is increasingly being split into two polar groups. ...

Literary intellectuals at one pole—at the other scientists, and as the most representative, the physical scientists. Between the two a gulf of mutual incomprehension—sometimes (particularly among the young) hostility and dislike, but most of all lack of understanding. They have a curious distorted image of each other. ...

The non-scientists have a rooted impression that the scientists are shallowly optimistic, unaware of man's condition. On the other hand, scientists believe that the literary intellectuals are totally lacking in foresight, peculiarly unconcerned with their brother men, in a deep sense anti-intellectual, anxious to restrict both art and thought to the existential moment. ...

[There was a somewhat well-known scientist] who, when asked what books he read, replied firmly and confidently: "Books? I prefer to use my books as tools." It was very hard not to let the mind wander—what sort of tool would a book make? Perhaps a hammer? A primitive digging instrument? ...

continued on next page

Quotation 0.1, ***continued***

It isn't that they lack the interests. It is much more that the whole literature of the traditional culture doesn't seem to them relevant to those interests. They are, of course, dead wrong. As a result, their imaginative understanding is less than it could be. They are self-impoverished. But what about the other side? They are impoverished too—perhaps more seriously, because they are the vainer about it. ...

As with the tone-deaf, they don't know what they miss. They give a pitying chuckle at the news of scientists who have never read a major work of English literature. They dismiss them as ignorant specialists. Yet their own ignorance and their own specialization is just as startling. A good many times I have been present at gatherings of people who, by the standards of the traditional culture, are thought highly educated and who have with considerable gusto been expressing their incredulity at the illiteracy of scientists. Once or twice I have been provoked and have asked the company how many of them could describe the Second Law of Thermodynamics. The response was cold: it was also negative. Yet I was asking something which is about the scientific equivalent of: Have you read a work of Shakespeare's? I now believe that if I had asked an even simpler question—such as, What do you mean by mass, or acceleration, which is the scientific equivalent of saying, Can you read?—not more than one in ten of the highly educated would have felt that I was speaking the same language. So the great edifice of modern physics goes up, and the majority of the cleverest people in the western world have about as much insight into it as their Neolithic ancestors would have had. ...

In our society (that is, advanced western society) we have lost even the pretence of a common culture. Persons educated with the greatest intensity we know can no longer communicate with each other on the plane of their major intellectual concern. This is serious for our creative, intellectual, and, above all, our normal life. It is leading us to interpret the past wrongly, to misjudge the present, and to deny our hopes of the future. It is making it difficult or impossible for us to take good action.

There is, of course, no complete solution ... But we can do something. The chief means open to us is education—education mainly in primary and secondary schools, but also in colleges and universities. There is no excuse for letting another generation be as vastly ignorant, or as devoid of understanding and sympathy, as we are ourselves.

—C. P. Snow, *The Two Cultures and the Scientific Revolution,* 1959 [pp. 4–16]

experts, but by providing them with the experimental setup used by the discoverer of the law, so that with the help of the experiments, the students can *rediscover the laws for themselves.* Yet in reality, such attempts are frequently good only for giving the student a completely false impression of the degree of difficulty in discovering new laws, with the result that they are unable to appreciate adequately the contributions of the great thinkers. Only a historical approach can show the decisive steps in a new discovery, which often required not only genius, but in many cases also an unusual degree of human courage.

As an example, we might mention here the inclined plane, a typical means by which students rediscover the laws of motion under constant acceleration, allowing them to reproduce an intellectual leap of Galileo (1564–1642). But if we give the students an inclined plane and some smooth spheres to roll down it, *we have removed the only significant new element of discovery and originality.* All that remains is mechanical work, which from the point of view of an experimental psychologist would not be much different from studying the behavior of a laboratory rat traversing a maze.

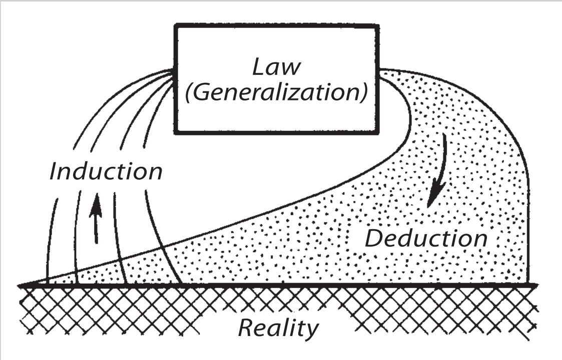
Galileo's great achievement was to have found an experimental approach that does not use materials found in nature. In this case, *the description of the experimental setup is the crucial step,* which by abstraction from reality simplifies the problem to such an extent that it can be investigated with the tools of mathematics. To be sure, experimental procedures like that of the inclined plane have their purpose, but they fulfill a quite different pedagogical goal. Thus reproducing some of the measuring apparatus used by Galileo, for instance, brings the student through his or her own experience nearer to both the natural phenomenon under investigation and the historical background of the scientific discovery. It is even capable of eliciting ideas indirectly: Galileo measured time by measuring the mass of the water that flowed out a vessel during the time to be measured; similarly, in today's technology, very small intervals of time can be measured by the tiny amounts of electrical charge that flow out of a capacitor.

Care must be taken not to present an over idealized image of the great personalities who changed the course of physics: We should not forget that their opponents were nearly their equals in intellectual outlook and were even their superiors on occasion in matters of ethics and morality. If we insist that these opponents were simply expounding nonsense or were somehow less moral, we are in effect devaluing the importance of the scientific discovery.

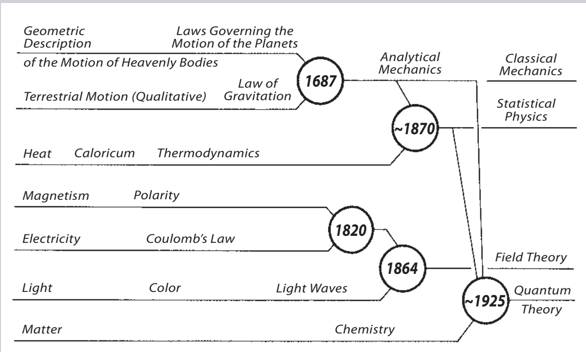
One could even imagine the traditional introductory course in physics being replaced by one on the history of physics—in both the basic courses for would-be physicists and engineers and those for students in the humanities.

The history of physics can also serve as a motivation for practicing physicists. In this regard we turn to two famous scholars of the twentieth century to demonstrate that the science, the philosophy, and the physics of the ancient Greeks remains a living force even to this day. The first is Bertrand Russell (1872–1970), who considered Plato (ca. 427–ca. 347 bce) to be the predecessor of the modern work of clarifying the concept of a number that was undertaken by Gottlob Frege (1848–1925), and Alfred North Whitehead (1861–1947), and himself. The second is Werner Heisenberg (1901–1975), who attributed to Plato the fundamental idea behind his unified field theory (see Quotation 1.20).

The history of physics can also be of use to active scientific researchers in other, more direct, ways: Namely, the theoretical underpinnings of some new theory are typically debated in great detail when it first appears. Opponents of the theory

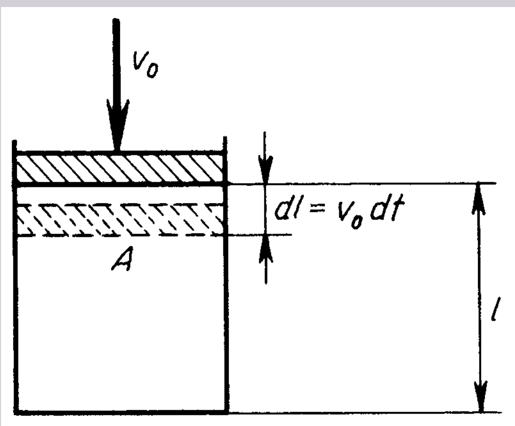


▲ **Figure 0.9** Simplified schematic representation of the scientific method. A law encompasses a greater range of phenomena than the individual observations on which it is based. The limitation of the domain of validity is also indicated in the figure.



▲ **Figure 0.10** Junction points in the history of physics. The dates indicate when the relationships between disparate groups of phenomena were recognized:

1687: Publication of Newton's *Principia*
1820: Ørsted's discovery of the magnetic properties of electric current
1864: Maxwell's electrodynamics
1870: Development of statistical mechanics
1925: Birth of quantum mechanics (after [Hund 1972, p. 16]).

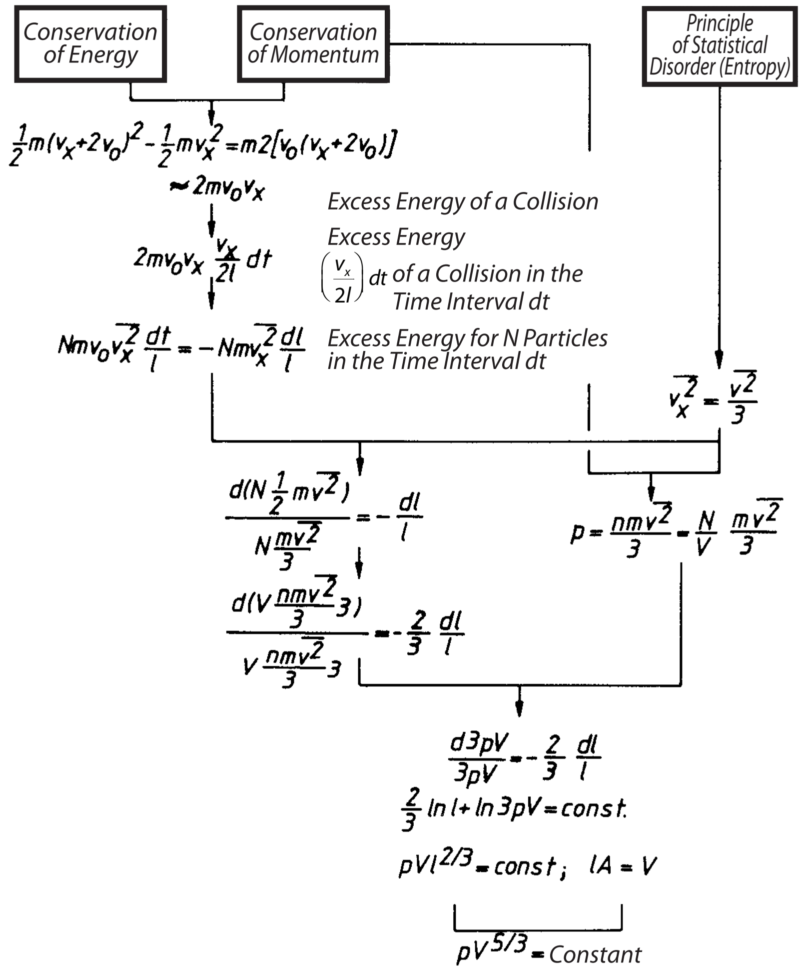


▲ **Figure 0.11** Molecular interpretation of the adiabatic state equation.

Figure 0.10 displays a logical and plausible chronological division of the history of physics into periods due to Friedrich Hund (1896–1997); the points at which branches of physics were united are indicated by the dates in circles.

Let us return now to the concrete physical example that we considered above and investigate in detail the theoretical and aesthetic consequences of the unification of two branches of physics and the practical results to which such unification has led. We can imagine, for example, that the gas particles enclosed in the cylinder are small spheres that on impact with the walls of the cylinder exert a pressure. If the piston enclosing one end of the cylinder is moving, then the speed of the particles on impact with the piston will be different from what it was earlier. The result will be a change (in this particular case an increase) in kinetic energy, and an increase in kinetic energy means an increase in the temperature of the gas (Figure 0.11).

In diagram form, a quantitative solution to the problem would appear as follows:



As we can see, among the fundamental laws from which we started, there is now a new one, which is also of a different nature, namely a law based on statistical probability. The result of this derivation contains more than the previous result, for we have now found a numeric value for the quantity κ. This value is furthermore in good agreement with the value found by experiment.

The derivation above is more satisfying than the previous one in a more general sense as well, since we have the feeling that by reducing macroscopic phenomena to processes in the world of atoms that also obey the laws of nature derived from macroscopic physics, we achieve a deeper insight into nature's workshop.

0.2.4 *The Role of Modeling*

If we look at the periods when particular areas of physics become quantitative, we see differences of nearly two thousand years. We may ask why is it that, in certain areas, our contemporary level of physical understanding was already reached in ancient

Greece—here we are thinking primarily of the principle of the lever, hydrostatics, and the kinematic description of the motions of the heavenly bodies—while the description of other phenomena, such as the motion of bodies here on earth, just to take a simple and important example, was not achieved until the seventeenth century.

It is clear that a significant impetus for the study of a given phenomenon is provided by the role it plays in daily life. As a first approximation, we might even say that for the development of a given area of knowledge, practical applications play the decisive role. But this is only very roughly the case. Specifically, this cannot be said for the Greeks, the founders of science: they were careful to make sure that their results had no practical use, since they wished to indulge only in the kind of science "befitting free men."

If we consider once more the example that we have been studying in detail, in both of the forms in which it has been presented, we may conclude that idealization and the abstraction from reality that results are of decisive importance. The experimental setup is already artificial, for in nature one will certainly not find cylinders closed at one end by a piston. But even in the context of such an artificial setup, we have to make further idealizations: we assume that the piston is perfectly sealed and that it moves without friction. During compression there is no heat transfer because it happens so *rapidly*. The gas is ideal, which is to say that its internal energy depends only on the temperature.

After so much abstraction, one cannot help asking if some essential element of the problem has been abstracted completely out of the picture, so that a comparison of the theoretical conclusion with experimental observation, that is, with the results of measurement, becomes illusory. For example, let us think of the treatment of adiabatic compression from the atomic viewpoint, in which we have assumed that the gas is compressed at an infinitely *slow* rate, and with this assumption have come to a conclusion that agrees with the macroscopic description involving rapid compression. Here we must now ask whether the two idealizations—the infinitely slow and the infinitely rapid compression—can be brought into any kind of agreement.

Although it is not terribly important for our further discussion, for the sake of completeness, we should mention that in using such expressions as "very rapidly" and "very slowly" in physics, one must always specify *in relation to what*. Clearly, in the two descriptions of compression, we are dealing with two different time constants. The first is the time constant for the transfer of heat from the gas to the environment, and the second is the time constant for the relaxation process of the gas itself. The time during which the piston is in motion should be small in relation to the first time factor, but large in relation to the second. A thorough investigation of the process shows that the two assumptions are compatible with each other to a sufficient degree.

Phenomena in nature—whether or not they are connected to human activities—generally appear in combinations. Just consider that the gas laws described above—in a more complex form and combined with the laws of motion—underlie atmospheric phenomena or the respiration process, the latter also involving chemical reactions.

For a science to become quantitative, the decisive factor, besides the practical importance of the phenomena in question, or the intellectual interest triggered by religious, mystical, or any other motives, is the possibility of abstraction. The sciences became sciences in the order of how close the situations found in nature or in practice were to the abstract situations that would make scientific treatment possible. It seems that in the history of science the most difficult step is that of abstraction, that is, the simplification of a phenomenon in a manner that does not affect its fundamental character while at the same time allows for quantitative investigation. In a similar manner, novelists as well frequently place their characters in abstract or paradoxical situations in order to emphasize the truth of what they are trying to say.

▲ **Figure 0.12** The balance and the harp as used in daily life are almost identical to the "abstract" balance and harp that can be treated mathematically. It is no coincidence that it was precisely for these instruments that the first quantitative natural laws were formulated. (*The Book of the Dead,* twenty-first dynasty, Metropolitan Museum of Art, New York; Wall painting from the tomb of Rekhmire, eighteenth dynasty.)

Quotation 0.7

It is a most remarkable demand that is often made, but never fulfilled, even by those who make it: One should present one's experience without any theoretical apparatus, and let the reader, the student, form his own conclusions. For merely looking at a subject cannot advance our understanding. Every look passes over into an observation, every observation into a meditation, every meditation into a connection, and so one may say that we theorize with every attentive glance at the world. However, to do so with consciousness, with self-knowledge, with freedom, and to make use of a daring word, much skill is needed if the abstraction that we fear is to be harmless and the result of our experience that we hope for is to come alive and be useful.

—Goethe, *On the Theory of Colors*, Preface

Conclusive knowledge rests in every individual as in a seedcase. Through the observation of things we come to wondering, from wondering to concluding, and from concluding, we come to true knowledge.

—Albertus Magnus [Liertz 1932, p. 15]

Quotation 0.8

Every age has scoffed at its predecessor, accusing it of having generalized too boldly and too naively. Descartes used to commiserate with the Ionians. Descartes in his turn makes us smile, and no doubt some day our children will laugh at us. Is there no way of getting at once to the gist of the matter, and thereby escaping the raillery which we foresee? Cannot we be content with experiment alone? No, that is impossible; that would be a complete misunderstanding of the true character of science. The man of science must work with method. Science is built up of facts, as a house is built of stones; but an accumulation of facts is no more a science than a heap of stones is a house. Most important of all, the man of science must exhibit foresight. Carlyle has written somewhere something after this fashion. "Nothing but facts are of importance. John Lackland passed by here. Here is something that is admirable. Here is a reality for which I would give all the theories in the world." Carlyle was a compatriot of Bacon, and, like him, he wished to proclaim his worship of the God of Things as they are.

But Bacon would not have said that. That is the language of the historian. The physicist would most likely have said: "John Lackland passed by here. It is all the same to me, for he will not pass this way again."

—Henri Poincaré, *Science and Hypothesis*, 1905

Quotation 0.9

[Heisenberg quoting Bohr:] "Science is the observation of phenomena and the communication of the results to others, who must check them. Only when we have agreed on what has happened objectively, or on what happens regularly, do we have a basis for understanding. And this whole process of observation and communication proceeds by means of the concepts of classical physics.... It is one of the basic presuppositions of science that we speak of measurements in a language that has basically the same structure as the one in which we speak of everyday experience. We have learned that this language is an inadequate means of communication and orientation, but it is nevertheless the presupposition of all science."

[Later, while washing the dishes after a meal taken at a hikers' hostel, Bohr continues:] "Our washing up is just like our language," Niels said. "We have dirty water and dirty dishcloths, and yet we manage to get the plates and glasses clean. In language, too, we have to work with unclear concepts and a form of logic whose scope is restricted in an unknown way, and yet we use it to bring some clarity into our understanding of nature.

—Werner Heisenberg, *Physics and Beyond: Encounters and Conversations*, 1971

Consider the balance scale. It has been used by mankind since ancient times. The gods of the underworld weighed the value of human deeds, and the kings of this world weighed gold and rare spices (Figure 0.12). The balance is therefore a practical tool, and at the same time if we look at the "abstract balance"—that is, one consisting of a rigid two-armed lever supported at a point at which the lever can move freely without friction—we see that the abstract balance and the real balance used in practice are identical to a high degree of approximation.

But now let us consider the laws of motion for objects set in motion under the power of people or draft animals. If we wish to remove all secondary phenomena, in order to make an abstract treatment possible, then we have to seek out conditions that are very different from those presented at the outset; one might say they do not even resemble the original practical problem. For example, Aristotle (384–322 BCE) derived the law of motion from the everyday observation that two horses can pull a wagon faster than one horse alone. To derive a proper—scientific—law of motion, Galileo had to work with smooth inclined planes and smooth spheres that are not found anywhere in nature, and strictly speaking, he really should have investigated the motion of the spheres in a vacuum.

A division into historical epochs better adapted to the internal structure of science than those previously suggested might begin with the points at which in a particular branch of physics a level of abstraction has been reached that makes the formulation of general laws possible.

Credit must be given to the Greeks—despite their exaggeration in this respect—for the recognition that laws cannot be formulated without abstraction and idealization. Their exaggeration consisted of viewing the abstracted concepts as well as the laws derived from them as the true nature of things; between the model and reality, they gave priority to the model. This point of view, while today outmoded in its fundamental conception, has played a decisive role in the history of science by contributing to the emergence of the fundamental characteristics of modern natural science, namely the tight coupling between physics and mathematics.

0.3 Elements of the Philosophy of Science

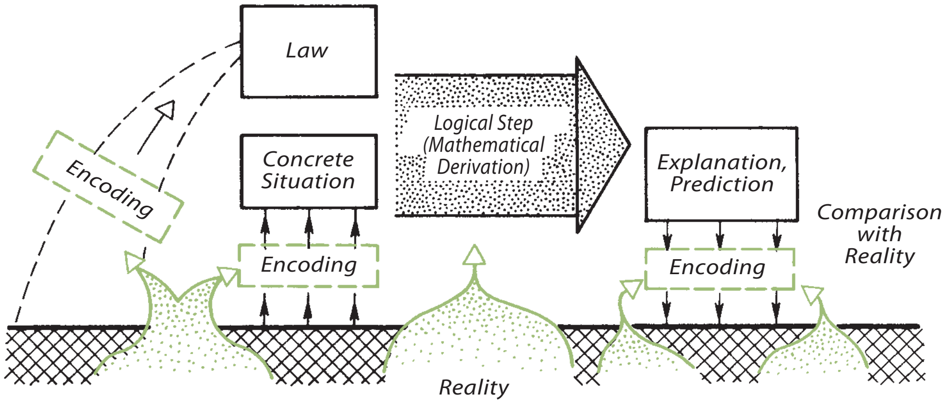
0.3.1 *Illusory Simplicity*

From reality by way of abstraction to natural law, and from law back again to reality—it is over this closed path that science walks. The correctness of a theory, and indeed the correctness of the whole methodology, is thus ensured by this twofold connection with reality.

As we shall see, this insight was long in coming, and it established itself only after significant intellectual struggle. No matter how obvious we consider this method to be today, historically it was not so at all. But even now, if we look more closely at the individual steps of the method, we come up against a jumble of questions for which we are able to supply only a more-or-less satisfactory answer.

In Figure 0.13, the simple diagram of Figure 0.9 is represented in greater detail. The problems that arise are detailed here:

1. For scientific investigation, reality is a formless raw material. Every measurement is already an intervention. By this we do not refer to the quantum-mechanical laws of the microworld, but simply note that the numerical values that our measuring instruments return are in units that are based on an also already established model that is itself based on a simplified structure. This



▲ **Figure 0.13** The path of science "from reality to reality" in greater detail.

◀ **Figure 0.14** Confrontation with reality: We use this apparatus to ask of nature directly what the magnetic moment of a particular particle is. Contact with "unadulterated reality" is possible only if a well-developed system of concepts and laws has been established. (*Brookhaven National Laboratory*, from *L'ère atomique*.)

means that reality appears to us to be already encoded into an "experimental language" even when we wish to describe a concrete situation in its "unadulterated reality" (Figure 0.14, Quotations 0.7 and 0.8). In other words, every experimental attempt already assumes a theory.

2. To interpret a phenomenon, we have assumed the existence of general physical laws. Of course, we have arrived at these laws based on perceived reality, using the inductive method. We thus extrapolate from a finite set of experiences collected in the past and from experiences to be observed in the future, the number of which is in principle infinite. What is to guarantee the validity of this extrapolation?
3. Beginning with a concrete situation and general laws, we arrive, via logical procedures—mathematics and geometry—at new hypotheses, which we wish to check against reality. But what guarantees do we have that the laws of mathematics and geometry apply to reality?
4. The results thus derived must of course again be checked against reality, which as we have already noted is just raw material to be observed and analyzed. Hypotheses derived from theory can be confronted only with hypotheses that in turn have been confirmed or refuted by yet other hypotheses.
5. In connection with all this, there arise the notions of subject and object, which are linked to the separation between the observer and the observed phenomenon. This issue does not arise because physicists have doubts about the objective existence of an external world independent of the observer, but rather because they view the experimental apparatus as an integral component of the external world. Furthermore, it also cannot be denied that the physicists themselves and their system of concepts are also a part of reality.

   Physicists believe in the objective nature of physics as a science, in that within physics, in relation to natural phenomena, assertions can be made that are "intersubjective," that is, that can be understood by anyone of sound mind possessing the requisite education. Moreover, these assertions are assumed to embody the possibility for persons of said sound mind and requisite education to experimentally check, reverify, or reproduce their contents. It is here that social practices for judging objectivity and for establishing the criteria for truth make their appearance (Quotation 0.9). The social practice is a long process: it verifies in the present the assertions of the past. The real problem arises when we want to make assertions for the future with some expectation of certainty.
6. Still another point has to be considered: In order to construct a diagram like that of Figure 0.13, we have to assume that the phenomena of reality can be subdivided into recognizable partial phenomena; that is, the identi-

The measurement method serves as the operational definition of those concepts that form the elements of the language of science, and as such, it does not methodologically belong to the theory. But, in addition, the measurement itself is also a physical process, and in this regard it *is* a part of the full theory. In this manner the very same process appears both as a premise and as a result in the theory and with this, the language of physics reaps a cyclic, self-consistent structure that is unheard of in other formal languages.

—Mittelstaedt, *Die Sprache der Physik* [*The Language of Physics*], 1972 [p. 85]

Quotation 0.10

The ancients established the axiom that all our ideas come from our senses; and this great truth is, today, no longer a subject of controversy. ...

However, all the sciences do not draw on the same experimental foundation. Pure mathematics requires less than all the others; next come the physic-mathematical sciences; then the physical sciences. ...

Certainly it would be satisfactory to be able to indicate exactly the point at which each science ceased to be experimental and became entirely rational [read: in order to develop rationally, starting from principles obtained from experiment]; that is, to be able to reduce to the smallest number the truths that it is necessary to infer from experiment and which, once established, suffice to embrace all the ramifications of the science, being combined by reason alone. But this seems to be very difficult. In the desire to penetrate more deeply by reason alone, it is tempting to give obscure definitions, vague and inaccurate demonstrations. It is less inconvenient to take more information from experiment than

continued on next page

0.4.4 *Physics in a New Role*

To a physicist, physics, with all its doubts and uncertainties and in spite of a potentially ignoble role in the future history of mankind, is nevertheless the most marvelous creation of the human imagination, a creation capable of filling an active life with meaning. Physics is by itself incapable of pointing the way to answering the great questions of human existence. Physics is ethically neutral, although the physicist is not. Yet the physicist is convinced that although no ethical categories are applicable to theories about the physical universe, aesthetic ones certainly are.

It is still the case today that the utility of the sciences takes precedence over all other arguments in their favor. Wherever one looks—on the front pages of the daily newspapers, in the proceedings of learned societies, or in long-range planning documents—everywhere one reads or hears about the implementation of scientific discoveries. Throughout the world, even scientific institutions involved exclusively in basic research justify their existence with claims that the results of their work will sooner or later find practical application. All this is as it should be, and considering the current state of the world economy, the usefulness of a scientific result is indeed of paramount importance. Nevertheless, especially in more highly developed societies, physics—and the other sciences as well—should gradually be given a new role—something similar to the role of the arts. In addition to their usefulness, we need to bring to the forefront the aesthetic qualities of the sciences and thus recognize the beauty of scientific results (Quotations 0.28 and 0.29). Saying it another way, we should extend the idea of usefulness: Science has been viewed as useful because it has contributed to mankind's material wellbeing by satisfying immediate material needs. However, beyond that, it should be recognized as being of crucial social significance in satisfying cultural and spiritual needs. The thirst for true knowledge about the world, independent of the practical utility of the knowledge, is a real social phenomenon; the joy of understanding, of learning is for many people the same as the joy and pleasure they derive from works of art. If we ask ourselves whether the study of semiconductors is of greater or lesser utility than theoretical speculation about the curvature of the universe, the answer will assuredly be in favor of semiconductors. We can offer as justification that with the use of semiconductors, cheap radio receivers can be built. And what do we need radios for? We need them, among other things, to listen to broadcasts about all those interesting theories regarding the nature of the cosmos, and in particular, about the curvature of the universe.

We do not need to further analyze the joy that one experiences from new knowledge. Nonetheless, it is undeniable that in order to derive pleasure from the beauty of science, one has to study in preparation; in effect one has to develop an "eye" for it. But the same holds for the aesthetic enjoyment of a work of art. Figure 0.19 shows the fundamental equations of general relativity, a modernist sculpture, and a poem of our era. Most physicists see in Einstein's equation derivable laws that, building on the Newtonian worldview, provide a vision of the cosmos, joining geometry and physics in an intimate bond, not only a concrete scientific and logical system, but also a work of art whose significance lies in its aesthetic value. Admittedly, it takes more effort to see the aesthetics behind the symbols than in the sculpture or poem. But the appreciation of abstract works of art also requires of the layman who is open to art a particular kind of education and preparation as well as a certain effort. It thus becomes a question of individual preference what sort of intellectual investment brings about the greatest satisfaction.

$$R_{ik} - \frac{1}{2} R g_{ik} = -\varkappa T_{ik}$$

(a)

(b)

Who, if I cried out, would hear me among the Angelic Orders?
And even if one were to suddenly
take me to its heart, I would vanish into its
stronger existence. For beauty is nothing but
the beginning of terror, that we are still able to bear,
and we revere it so, because it calmly disdains
to destroy us. Every Angel is terror.

…Early successes, Creation's favourite ones,
mountain-chains, ridges reddened by dawns
of all origin – pollen of flowering godhead,
junctions of light, corridors, stairs, thrones,
spaces of being, shields of bliss, tempests
of storm-filled, delighted feeling and, suddenly, solitary
mirrors: gathering their own out-streamed beauty
back into their faces again…

—Rainer Maria Rilke, *Duino Elegies*

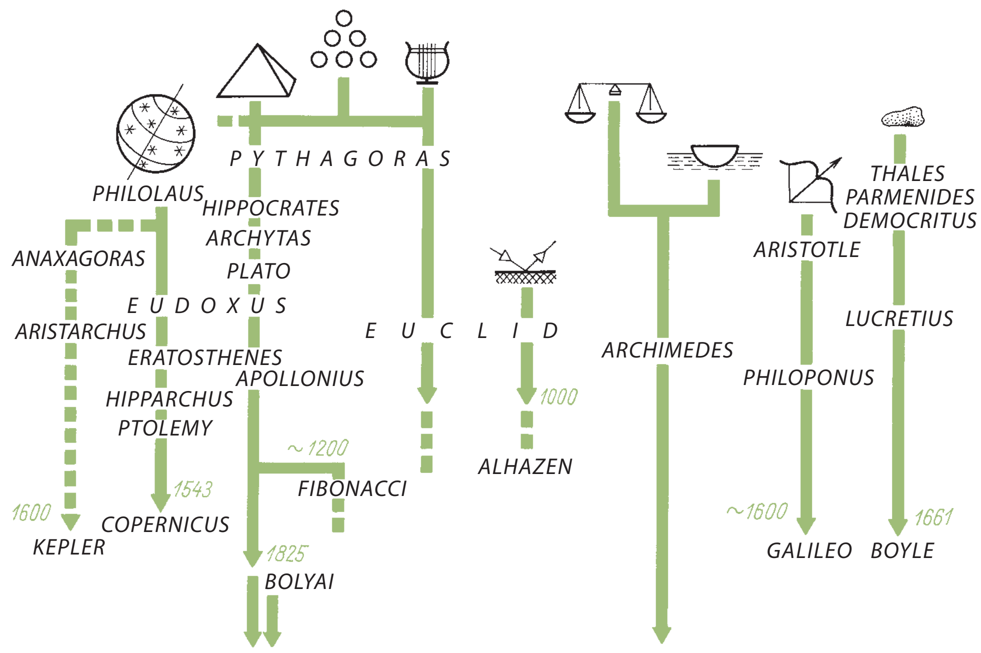
(c)

▲ **Figure 0.19** To appreciate the beauty of **(a)** the general theory of relativity, **(b)** a sculpture, or **(c)** a poem, one requires, in each case, a certain willingness to learn and a considerable investment of intellectual effort. Einstein's equation, which brings together the ideas of mass and the geometry of space, yields astounding new knowledge about our entire universe.

Einstein introduced the idea that something which is beautiful is very likely to be valuable in describing fundamental physics. This is really a more fundamental idea than any previous idea. I think we owe it to Einstein more than to anyone else that one needs to have beauty in mathematical equations which describe fundamental physical theories

—Dirac [Kragh 1980, p. 285]

Waiting for Godot, a statue by the Hungarian sculptor Miklós Borsos, inspired by the play of Samuel Beckett. *Duino Elegies* by Rainer Maria Rilke, translated by A. S. Kline



▲ **Figure 1.31** Themes in Greek natural science. The arrows indicate the length of time for which an idea was accepted as scientific truth.

geometry, the abstract model making possible a mathematical treatment is given, so to speak, by nature. In contrast, in the description of motion under terrestrial conditions and particularly in the question of the fundamental components of matter, much more abstraction is required. It is again no coincidence that the Greeks were able to give, with the Ptolemaic system, a precise and quantitative description of the motions of the heavenly bodies, for here again abstraction is easy because outside influences are insignificant. We might say that the Ptolemaic system as a *description* of the motions of the heavenly bodies can be viewed even today as correct, to be sure, with restricted validity—though at the same time the "restricted validity" qualification could be applied to all modern theories as well. The Ptolemaic system was displaced in the sixteenth and seventeenth centuries only because it offered no physical explanation of the observed phenomena and so was not suitable for the further development of dynamics.

From the viewpoint of the history of science, it is surprising with what boldness—equal at least to their courage in battle—the Greeks started with the most difficult questions at the outset: what is the fundamental nature of things, or—a bit simplified—what are the fundamental matter or matters that combine to form the diversity of the world? Regarding this question, they could give, of course, only qualitative pictures, and the qualitative picture left as a legacy by Aristotle could not be the source of continued development; only its complete abandonment could open the way to new ideas about the composition of matter. In contrast, the ancient atomic theory, even though also only qualitative, had the possibility of its transformation into a quantitative theory hidden within it.

In what follows, all the lines of development sketched here will be presented, even if we cannot go into every detail. In general, we shall content ourselves—as we did in the section on Egyptian and Babylonian science—to present the most important results. All the while, however, we should not neglect to indicate how certain ideas were formed and perfected, because only in this way can we truly discover the process by which great ideas develop.

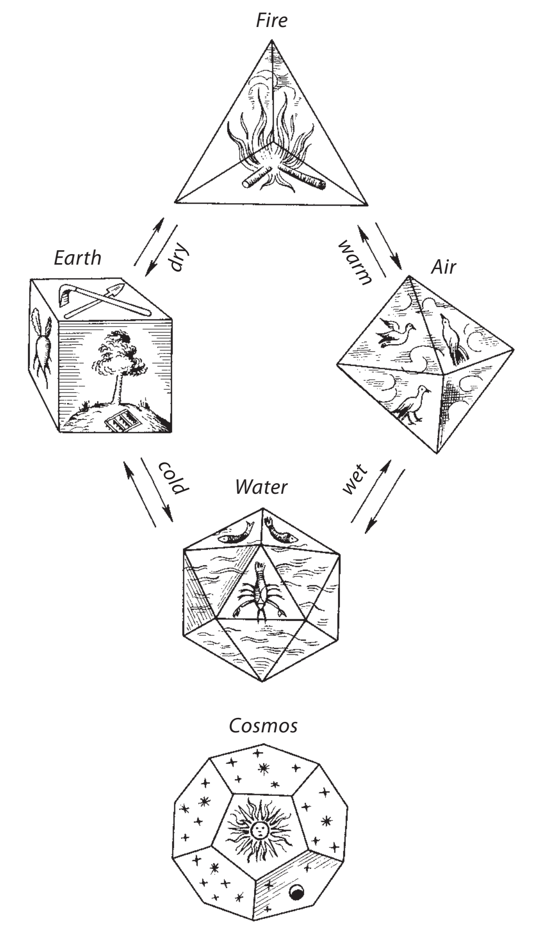
Quotation 1.9

Pythagoras is one of the most interesting and puzzling men in history. Not only are the traditions concerning him an almost inextricable mixture of truth and falsehood, but even in their barest and least disputable form they present us with a very curious psychology. He may be described, briefly, as a combination of Einstein and Mrs. Eddy. He founded a religion, of which the main tenets were the transmigration of souls and the sinfulness of eating beans. His religion was embodied in a religious order, which, here and there, acquired control of the State and established a rule of the saints. But the unregenerate hankered after beans, and sooner or later rebelled.

Some of the rules of the Pythagorean order were:
To abstain from beans.
Not to pick up what has fallen.
Not to touch a white cock.
Not to break bread ...
Not to stir the fire with iron ...
Not to walk on highways.
Not to let swallows share one's roof.
When the pot is taken off the fire, not to leave the mark of it in the ashes, but to stir them together.

—Bertrand Russell, *A History of Western Philosophy*, 1945 [pp. 31–32]

◀ **Figure 1.32** Pythagoras and music (miniature, about 1210; Bayrische Staatsbibliothek).



▲ **Figure 1.44** Association of the four Platonic solids with the four elements of Parmenides. The fifth Platonic solid represents the idea of the cosmos (after Kepler).

New groups were appended to this group of four over the course of time, with repercussions detectable to this day. Hippocrates founded, and Galen refined, the idea of "humoral pathology": Health is determined by the proper proportions (*eukrasia*) of the four humors. Sickness is caused by a disturbance in these proportions (*dyskrasia*). The four humors are blood, phlegm, yellow bile, and black bile. The differences in human temperaments can be traced to an excess of the humors: sanguine (*sanguis* = blood), choleric (*chole* = bile, anger, hate), melancholy (*melancholia* = black bile), phlegmatic (*phlegma*; fire, inflammation, phlegm causing inflammation).

We thus arrive at the following groups of four:

octahedron	air	warm–wet
tetrahedron	fire	warm–dry
hexahedron	earth	cold–dry
icosahedron	water	cold–wet

spring	blood	sanguine
summer	yellow bile	choleric
autumn	black bile	melancholic
winter	phlegm	phlegmatic

continued on next page

the Western world completely ignored the atomic theory until as late as Gassendi (1592–1655)—even though Lucretius's poem, written in Latin, did not need to be transmitted from the Islamic world—in part because of the poem's atheistic point of view, and in large measure because the Aristotelian tradition—even while assigning a certain value to it—rejected the atomic theory.

Plato approaches the problem of constancy and change from quite a different point of view. He projects *all* true knowledge, including truths relating to the structure of matter, into the realm of ideas. The four elements of Empedocles that appear to us through our senses—earth, water, air, and fire—assume abstract forms in the world of ideas that are as perfect as possible. Thus the four elements are the shadow images of their underlying ideals, that is, four regular solids, and these images are what our senses recognize. The tetrahedron is the ideal behind fire, while the hexahedron (cube) belongs to earth, the octahedron to air, and the icosahedron to water. The fifth regular solid, the dodecahedron, assumes the role of the ideal underlying the structure of the cosmos (Figure 1.44). This association of regular solids with the four elements postulated by Aristotle and Empedocles held sway for over two thousand years. Figure 1.44, for example, comes from a book by Kepler. Plato further subdivided the elements. He realized that their faces can be assembled from various right triangles: for the tetrahedron, octahedron, and icosahedron, one needs, for each face, six triangles with an angle of 30º, and for the cube, one needs four triangles with two 45º angles (Figures 1.45 and 1.46).

In the abstract world of ideas, relationships can be found among the various elements. Thus eight equilateral triangles can form an atom of air, but also two atoms of fire, which might be expressed by a formula as $A = F_2$. From the twenty equilateral triangles of an icosahedron, representing the idea of water, we could make two air atoms and one fire atom, and thereby obtain the formula $W = A_2F$. As absurd as these ideas may seem, they contain, like all of Plato's ideas, a kernel of truth, or at least one leading to truth. In this case, we may see the kernel of truth in the attempt to find an abstract model of reality that makes a description or characterization using numerical proportions possible. The path leading from here to the formula H_2O for water will be very long indeed, but one can at least say that the path began with Plato. The idea that the structural elements of matter could be imagined in terms of regular solids or in terms of the shapes of their faces is not at all absurd in contemporary particle physics. One of the most important, and indeed macroscopically detectable, properties of fundamental particles is their symmetry. Since regular solids can also be characterized by their symmetry properties, they can serve here as very practical examples. Heisenberg himself emphasized the close relationship between the fundamental ideas of his field theory and the ideas of Plato (Quotations 1.20 and 1.21).

Aristotle maintained the four elements of Empedocles. With each of the elements earth, water, air, and fire, he associated two characteristics from the pairings dry–wet and cold–warm. Thus, as can be seen in Figure 1.44, earth is dry and cold; fire, dry and warm; air, wet and warm; and water, wet and cold. According to Aristotle, the elements can be transformed into one another under certain conditions, and such a transformation is easiest between two elements that possess a common characteristic. In the figure, these simple or natural transformations are indicated by arrows.

In the real world, these four elements exist in various combinations, or mixtures (*mixtio*, μῖξις). Aristotle left much room for the opinions of later commentators regarding the properties of elements in mixtures, that is, with regard to the question of whether the elements retain their original properties in mixtures or form different substances altogether. Aristotelian chemistry assumed that matter is infinitely divisible and that every part after a division will have the same structure as the whole had prior to the division. The limits of divisibility, the *minima naturalia*, appear at the time of the Late Scholastics, but they fail to bring the Aristotelian theory any closer to an atomic theory, even to the slightest degree.

1.3.1.1 Plato and the "Elementary Particles"

First of all, everyone knows, I'm sure, that fire, earth, water and air are bodies. Now everything that has bodily form also has depth. Depth, moreover, is of necessity comprehended within surface, and any surface bounded by straight lines is composed of triangles. Every triangle, moreover, derives from two triangles, each of which has one right angle and two acute angles. Of these two triangles, one [the isosceles right-angled triangle] has at each of the other two vertices an equal part of a right angle, determined by its division by equal sides; while the other [the scalene triangle] has unequal parts of a right angle at its other two vertices, determined by the division of the right angle by unequal sides. This, then, we presume to be the originating principle of fire and of the other bodies, as we pursue our likely account in terms of Necessity. Principles yet more ultimate than these are known only to the god, and to any man he may hold dear.

We should now say which are the most excellent four bodies that can come to be. They are quite unlike each other, though some of them are capable of breaking up and turning into others and vice-versa. If our account is on the mark, we shall have the truth about how earth and fire and their proportionate intermediates [water and air] came to be. For we shall never concede to anyone that there are any visible bodies more excellent than these, each conforming to a single kind. So we must wholeheartedly proceed to fit together the four kinds of bodies of surpassing excellence, and to declare that we have come to grasp their natures well enough.

Of the two [right-angled] triangles, the isosceles has but one nature, while the scalene has infinitely many. Now we have to select the most excellent one from among the infinitely many, if we are to get a proper start. So if anyone can say that he has picked out another one that is more excellent for the construction of these bodies, his victory will be that of a friend, not an enemy. Of the many [scalene right-angled] triangles, then, we posit as the one most excellent, surpassing the others, that one from [a pair of] which the equilateral triangle is constructed as a third figure. Why this is so is too long a story to tell now. But if anyone puts this claim to the test and discovers that it isn't so, his be the prize, with our congratulations. So much, then, for the selection of the two triangles out of which the bodies of fire and the other bodies are constructed—the [right-angled] isosceles, and [right-angled] scalene whose longer side squared is always triple its shorter side squared [i.e., the half-equilateral].

At this point, we need to formulate more precisely something that was not stated clearly earlier. For then it appeared that all four kinds of bodies could turn into one another by successive stages. But the appearance is wrong. While there are indeed four kinds of bodies that come to be from the [right-angled] triangles we have selected, three of them come from triangles that have un-

Figure 1.44 *continued*

Below, we quote from the *Labyrinthus medicorum* (1538) of Paracelsus to show the first uncertain steps from humoral pathology to iatrochemistry (that is, to the idea that life processes and methods of cure have a chemical basis).

And such the physician should understand of the cause that he not indicate the qualtates and humores: but the elements as mothers and their procreationes as species, not [as] humores. Not that one should say: Cuius humoris? Melancholici: yet melancholia is nothing other than a mad, senseless phantastica illness, not a pillar of the four [elements]. Also do not say: Cuius Complexionis? Cholericae, but Calidae Sectae. Now, Cholera is not one of the four pillars, but a Morbus of all types of expulsion. Thus also: Cuius Qualitatis? Sanguineae: thus Sanguis is not one of the four pillars, but the Corpus Venarum, like the wine in a barrel. Thus also not: Cuius Naturae? Phlegmaticae: now, is not Phlegma snot from the nose, what has it to do with the stomach? But Cuius Elementi? Aquae, Terrae, Ignis, Aeris: now the answer arises: from what element does sickness arise? From fire, not Cholera: from earth, not Melancholia: from water, not Phlegmate: from air, not Sanguine. So it would appear. And do not say: that is Melancholicum, because neither heaven nor earth knows about melancholy. Do not say: that is Cholera, Phlegma, Sanguis, etc. So it is that nature knows nothing of its process and order. So as the physician becomes acquainted with the element, so will he find in the Generatis all illnesses of which mankind suffers.

We can also mention the following noteworthy parallel. H. J. Eysenck (1916–1997) finds the precursors of his model of personality in Hippocrates. Based on his statistical investigations, Eysenck maintained that individuals can be grouped in the categories stable/unstable and introvert/extrovert. Thus he arrives at the following four groups, where we have added the corresponding Hippocratic types:

stable–extrovert	→	sanguine
unstable–extrovert	→	choleric
unstable–introvert	→	melancholic
stable–introvert	→	phlegmatic

Quotation 1.21

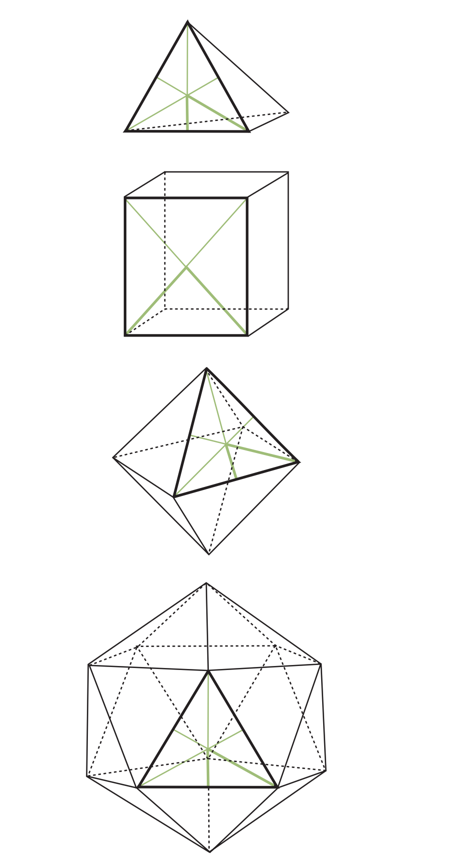
This attempt to assign geometrical figures to the simple bodies is on all counts irrational. In the first place, the whole of space will not be filled up. Among surfaces it is agreed that there are three figures which fill the place that contains them—the triangle, the square, and the hexagon: among solids only two, the pyramid and the cube. But they need more than these, since they hold that the elements are more. Secondly, the shape of all the simple bodies is observed to be determined by the place in which they are contained, particularly in the case of water and air. The shape of the element therefore cannot survive, or it would not be everywhere in contact with that which contains the whole mass. But if its shape is modified, it will no longer be

continued on next page

Quotation 1.21, ***continued***

water, since its shape was the determining factor. Clearly therefore the shapes of the elements are not defined. Indeed it seems as if nature itself here shows us the truth of a conclusion to which more abstract reasoning also points. Here, as in everything else, the underlying matter must be devoid of form and shape, for so, as is said in the *Timaeus*, the "receiver of all" will be best able to submit to modification. It is like this that we must conceive of the elements, as the matter of their compounds, and this is why they can change into each other, and lose their qualitative differences.

—Aristotle, *On the Heavens* [Guthrie, p. 319]



▲ **Figure 1.45** The four Platonic solids associated with the four elements together with the "elementary particles" that constitute them. Plato considered the possibility of imagining the regular solids, that is, the elements, as built up from two types of triangles, that is, from still simpler elements. The triangles of the first kind are isosceles right triangles, whereas those of the second type are right triangles whose hypotenuse is twice the length of the shorter leg, that is, triangles obtained by halving an equilateral triangle. The regular solids correspond in a way to our chemical elements; the triangles, to the elementary particles.

continued on next page

equal sides, whereas the fourth alone is fashioned out of isosceles triangles. Thus not all of them have the capacity of breaking up and turning into one another, with a large number of small bodies turning into a small number of large ones and vice-versa. There are three that can do this. For all three are made up of a single type of triangle, so that when once the larger bodies are broken up, the same triangles can go to make up a large number of small bodies, assuming shapes appropriate to them. And likewise, when numerous small bodies are fragmented into their triangles, these triangles may well combine to make up some single massive body belonging to another kind.

So much, then, for our account of how these bodies turn into one another. Let us next discuss the form that each of them has come to have, and the various numbers that have combined to make them up. Leading the way will be the primary form [the tetrahedron], the tiniest structure, whose elementary triangle is the one whose hypotenuse is twice the length of its shorter side. Now when a pair of such triangles are juxtaposed along the diagonal [i.e., their hypotenuses] and this is done three times, and their diagonals and short sides converge upon a single point as center, the result is a single equilateral triangle, composed of six such triangles. When four of these equilateral triangles are combined, a single solid angle is produced at the junction of these plane angles. This, it turns out, is the angle which comes right after the most obtuse of the plane angles. And once four such solid angles have been completed, we get the primary solid form, which is one that divides the entire circumference [sc. of the sphere in which it is inscribed] into equal and similar parts.

The second solid form [the octahedron] is constructed out of the same triangles which, however, are now arranged in eight equilateral triangles and produce a single solid angle out of four plane angles. And when six such solid angles have been produced, the second body has reached its completion.

Now the third body [the icosahedron] is made up of a combination of one hundred and twenty of the elementary triangles, and of twelve solid angles, each enclosed by five plane equilateral triangles. This body turns out to have twenty equilateral triangular faces. And let us take our leave of this one of the elementary triangles, the one that has begotten the above three kinds of bodies and turn to the other one, the isosceles [right-angled] triangle, which has begotten the fourth [the cube]. Arranged in sets of four whose right angles come together at the center, the isosceles triangle produced a single equilateral quadrangle [i.e., a square]. And when six of these quadrangles were combined together, they produced eight solid angles, each of which was constituted by three plane right angles. The shape of the resulting body so constructed is a cube, and it has six quadralinear equilateral faces....

Let us now assign to fire, earth, water and air the structures which have just been given their formations in our speech. To earth let us give the cube, because of the four kinds of bodies earth is the most immobile and the most pliable—which is what the solid whose faces are the most secure must of necessity turn out to be, more so than the others. Now of the [right-angled] triangles we originally postulated, the face belonging to those that have equal sides has a greater natural stability than that belonging to triangles that have unequal sides, and the surface that is composed of the two triangles, the equilateral quadrangle [the square], holds its position with greater stability than does the equilateral triangle, both in their parts and as wholes. Hence, if we assign this solid figure to earth, we are preserving our "likely account." And of the solid figures that are left, we shall next assign the least mobile of them to water, to fire the most mobile, and to air the one in between. This means that the tiniest body belongs to fire, the largest to water, and the intermediate one to air—and also that the body with the sharpest edges belongs to fire, the next sharpest to air, and the third sharpest to water. Now in all these cases the body that has the fewest faces is of necessity the most mobile, in that it, more than any other, has edges that are the sharpest and best fit for cutting in every direction. It is also the lightest, in that it is made up of the least number of identical parts. The second body ranks second in having these same properties, and the third ranks third. So let us follow our account, which is not only likely but also correct, and take the solid form of the pyramid that we saw constructed as the element or the seed of fire. And let us say that the second form in order of generation is that of air, and the third that of water.

Now we must think of all these bodies as being so small that due to their small size none of them, whatever their kind, is visible to us individually. When, however, a large number of them are clustered together, we do see them in bulk. And in particular, as to the proportions among their numbers, their motions and their other properties, we must think that when the god had brought them to complete and exact perfection (to the degree that Necessity was willing to comply obediently), he arranged them together proportionately.

Given all we have said so far about the kinds of elemental bodies, the following account [of their transformations] is the most likely: When earth encounters fire and is broken up by fire's sharpness, it will drift about—whether the breaking up occurred within fire itself, or within a mass of air or water—until its parts meet again somewhere, refit themselves together and become earth again. The reason is that the parts of earth will never pass into another form. But when water is broken up into parts by fire or even by air, it could happen that the parts recombine to form one corpuscle of fire and two of air. And the fragments of air could produce, from any single particle that is broken up, two fire corpuscles. And conversely, whenever a small amount of fire is enveloped by a large quantity of air or water or perhaps earth and is agitated inside them as they move, and in spite of its resistance is beaten and shattered to bits, then any two fire corpuscles may combine to constitute a single form of air. And when air is overpowered and broken down, then two and one half entire forms of air will be consolidated into a single, entire form of water.

Let us recapitulate and formulate our account of these transformations as follows: Whenever one of the other kinds is caught inside fire and gets cut up by the sharpness of fire's angles and edges, then if it is reconstituted as fire, it will stop getting cut. The reason is that a thing of any kind that is alike and uniform is incapable of effecting any change in, or being affected by, anything that is similar to it.

—Plato, *Timaeus* [pp. 1256–1259]

1.3.2 *Motion under Terrestrial Conditions: Peripatetic Dynamics*

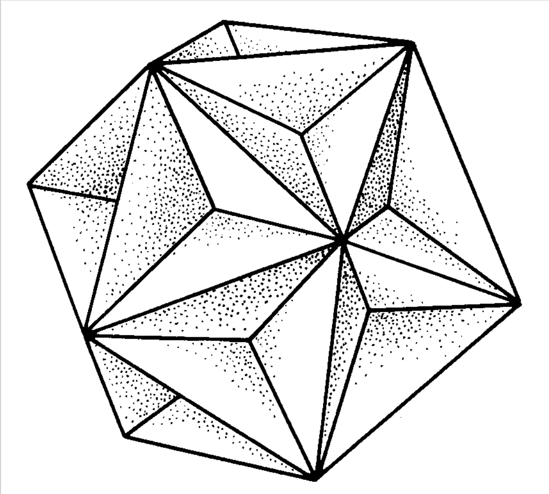
Dynamics and the theory of the structure of matter are the two branches of science in which, behind everyday manifestations, the fundamental nature of the phenomena that can be reduced to a mathematical model is most deeply hidden. The puzzles here cannot be solved on the basis of immediate experience, not even the sharpest observation and cleverest thinking. Instead, experiments have to be

Figure 1.45 *continued*

As mentioned earlier, the Pythagoreans knew that there were *at least* five regular solids; the proof that there are *exactly* five is due to Plato's friend Theaetetus, who appears as an interlocutor in the *Dialogues*. In his *Elements*, Euclid gives a proof that relies on a previously proved theorem, that the sum of the dihedral angles at the vertex of a solid must be less than 360°. If we now wish to obtain a regular solid whose faces are equilateral triangles, we may have three, four, or at most five such triangles at each vertex. Thus arise the tetrahedron, octahedron, and icosahedron. With squares as faces, there must be three—neither more nor less—and we obtain the cube. Finally, we may have three regular pentagons at a vertex, giving us the dodecahedron.

Today, one may obtain the proof from a 1758 theorem of Euler: The numbers v of vertices, e of edges, and f of faces in a convex solid are related by the formula

$$v - e + f = 2.$$



▲ **Figure 1.46** Euclid mentions only convex regular solids. In 1809, Poinsot constructed four regular nonconvex solids. Then in 1811, Cauchy proved that there are exactly four such solids. The figure shows one of these (from the *Great Soviet Encyclopedia*).

Archimedes considered semiregular solids, that is, solids composed of regular polygons, but not all identical. Plate XII shows one of these *Archimedean solids*, the rhombicuboctahedron, composed of eight triangles and eighteen squares (on the left in Pacioli's painting).

In our time, the Archimedean solid composed of twelve regular pentagons and twenty regular hexagons—the truncated icosahedron—has acquired a particular significance (see also Figure 2.66). Sixty carbon atoms arranged at the vertices of this solid yield a stable carbon molecule, called buckminsterfullerene or (C_{60}-I_h)[5,6]fullerene. It is named for the architect Buckminster Fuller. Its discoverers were awarded the 1996 Nobel Prize in chemistry.

Buckminsterfullerene is also called the "soccer-ball molecule," since the stitching pattern on many of the world's soccer balls is that of this Archimedean solid.

Quotation 1.22

The Pythagoreans ... did not accept, in things divine and eternal, such disorder as [the heavenly bodies] moving sometimes more quickly, sometimes more slowly, and sometimes standing still. ... One would not accept such anomaly of movement in the goings of an orderly and well-mannered man. The business of life is often the cause of slowness or of swiftness for men. But in the case of the incorruptible nature of the stars, it is not possible to adduce any cause of swiftness or slowness. For this reason, they put forward the question: how would the phenomena be accounted for by means of uniform and circular motions?

—Geminos of Rhodes, *Introduction to the Phenomena* [pp. 117–118]

Quotation 1.23

It is instructive to see how the ideas in Quotation 1.22 are later echoed in the writings of the great Jewish philosopher Maimonides (1135–1204):

That the sphere is endowed with a soul is clear upon reflection. However, he who hears this may deem this a matter that is difficult to grasp or may regard it as impossible because of his imagining that when we say, "endowed with a soul," the soul referred to is like the soul of a man, or an ass and a bull. Now this is not the meaning of the dictum. This meaning is rather that the local motion of the sphere is a proof of there indubitably being in it a principle in virtue of which it is moved. And this principle is undoubtedly and incontestably a soul. This may be explained as follows. It is absurd that the circular motion of the sphere should be similar to the rectilinear motion of the stone downwards or to the motion of the fire upwards, so that the principle of that motion would be a nature and not a soul. For what is moved in natural motion is only moved by the principle subsisting in it, when the object to be moved is not in its place, and it is moved in order that it may seek to come to its place. However, when the object in question reaches its place, it comes to rest. The sphere, on the other hand, is moved in its own place in a circular motion. ... In consequence this circular motion can only come about in virtue of a certain mental representation, which determines the sphere's moving in that particular way. Now there is no mental representation without intellect. In consequence the sphere must be endowed with an intellect. ... [T]he soul, in virtue of which there is the

continued on next page

set up in ways that differ greatly from what is found directly in nature, and new concepts have to be created with a bold departure from immediate experience. It is therefore understandable that in ancient Greece, little progress was made in these fields. Even Aristotle—despite his skills as a very acute observer to whom biology owes some observations that remain valid to this day—made no attempt to carry out any experiments to clarify the fundamental laws of motion. Furthermore, he lacked the soaring imagination of his teacher Plato, as well as Plato's abstract mathematical point of view. Aristotle's dynamics is therefore only a summation of everyday observations that can be viewed as science only because Aristotle with his outstanding capacity for systematization was able to fit his dynamics into an all-encompassing worldview. However, it was precisely the effect of the universality of the Aristotelian worldview that compelled posterity to accept even the erroneous details. We shall return to this issue later.

Aristotelian dynamics, which for over two thousand years was the final word in this area, could be superseded only by casting off the *entire* Aristotelian worldview. In general, one may say that the Peripatetic theory of motion, while on the surface it correctly described the relevant phenomena and systematically organized them, it nevertheless lacked depth, and in the end hindered rather than advanced the development of dynamics as a science.

Here, we would like to demonstrate that Aristotle was led to the establishment of his fundamental laws of dynamics and to his classifications of motion by perfectly clear-headed considerations, so that some of his rules remain valid today as limited cases. Conversely, we would like to identify the decisive step that Aristotle was not able to take, nor were many generations of physicists after him able to do so (Plate III).

Let us imagine that we have forgotten everything we learned in school about Newton's laws of motion and seek to discover, from our everyday observations, without the help of experiment, some system that will account for the various forms of motion and at the same time establish a connection between some characteristic of motion, such as velocity, for example, and its effective cause. We think about these matters as we stroll along the shore of a lake, where we observe the various motions caused by man and by nature. In the shallow water, many small fish are swimming, gulls fly about in the air, and other people out for a walk stroll past us. All of these motions have something in common: the cause of independent motion is to be found in the fact that these are living beings.

As we play with a handful of pebbles, we drop one accidentally. Of course, it falls to the ground. From the stack of a passing ship, a stream of smoke is belching skyward, which also strikes us as natural. A child is pulling a small wagon on a string, while a toy car races in front of another child without any visible connection between car and child. We do not consider these two motions to be naturally caused; in each case we look for a cause of the motion, for the impetus. Evidently, in both cases the motion is caused by some action, in one case by the child, that is a living being, and in the other, by some mechanism inside the toy.

It is evening; the Sun is slowly sinking below the horizon, and the stars are becoming visible. The promenade along the shore is becoming empty, but we still hear the wind blowing and see the play of the waves. Compared to movement on Earth, we see something strikingly different in the sky: movements there with their measured stateliness and everlasting regularity are in sharp contrast with our experiences on Earth. It is clear, or in any case it is our immediate impression, that the laws of motion in the heavens and those on Earth *must be different*.

We have thus arrived at the Aristotelian classification of motions:

1. Eternal motions: motions of the celestial spheres (*motus a se*).
2. Terrestrial motions:
   a. Motions of living organisms (*motus a se*).
   b. Natural motions or restoration of a disturbed order: heavy bodies fall downward; light bodies move upward (*motus secundum naturam* or *motus naturalis*).
   c. Violent motion due to a force forcing (*motus violentus*).

The celestial bodies move of their own accord, so they must have a soul, and they move—in contrast to human beings in their daily lives—in perfect circles, so they must therefore be of a godly nature of a higher order than that of mankind. The perfect circular motion, or motion composed of several perfect circles, is fitting only to such beings (Quotations 1.22 and 1.23).

For the motion of terrestrial living beings, we cannot give such laws

Here we have arrived at the first characteristic assertion of Peripatetic dynamics: Fundamentally different laws hold for the celestial and terrestrial (sublunar) spheres. As we shall see, the distinction between these two domains will be important in all respects.

The second characteristic of Peripatetic dynamics follows from the first: Since a definite order exists in the cosmos, heavy bodies have their place below, light bodies above, and heavenly bodies must be in the firmament. Thus, the nature of a body determines the types of motion that it is able to undergo.

In our everyday lives, when something moves we ask: why does it move? This is also the question posed by Aristotelian dynamics, and the third thesis provides an answer: Every motion is due to an effective cause, or as we would say today, is due to a force (*omne quod movetur ab alio movetur*). Therefore, motion is a process and not a state, which means that when the cause ceases, the motion ceases, too.

Peripatetic dynamics also assumes that the effective cause or force can be applied only through immediate contact; that is, for every motion, we need to look for some connected driving force (*motor conjunctus*). In Aristotelian dynamics, the motive cause or force is related to the velocity of the body. Of course, both velocity and force are to be considered here only qualitatively. The proportionality between the two was built into the theory only by later Aristotelian commentators (Quotation 1.24). From our point of view, it follows immediately that a body in motion must overcome resistance and that the velocity is inversely proportional to the force of resistance. We are going well beyond the ideas of both Aristotle and his commentators in the following when we use today's customary notations and concepts in stating the fundamental law of Peripatetic dynamics.

The velocity of a body is determined by the motive force and the resistance. Velocity and motive force are closely linked, since a large velocity is associated with a large force, and a small velocity with a small force. In today's notation, we may write

$$\text{velocity} \approx \frac{\text{effective cause}}{\text{resistance}} \Rightarrow v \approx \frac{F}{R}.$$

We stress once again that, although this law states the fundamental law of dynamics falsely, it nevertheless corresponds to everyday observations. It expresses the simple fact that, for example, a chariot travels more rapidly if there are more horses pulling it, or that a block of stone of a certain weight can be pulled faster by a larger number of slaves than by a smaller number.

Quotation 1.23, ***continued***

motion, and the intellect, by which the object is represented to oneself, are not both of them together sufficient to account for the coming-about of such a motion until desire for the notion represented is conjoined with them. Furthermore, it follows necessarily from this that the sphere has a desire for that which it represents to itself and which is the beloved object: namely, the deity, may He be exalted. Aristotle says that it is in this manner that the deity causes the sphere to move, I mean to say through the fact that the sphere desires to come to be like that which it apprehends, which is the notion represented—a notion that is most exceedingly simple, in which there is no change and no coming-about of a new state, and from which good always overflows. This is impossible for the sphere qua a body unless its activity be a circular motion and nothing else. For this is the final perfection of what is possible for a body to have as its perpetual activity. ...

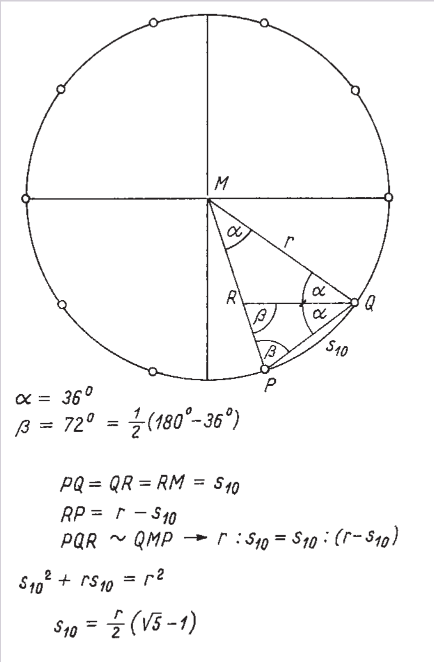
As for the assertion that the spheres are living and rational, I mean to say endowed with apprehension, it is true and certain also from the point of view of the Law; they are not dead bodies similar to fire and earth—as is thought by the ignorant—but they are—as the philosophers say—living beings who obey their Lord and praise Him and extol Him greatly. Thus Scripture says: *The heavens tell of the glory of God,* and so on.

—Maimonides, *The Guide of the Perplexed*, Chapters 4 and 5 [pp. 255, 256, 259]

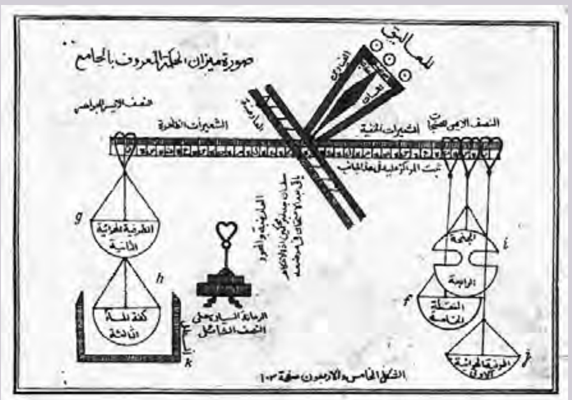
Quotation 1.24

We observe that the same weight or body travels faster for two *reasons*, either because there is a difference in the medium through which it travels, as through water or earth or air, or because, other things being the same, the traveling body has an excess of density [or weight] or of lightness. The medium through which the body travels is a cause by the fact that it obstructs the body, most of all if it [the medium] is travelling in the opposite direction, but even if it is *resting*; and it does so more if it is not easily divisible, and such is a more viscous medium.

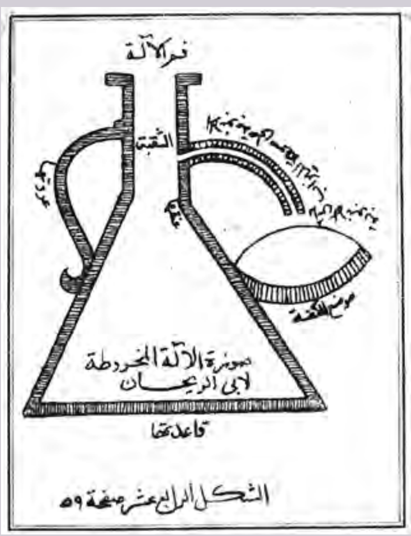
continued on next page



◀ **Figure 2.35** The relationships in a regular decagon.



▲ **Figure 2.36** Illustration of a balance from AL-KHAZINI's *Book of the Balance of Wisdom*, 1121.



◀ **Figure 2.37** The apparatus of AL-BĪRŪNĪ for measuring specific gravity in AL-KHAZINI's book [Dorfman 1974].

The Arabs who had the greatest influence on the Western world in the Middle Ages were AVICENNA (IBN SINA, ca. 980–1037) and AVERROES (IBN-RUSHD, 1126–1198). AVICENNA remained the preeminent authority in medicine for centuries. His philosophy was Aristotelian with a touch of Platonism. His philosophical poems speak to our time as much as those of the poet and scholar OMAR KHAYYÁM, who was two generations younger (Quotation 2.9). AVERROES was referred to in the Middle Ages as "The Commentator." He is even mentioned as such in DANTE's *Divine Comedy*. For him, ARISTOTLE was the philosopher par excellence (Quotation 2.10). We have already spoken of his unique interpretations of ARISTOTLE, which moved THOMAS AQUINAS to take the field against the antireligious views of AVERROES' supporters. Namely, AVERROES had interpreted the Aristotelian natural laws in such a way that the world is predetermined in every detail and was not created; thus, any role for God or Providence in the creation of the cosmos was ruled out.

2.3.3 *Some Outstanding Contributions of Arab Science*

Arab mathematics and physics reached their developmental peak in the fifteenth century. At that time, Europe was surpassed in both disciplines in a number of details. Here we summarize some of the principal achievements of Arab science.

In 1459, the Persian mathematician JAMSHID AL-KASHI calculated the number π accurately to 17 decimal places.

The binomial theorem was known (for positive numbers n) in the form

$$(a+b)^n - a^n = C_{n,1}a^{n-1}b + C_{n,2}a^{n-2}b^2 + \cdots + C_{n,n-1}ab^{n-1} + b^n.$$

The following relationship was known for the binomial coefficients appearing in the above equation:

$$C_{n,m} = C_{n-1,m} + C_{n-1,m-1}.$$

This relationship was used later in Europe to construct Pascal's triangle.

Formulas for the summation of series of natural numbers with various exponents were determined, that is, sums of the form

$$\sum_{a=1}^{n} a^k, \quad k = 1,2,3,4,\ldots.$$

Thus, for example, the sum of the fourth powers of the first n natural numbers was calculated by the formula

$$\sum_{a=1}^{n} a^4 = 1 + 2^4 + 3^4 + \cdots + n^4 = \sum_{a=1}^{n} a^2 \left[\sum_{a=1}^{n} a + \frac{\left(\sum_{a=1}^{n} a\right) - 1}{5} \right].$$

The mathematician AL-KASHI, mentioned above, created a table of sines with a step size of 1′ and a precision of nine decimal places. To create the table, he first calculated the value sin 3º from sin 72º and sin 60º by using the relations

$$\sin(72^\circ - 60^\circ) = \sin 12^\circ = \sin 72^\circ \cdot \cos 60^\circ - \cos 72^\circ \cdot \sin 60^\circ$$

and

$$\sin 3^\circ = \sin(15^\circ - 12^\circ).$$

To determine sin 1°, he used the identity

$$\cos\phi = 4\cos^3\frac{\phi}{3} - 3\cos\frac{\phi}{3}$$

to derive the third-degree equation

$$x^3 + 0.7850393433644006 = 45x,$$

which he solved to an accuracy of 17 places.

With this method, he was able to produce tables with accuracy up to the ninth decimal place. He solved the third-degree equation with a remarkable iteration procedure.

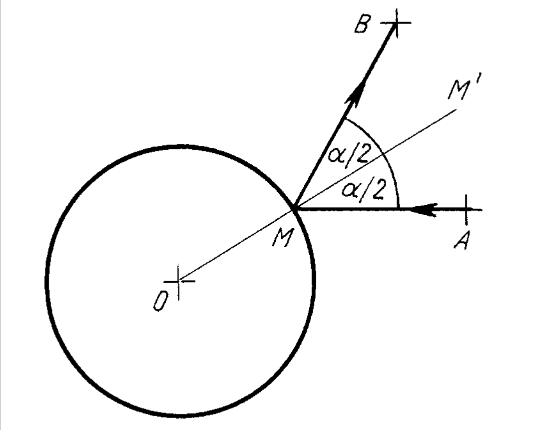
To determine sin 72°, he used the fact that the length of a side of a regular decagon (in which all the central angles equal 36° and all angles between two edges measure $2 \times 72° = 144°$) inscribed in a circle of radius r is equal to

$$\frac{r}{2}\left(\sqrt{5}-1\right)$$

(Figure 2.35).

In physics, the Arabs surpassed the contributions of the Greeks in the field of optics and in the working out of methods for measuring specific gravity (Figure 2.36 and 2.37). In geometry, ALHAZEN (IBN AL HAYTHAM, 965–ca. 1039) was considered to be the greatest authority in Europe for several centuries. He called PTOLEMY's law of refraction into question based on his observations that when light is refracted, the angles of incidence and refraction are not proportional. However, he was unable to derive the correct law. He is the source of theories of parabolic and spherical mirrors, the principle of the camera obscura, and a description of how the eye functions. Moreover, the solution of the problem depicted in Figure 2.38, which at first glance appears to be a geometric one, is generally seen as ALHAZEN's greatest achievement. The task is this: Given two arbitrary points A and B in a plane external to a given circle, to find the point M on the circle's circumference such that the line OMM' bisects the angle α formed by the lines MB and MA. This is in fact closely related to the problem in optics of finding the point on a spherical mirror at which a light ray emanating from a given point A must be reflected in order to arrive at a given point B. ALHAZEN reduced the problem to a fourth-degree polynomial equation, which he was able to solve.

The Arabs translated PTOLEMY'S astronomical works as a matter of course, considering it the *ne plus ultra*, making no effort, at least not with respect to theory, to build upon his results. However, for the astrological work that was so important to them, they required precise astronomical data. Therefore, in the first half of the fifteenth century, they had an observatory built by the Timurid ruler ULUGH BEG. Here AL-KASHI was involved as well. He prepared the aforementioned tables of sines for ULUGH BEG. The largest apparatus belonging to the observatory is an object of wonder to this day: a giant sextant made of marble with a radius of 40 meters covering an arc of 60° (Figure 2.39).



▲ **Figure 2.38** On the problem of ALHAZEN. A ray of light emitted from point A should, after reflection in a spherical mirror, arrive at point B. According to the law of reflection, the angles AMM' and $M'MB$ should be equal. (LEONARDO also had a solution to this problem.)

Quotation 2.10

Nature created him [ARISTOTLE] to place before our eyes an example of human perfection. Providence has given him to us so that we might know what can be known. His teaching is the highest truth; his reason, the highest form of human powers of comprehension that can exist.

—AVERROES

(a)

(b)

◀ **Figure 2.39**
(a) The sextant of the observatory built by ULUGH BEG in Samarkand.
(b) ULUGH BEG (portrait from the 1690 book *Prodromus Astronomiae* by HEVELIUS).

However, Aquinas enunciates a condition for the use of knowledge that not only was valid for the Middle Ages, but remains valid to this day: The benefits of knowledge do not depend on what it pertains to, but rather on how it is put to use, as was propounded also by Aquinas's teacher Albertus Magnus.

The other possibility for organically fitting actual philosophical problems into a worldview determined by faith, is connected to questions of epistemology. In investigating the relationship between faith and knowledge, the questions naturally arise as to when the truths of faith are already directly given by revelation, to what extent can man gain knowledge, and how reliable is such knowledge if it is not buttressed by the revealed truths. Discussion of these questions had a long tradition among the Scholastics, going back at least to Saint Augustine, probably the most important of the Church Fathers, who posed the questions of what truth is and how it can be acquired. His ideas, as we saw earlier in Section 1.5.1, are quite modern. Beginning with doubt, he stated that all knowledge, direct or indirect, that comes from our sensory organs is uncertain. Everything is subject to doubt, and one is never free of the possibility of error. From doubt, he arrived at one of his fundamental truths (Quotation 2.22), which may be summarized in the phrase *si enim fallor sum* (I err, therefore I am), which is quite similar to the basic truth formulated by Descartes a millennium later: *cogito ergo sum* (I think, therefore I am). Augustine arrives at certainty through divine inspiration (*illuminatio Dei*). Thus we find another parallel to Descartes in the Augustinian assumption that man is born with the idea of a perfect God.

Aquinas did not adopt Augustine's point of view. In his opinion, knowledge begins with sensory perception, but it goes beyond this. In a nice parable, Aquinas compares Augustine's *illuminatio*, which alone leads to truth, with the Sun, which illuminates everything: The Sun's light is necessary for knowledge, but we must look not only at the Sun, but at the illuminated objects as well.

2.5.2 *Faith and Experience*

The daily contact the monastic orders had with secular life coupled with the reconciliation of faith and science made it possible that empirical observation could slowly work its way into the canon of favored methods for gaining knowledge. It is no coincidence that Albertus Magnus (ca. 1200–1280, Figures 2.54 and 2.55), the *doctor universalis* and teacher of Aquinas, knew nature so well because the rules of the Dominican order permitted its members to travel only on foot. When Albertus Magnus became his order's provincial superior for Germany, he visited all of the Dominican monasteries, walking all the way. This close relationship with nature is palpable in his philosophical works . In Albertus's writings, one frequently encounters the sentence *Fui et vidi experiri* (I was there and saw that it happened in this way). He professes (Quotations 2.23 and 2.24) that mankind's task is to discover what transpires in the natural world as a result of immanent causes. He therefore rejects all conclusions that contradict the evidence of the senses. He defends science against the theologians who are not scientifically minded: Theologians who belittle science are like mindless dogs that bark at the unfamiliar.

The importance of experiment and experience was emphasized by the Oxford School, above all by Grosseteste (ca. 1175–1253) and his student Roger Bacon (Figures 2.56 and 2.57). These two men laid the foundations for the English empirical tradition, which maintained its influence well into the twentieth century. Grosseteste studied the development of general concepts. He maintained that we

▲ **Figure 2.55** Albertus Magnus: *Philosophia naturalis.* (Incunabula, 1487, Székesfehérvár Diocesan Library.)

Quotation 2.21

It is one thing to inquire which is the true history of creation, another to ask what Moses, who was so good a servant to the family of your faithful, meant those who read or heard his words to understand by them.

As for the first sort of disagreement, I wish to have no dealing with any who think things which in reality are false; and as for the second, I wish to have none with any who think that Moses wrote what was not true.

—Augustine, *Confessions* XII.23 [p. 300]

Quotation 2.22

If I am mistaken, I exist. He who does not exist clearly cannot be mistaken; and so, if I am mistaken, then, by the same token, I exist. And since, if I am mistaken, it is certain that I exist, how can I be mistaken in supposing that I exist? Since, therefore, I would have to exist even if I were mistaken, it is beyond doubt that I am not mistaken in knowing that I exist. And, consequently, neither am I mistaken in knowing that I know.

—Augustine, *The City of God against the Pagans* are able to arrive at general statements with the help of our sensory organs when we repeatedly perceive the same connection between two phenomena (Quotation 2.25). He instructs how to avoid all irrelevant factors when investigating a particular phenomenon. This is reminiscent of the ideas of Francis Bacon in the seventeenth century. Grosseteste's greatest disciple, Roger Bacon, honored by his contemporaries with the title *doctor mirabilis*, gave the resolute rallying cry that philosophy has no other task than to expound nature and the properties of objects (*tota philosophiae intentio non est nisi verum naturas et proprietates evolvere*). To the two long-acknowledged sources of knowledge, authority and reason, he added a third, namely, experience (*per auctoritatem et rationem et experientiam*). Bacon went even further. All knowledge outside of experience, that is, knowledge based solely on authority and reason, must ultimately be rooted in experience: Everything is to be proved on the basis of experience (*Oportet ergo omnia certificari per viam experientiae*).

With respect to this quotation, one should point out a danger that always arises when one attempts to interpret a quotation of any length removed from its original context. It can be said that for a proper interpretation, one has to consider not only the complete work, but also the intellectual background of the period as well as the other works of the author in question. Naturally, this danger exists for all the quotations in this book. But, let us see in this concrete example how Bacon continues his thoughts after the seemingly very modern statement just cited. Bacon distinguishes two forms of experience: external experience transmitted through the sensory organs, and internal experience, namely, divine inspiration (*divina inspiratio*). The latter is applicable not only to spiritual matters, but also with respect to material bodies and the philosophical sciences (*divinae inspirationes non solum in spiritualibus sed et in corporalibus et scientiis philosophiae*). Bacon distinguishes seven levels of internal experience or divine inspiration, of which the highest is rapture (*raptus*), which corresponds to religious ecstasy. So according to Bacon, science obtained in a state of rapture also qualifies as knowledge rooted in experience.

It was not only in England that empiricism began to develop. Here a book by the Frenchman Peter of Maricourt (Peter Peregrinus) on the properties of magnets (*Epistola de Magnete*, 1269) needs special mention, not for its actual content, which will be discussed in Section 4.4.1, but above all because of the methods that are described therein. Peter refers not only to experiments, but explicitly points out that an experimenter in the natural sciences must acquire the appropriate practical skills; for the first time, we see here stated the necessity of technical ability for scientists.

An extreme offshoot of philosophical empiricism is represented by Nicholas of Autrecourt (ca. 1299–ca. 1369). His critical analysis of knowledge obtained through the senses—reminiscent of David Hume—concludes that a supposedly recognized connection between cause and effect does not give us any guarantees that under the given conditions, the effect will necessarily occur in the future (Quotation 2.26).

Grosseteste already offers a method that should lead to the correct fundamental principles in scientific investigations: the principle of uniformity of nature, whereby objects of the same composition will behave the same way under identical circumstances; and the principle of economy, whereby all things being equal, one should prefer a proof that requires fewer questions to be answered or requires fewer assumptions and axioms to arrive at the derivation.

Here we should mention the principle of Ockham's razor. William of Ockham (also Occam, ca. 1288–ca. 1348), a restless soul, excommunicated Franciscan

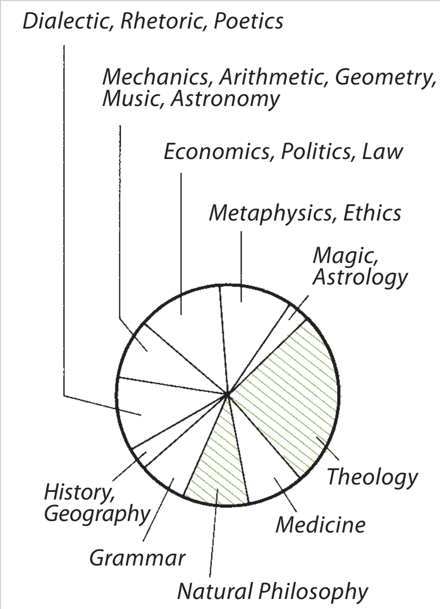
◀ **Figure 2.56** Roger Bacon (ca. 1214–1294). Studied in Paris, where he later held his first lectures on Aristotle. After 1247, he studied a wide variety of subjects at Oxford and built himself a laboratory. In 1257, he entered the Franciscan order. Between 1266 and 1268 he wrote *Opus majus*, *Opus minus*, and *Opus tertium*. From 1277, he was imprisoned by his order on charges of heresy. In general, Bacon's modernity is exaggerated. But in any case, it is correct that he recognized the importance of experimentation. He valued highly the work of Pierre de Maricourt, calling him *dominus experimentorum*. Bacon himself experimented with lenses and mirrors. Above all, he was interested in alchemy. He was the first European to provide a precise recipe for the manufacture of gunpowder (1242). He seriously investigated the problem of flight, making use of a balloon made of thin copper foil with movable wings. He built a camera obscura and actually used it for observations of a solar eclipse. Bacon appreciated the importance of mathematics for the sciences, encouraged the study of languages, and even sketched the outlines of a utopian society.

Having laid down fundamental principles of the wisdom of the Latins so far as they are found in language, mathematics and optics, I now wish to unfold the principles of experimental science, since without experience nothing can be sufficiently known. For there are two modes of acquiring knowledge, namely, by reasoning and experience. Reasoning draws a conclusion and makes us grant the conclusion, but does not make the conclusion certain, not does it remove doubt so that the mind may rest on the intuition of truth, unless the mind discovers it be the path of experience; since many have the arguments relating to what can be known, but because the lack experience they neglect the arguments, and neither avoid what is harmful nor follow what is good. For if a man who has never seen a fire should prove by adequate reasoning that fire burns and injures things and destroys them, his mind would not be satisfied thereby, nor would he avoid fire, until he placed his hand or some combustible substance in the fire, so that he might prove by actual experience that which reasoning taught. But when he has actual experience of combustion his mind is made certain and rests in the full light of truth. Therefore, reasoning does not suffice, but experience does.

—Roger Bacon [Newman 1956, p. 1758]

A fifth part of experimental science concerns the fabrication of instruments of wonderfully excellent usefulness, such as machines for flying, or for moving in vehicles without animals and yet with incomparable speed, or of navigating without oarsmen more swiftly than would be thought possible through the hands of men. For these things have been done in our day, lest anyone should ridicule them or be astonished. And this part teaches how to make instruments by which incredible weights can be raised or lowered without difficulty or labor. … Flying machines can be made, and a man sitting

continued on next page



▲ **Figure 3.3** The distribution of scientific books published before 1545 according to Conrad Gesner.

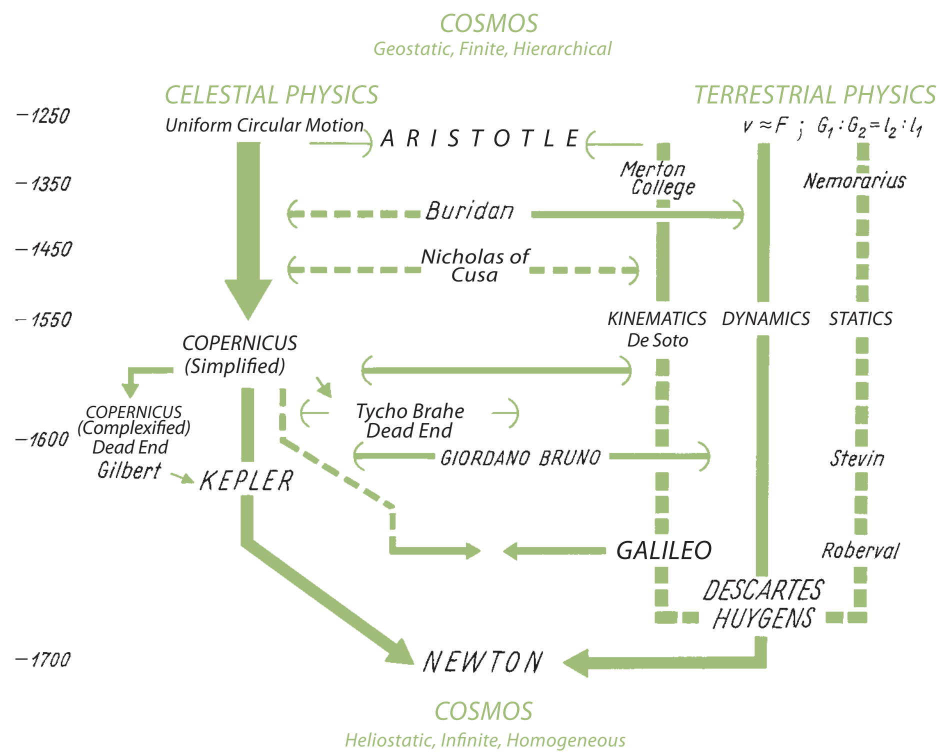
Quotation 3.3

I speak thus to my listeners: Look, this is taught by Aristotle, that is the opinion of Plato; so speaks Galen, and thus Hippocrates. Who listens to me must concede: The works of Borrius command complete trust, for not one of them is his own; rather, the most illustrious minds speak through his mouth ... If thoughts come to me that I don't find in their works, I discard them at once as suspicious or put them aside until they become old and die out before they have seen the light of day.

—Girolamo Borrio, Pisa, 1676, in Lalande, *Lectures sur la philosophie des sciences*

that of books on theological subjects. At first glance, natural philosophy appears to be adequately represented, since it comprises about one-third of the total number of theological texts. However, when we take a closer look at what books fall into this category, the proportion no longer seems so favorable, since books on plants, animals, the soul, as well as curiosities of nature are included here. Indeed, books on natural curiosities enjoyed great popularity even in the seventeenth and eighteenth centuries because they apparently satisfied a universal human craving for sensation.

What, then, were the tasks standing before the natural sciences at the beginning of the seventeenth century? A very general answer to this question may easily be given: to upend the Aristotelian worldview and replace it with a new one. We see in Figure 3.4 what natural scientists would have to accomplish, whether they knew it or not: They needed to replace the cosmology of antiquity and the Middle Ages, which was geocentric, finite, and hierarchical, with a model of a heliostatic (that is, with the Sun at rest), infinite, and homogeneous cosmos governed by a universal set of laws. To accomplish this goal, the main task would then to be to unify the physics of the heavens with the physics of the Earth. Figure 3.4 gives the names of the most important figures who were involved in this unification. A complete synthesis was eventually achieved with Newton's laws of motion and his law of universal gravitation. After Newton, the physics of the heavens again diverged from terrestrial physics, no longer from philosophical necessity, but as a step in the practical specialization of the sciences.



▶ **Figure 3.4** The stages along the path to the unification of celestial and terrestrial physics.

New ideas were born in books and libraries (Table 3.1), and the modern world began to take shape. However, we should not forget that this process took place against the background of a declining guild structure and the rise of manufacturing with continually increasing productivity, accompanied, however, by a commoditization of manual labor. In short, the pros and cons of capitalism were already becoming apparent. The concomitant technical problems needing to be solved represented an enormous challenge for physics (Figure 3.5).

We must not overlook the fact that ideological arguments were in no way limited to verbal exchanges, particularly in cases where economic and ideological issues were

Quotation 3.4

And albeit, it may be said by the learned in the Mathematicalles, as hath beene already written by some, that this is no question or matter for a Mechanitian or Mariner to meddle with, no more than is the finding of the Longitude, for that it must bee handled exquisitely by Geometrical

continued on next page

▼ **Table 3.1** Significant ideas in significant books of the time.

1543	Copernicus	*De revolutionibus orbium coelestium*
1585	Giordano Bruno	*Del infinito, universe e mondi*
1585	Stevin	*Weeghconst*
1600	Gilbert	*De magnete*
1609	Kepler	*Astronomia nove aitiologethos seu Physica coelestis*
1610	Galileo	*Sidereus Nuncius*
1619	Kepler	*Harmonices mundi …*
1620	Bacon	*Novum Organum*
1623	Galileo	*Saggiatore*
1632	Galileo	*Dialogo sopra I due massimi sistemi del mondo*
1638	Galileo	*Siscorsi e dimonstrazioni matematiche intorno a due nuove scienze*
1637	Descartes	*Discours de la method*
1644	Descartes	*Principia philosophiae*
1647	Pascal	*Expériences Nouvelles touchant le Vide*
1660	Boyle	*Touching the Spring and Weight of Air*
1672	Guericke	*Experimenta nova Magdeburgica*
1673	Huygens	*Horologium oscillatorium*
1687	Newton	*Philosophiae naturalis principia mathematica*
1690	Huygens	*Traité de la lumière*
1690	Locke	*An essay concerning human understanding*

closely connected. Among the events that finally led to the vision of a homogeneous universe—or, more concretely, to the replacement of the relation $\mathbf{F} \propto \mathbf{v}$ by $\mathbf{F} \propto \Delta\mathbf{v}$—belong also the burning of heretics at the stake and the horrors of the religious wars (Figure 3.6).

Quotation 3.4, ***continued***

demonstration, and Arithmeticall Calculation: in which Artes, they would have all Mechanitians and Sea-men to be ignorant, or at leaste insufficientlie furnished to performe such a matter. … But I doe verily thinke, that notwithstanding the learned in those Sciences, being in their studies amongst their bookes, can imagine greate matters, and set downe their farre fetcht conceits, in faire showe, and with plawsible wordes, wishing that all Mechanicians were such, as for want of uttereance, should be forced to deliver unto them their knowledge and conceites, that they might flourish upon them, and applye them at their pleasures: yet there are in this land divers Mechanicians, that in their severall faculties and professions, have the use of those Artes at their fingers endes, and can apply them to their severall purposes, as effectually and more readily, then those that would most condemne them.

—Robert Norman, *The Newe Attractive* [p. ii]

▼ **Figure 3.5** The book *De re metallica*, by Agricola (Georg Bauer, 1494–1555), was an epoch-making event in mining and metallurgy. Of particular interest for us are the methods of measurement described and, above all, the construction of multistage pumps. The Scholastic problem of *horror vacui* has here become a technical problem.

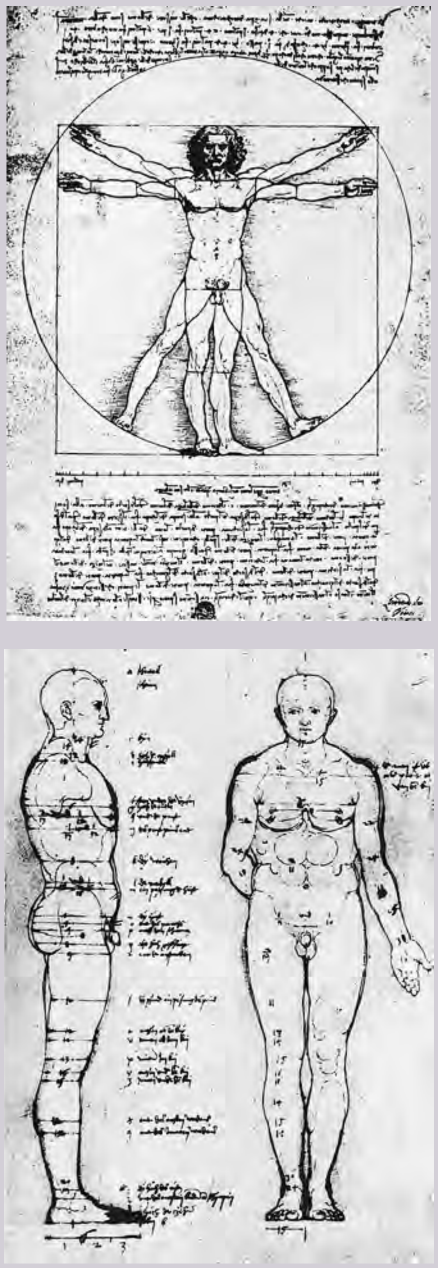
▶ **Figure 3.6** Theoretical arguments were not the decisive factor in the formation of a new worldview. (Hans Holbein the Younger: *Bad War*.)

Quotation 3.5

Following Plato and the Pythagoreans, the greatest mathematicians of that divine age, my teacher thought that in order to determine the causes of the phenomena circular motions must be ascribed to the spherical earth.

—Rheticus, "Narratio Prima" [pp. 147–148]

▼ **Figure 3.7** Canon of proportions for the human figure by Leonardo (top) and Dürer (bottom).



3.2 Numerology and Reality

3.2.1 *Back to Plato in a New Spirit*

Earlier, we saw that during the Renaissance, the arts and classical philology became the focus of intellectual activity. Only two important aspects of the natural sciences were preserved and further developed. First, an attempt was made to describe artistic ideals in terms of numbers and geometric figures, which to some extent reached beyond Aristotle all the way to Plato and Pythagoras. It is enough to observe that just about every artist had formulated his own canon of harmonious proportions for the human figure (Figure 3.7). Attempts were made to bring numeric or geometric harmony not only to the human figure, but also to buildings and even the proportions of printed letters.

The second important aspect of the natural sciences was a new emphasis on nature. This expressed itself in a meticulous description of natural phenomena and objects that at times could be considered scientific in today's sense of the word. Here we are not thinking of Leonardo, in whose person the artist and natural scientist are so inseparably combined that it is often difficult to say whether his drawings are of greater significance for art or for science.

The dominant characteristic of modern science is the close interplay between observation and mathematical description; hence, in the above aspects we see the emergence of the basic conditions for the new science. In contrast with the starting point espoused by Pythagoras and Plato, we can see that a great step forward had already been taken. As we have seen, for the idealistic philosophers of antiquity, harmony was the starting point (Section 1.2.3). Nevertheless, the shadow-world of phenomena had to be "rescued" at the same time, but they did not care much whether this rescue was complete or not. After all, everyday reality could hope to mirror the world of Platonic ideals only in rough outline, so that, for example, a triangle drawn on a piece of paper could reproduce the geometric idea of a triangle only in some approximate sense.

Seventeenth-century thinkers were still convinced of the mystical role of numbers, but they also had an unconditional respect for *facts*. As we shall see, for Kepler, the slightest discrepancy between theory and observation was cause enough for him to cast aside previous notions and to search for new harmonies, regardless of how strongly he believed in the construction of the universe according to Platonic ideals.

The rejection of medieval Aristotelianism through the embracing of Greek science before Aristotle can be seen as a step in the right direction. At the same time, the complete dismissal of medieval achievements interrupted the development of the natural sciences and, above all, of physics, which had begun in the late Middle Ages. The Renaissance turned a blinding light on ancient science, but this very action obscured the accomplishments of the so-called Dark Ages.

3.2.2 *The Retrograde Revolutionary: Copernicus*

The first and most important achievement of the Neo-Pythagorean point of view was the elaboration of the Copernican heliocentric system. A precursor of Copernicus was Regiomontanus, who perhaps only because of his untimely death was unable to take the decisive step (Section 2.6.5).

It was in the first years of the sixteenth century, while visiting the Italian universities, that Copernicus (Figure 3.8, Plate XIV) most likely became acquainted with the ideas of Aristarchus of Samos, according to which the Sun occupies the central position in the universe, and the planets—including our own Earth—revolve about the Sun in circular orbits. In a strange way, what especially pained Copernicus, as he described it in the dedication to his magnum opus, was the necessity of introducing *equants* into the Ptolemaic system, which amounted to an obvious betrayal of the Platonic conception that the planets, in their perfection, could only move along perfect—that is, circular—paths *with constant velocity*, and that at the outset, one should have to allow combinations of such perfect paths in order to achieve agreement with observation. As we might put it today, Copernicus did not attack the Ptolemaic system from the left, but from the right (Quotations 3.5 and 3.6).

The scientific world awaited the publication of Copernicus's works with great expectation. In his 1514 manuscript *Commentariolus*, Copernicus at first sketched out only the basic idea of his system. Then, in a 1540 book, *Narratio prima*, Rheticus described Copernicus's ideas in detail. Copernicus himself saw his own great work, *De revolutionibus orbium coelestium* (On the revolutions of the celestial spheres), only on his deathbed in 1543, a year that is frequently cited as marking the beginning of modern science; see Figure 3.9.

Quotation 3.6

People give ear to an upstart astrologer who strove to show that the earth revolves, not the heavens or the firmament, the sun and the moon, as if someone moving by carriage or by ship thought himself to be stationary and the land and trees to be moving. But the case is more like this: One who wants to appear clever cannot go along with what everyone seems to observe; he must come up with something different. So this clever soul, who wants to turn the whole of science of astronomy upside down. Yet even in those difficult matters I put my faith in Sacred Scriptures, for Joshua commanded the sun to stand still, and not the earth.

—Martin Luther, June 4, 1539 [Deely 2001, pp. 495–496]

◀ ▼ **Figure 3.8** According to Hevelius, the predecessors of Copernicus were Ptolemy, Albategnius (al-Battani), and Regiomontanus. Prince William IV of Hessen (1532–1592) became known for his catalog of stars. The picture is from Hevelius's book *Uranographia* (1687).

Nikolaus Copernicus (Mikołaj Kopernik): born 1473 in Toruń, son of a merchant, raised after his father's death by his uncle, the bishop of Warmia. Studied in Kraków, then in Bologna, Padua, Ferrara (where in 1503 he received a doctorate in ecclesiastical law), and Rome. Also studied medicine and served as his uncle's personal physician. From 1512, without ordination, was canon at the Frombork cathedral. Died in Frombork, 1543. Published his ideas about astronomy first in 1512 in his *Commentariolus*, which was distributed in manuscript as a pamphlet. An extensive description of his cosmology is contained in the 1540 article by the Wittenberg professor Rheticus: *Narratio Prima*. His magnum opus, *De revolutionibus orbium coelestium*, was published in Nuremberg shortly before his death.

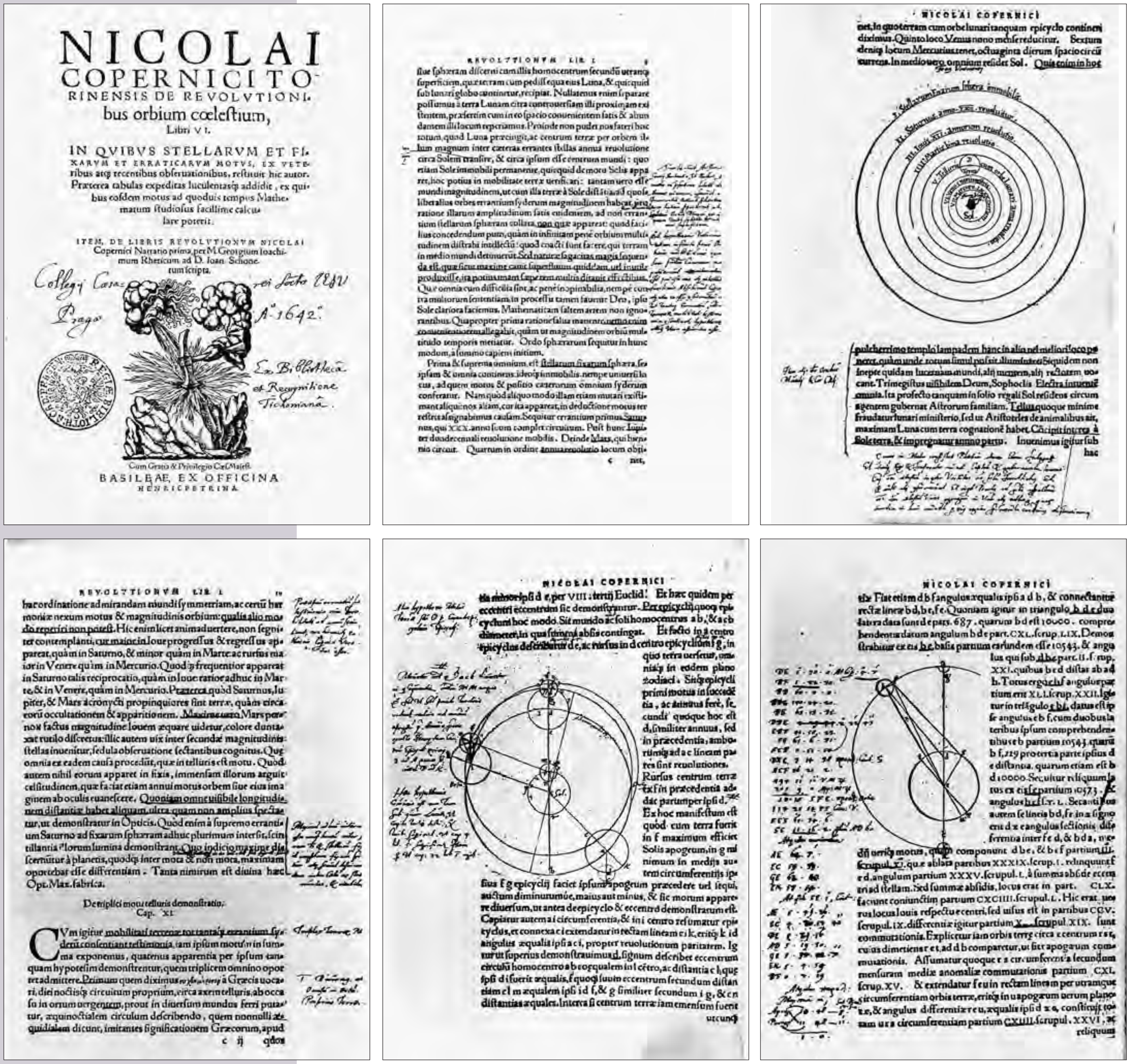
First of all I wish you to be convinced … that this man whose work I am now treating is in every field of knowledge and in mastery of astronomy not inferior to Regiomontanus. I rather compare him with Ptolemy, not because I consider Regiomontanus inferior to Ptolemy, but because my teacher shares with Ptolemy the good fortune of completing, with the aid of divine kindness, the reconstruction of astronomy which he began, while Regiomontanus—alas, cruel fate—departed this life before he had time to erect his columns.

—Rheticus, *First Narration (Narratio Prima)* [Boas Hall 1962]

▶ Figure 3.9 The book *De revolutionibus orbium coelestium*, one of the most important works in the history of European culture, was published in 1543 in Nuremberg. The book contains a brief foreword directed to the reader that is attributed not to COPERNICUS, but to OSIANDER. Following the foreword is a letter from Cardinal SCHÖNBERG to COPERNICUS, and finally a dedication to Pope PAUL III.

The entire work consists of six books. The first book describes a simple model of a heliocentric solar system and contains, moreover, a summary of the necessary mathematical theorems of trigonometry, plane and spherical. In the following five books, COPERNICUS offers a description of the orbits of Earth, the Moon, and the planets using tables, epicycles, and deferents.

The pages reproduced here from the second edition (Basel, 1566) are taken from the exemplar at Charles University, Prague, whose unique feature is that it contains TYCHO BRAHE's handwritten notes. The Basel edition also contains the book *Narratio Prima* by RHETICUS (facsimile edition, Prague, 1971).


NICOLAI COPERNICI TO-RINENSIS DE REVOLVTIONIbus orbium cœlestium, Libri VI.

IN QVIBVS STELLARVM ET FIXARVM ET ERRATICARVM MOTVS, EX VETERIBUS atq; recentibus obseruationibus, restituit hic autor. Præterea tabulas expeditas luculentasq; addidit, ex quibus eosdem motus ad quoduis tempus Mathematum studiosus facillime calculare poterit.

ITEM, DE LIBRIS REVOLVTIONVM NICOLAI Copernici Narratio prima, per M. Georgium Ioachimum Rheticum ad D. Ioan. Schonerum scripta.

Cum Gratia & Priuilegio Cæs. Maiest.

BASILEAE, EX OFFICINA HENRICPETRINA

I have no doubt that certain learned men, now that the novelty of the hypotheses in this work has been widely reported—for it establishes that the Earth moves, and indeed that the Sun is motionless in the middle of the universe—are extremely shocked, and think that the scholarly disciplines, rightly established once and for all, should not be upset. But if they are willing to judge the matter thoroughly, they will find that the author of this work has committed nothing which deserves censure. For it is proper for an astronomer to establish a record of the motions of the heavens with diligent and skilful observations, and then to think out and construct laws for them, or rather hypotheses, whatever their nature may be, since the true laws cannot be reached by the use of

continued on next page

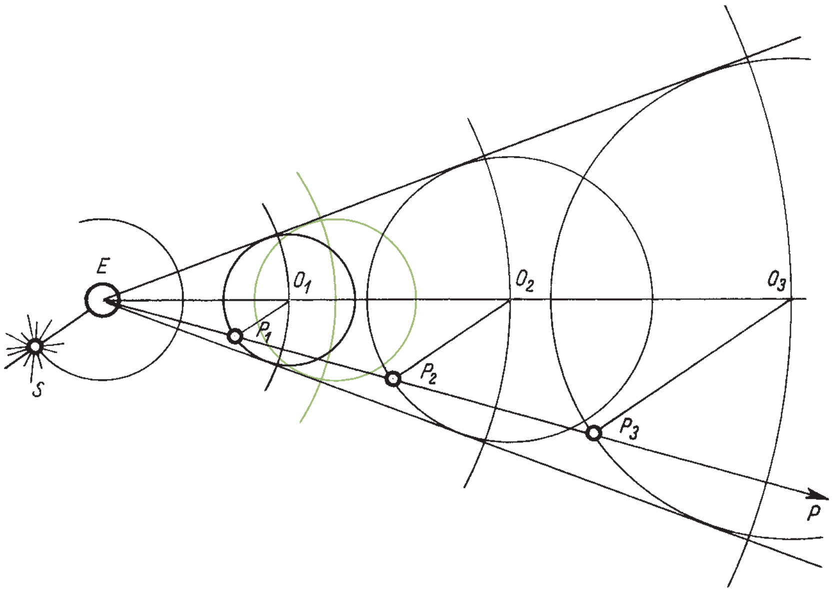
In the history of human culture, the displacement of Earth by the Sun as the midpoint of the cosmos is referred to as the *Copernican revolution*, and any important idea could hardly be given higher praise than to be compared with it. Thus, for example, KANT speaks with great pride of his "Copernican revolution" in his investigation of the role of reason in the process of understanding nature.

In what follows, we will first look at the Copernican system and then investigate the extent to which it represents progress with respect to methods of calculation and to physical and ideological foundations.

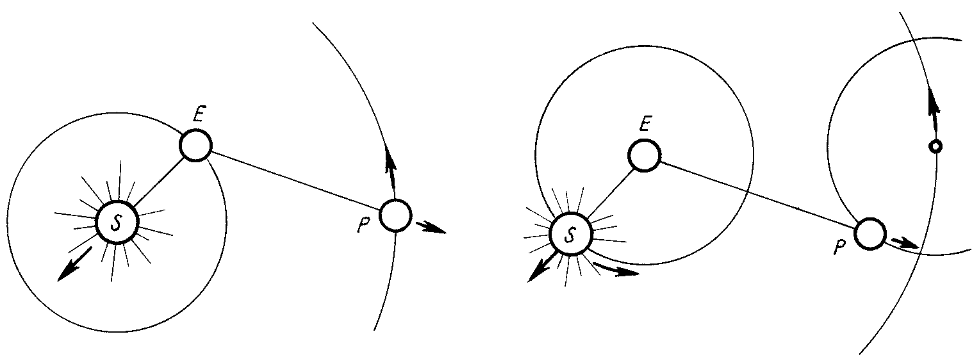
COPERNICUS describes his system in the first part of his book (Quotation 3.7). First let us make clear that the simplified Copernican system and the simplified Ptolemaic system (Figure 3.10) provide identical descriptions of the motions of the Sun and planets from the point of view of a terrestrial observer. In both cases, the observer is viewing the movement from Earth and can follow the paths of the celestial spheres based on their relative positions with respect to the fixed stars. The two systems, *from this viewpoint,* are equivalent when both the Copernican and Ptolemaic observers see the same angular coordinates for the Sun and planets in relation both to one another and to a selected fixed star, and therefore both observers can record the same trajectory on their star maps.

We begin the proof of this equivalence with the observation that in the Ptolemaic system, only the *ratio* of the radius of the deferent and that of the epicycle have any significance; the *radius* of the latter can therefore be chosen *arbitrarily* (Figure 3.11). For the convenience of the proof, let us choose it to be equal to the radius of Earth's orbit (Figure 3.12). The following illustrations demonstrate the equality of the relevant angles to a terrestrial observer in the cases of an inner (Figure 3.13) and an outer (Figure 3.14) planet.

Let us carry out the proof in somewhat more detail in the case of an outer planet. We begin with the Copernican system and draw in Figure 3.14, in black, the resulting paths. At a given point in time, suppose that Earth is located at the point *E* and a planet at point *P*. The directions are then shown in which an observer on Earth views the Sun (*S*) and the planet. Now we let Earth assume the role played by the Sun and move the point *E* into the place previously occupied by *S*, resulting in the point *S* being mapped to *S′*, so that the Sun is again viewed from Earth at the same



▲ **Figure 3.11** In the Ptolemaic system, the radii of the epicycles and deferent circles can be chosen arbitrarily, as long as their ratio is kept fixed. The line joining the center of an epicycle to its planet (for the outer planets) is, however, always parallel to the line connecting Earth and the Sun.

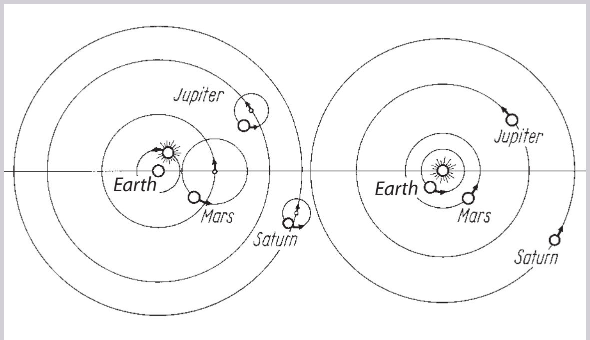


▲ **Figure 3.12** We have here chosen the deferent circle of the Ptolemaic system in such a way that the epicycle's radius is the same as that of the orbit of Earth. It is clear that the observable angles are equal.

Figure 3.9 *continued*

reason; and from those assumptions the motions can be correctly calculated, both for the future and for the past. Our author has shown himself outstandingly skilful in both these respects. Nor is it necessary that these hypotheses should be true, nor indeed even probable, but it is sufficient if they merely produce calculations which agree with the observations. That is, unless anyone is so ignorant of geometry and optics that the epicycle of Venus seems to him probable, or he thinks that it is in accordance with its law that it is sometimes ahead of the Sun and sometimes lags behind it by forty degrees or more. For who does not see that from that assumption it necessarily follows that the star's diameter appears more than four times greater, and its area more than sixteen times greater, at perigee than at apogee, to which all the experience of the ages is opposed. There are other things also in this discipline which are no less absurd, which it is quite unnecessary to examine for the present purpose. For it is clear enough that this subject is completely and simply ignorant of the laws which produce apparently irregular motions. And if it does work out any laws—as certainly it does work out very many—it does not do so in any way with the aim of persuading anyone that they are valid, but only to provide a correct basis for calculation. Since different hypotheses are sometimes available to explain one and the same motion (for instance eccentricity or an epicycle for the motion of the Sun) an astronomer will prefer to seize on the one which is easiest to grasp; a philosopher will perhaps look more for probability; but neither will grasp or convey anything certain, unless it has been divinely revealed to him. Let us therefore allow these new hypotheses also to become known beside the older, which are no more probable, especially since they are remarkable and easy; and let them bring with them the vast treasury of highly learned observations. And let no one expect from astronomy, as far as hypotheses are concerned, anything certain, since it cannot produce any such thing, in case if he seizes on things constructed for any other purpose as true, he departs from this discipline more foolish than he came to it. Farewell.

—Osiander, "To the Reader Concerning the Hypotheses of This Work" in Copernicus, *On the Revolutions of the Heavenly Spheres* [pp. 22–23]



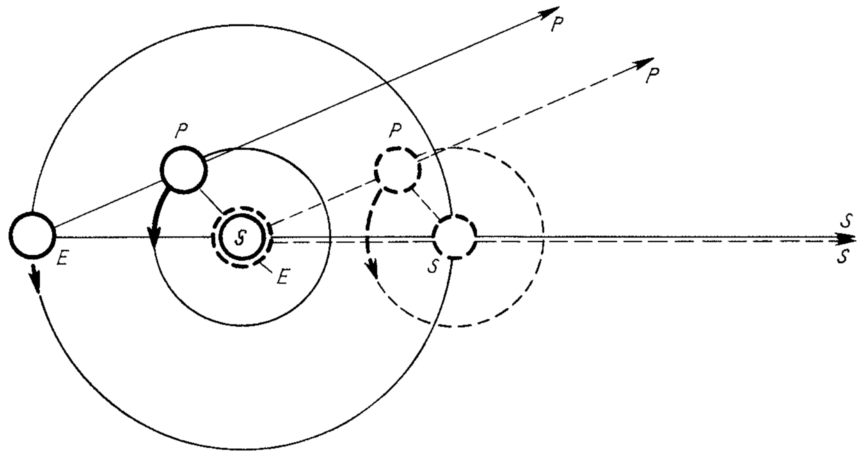
▲ **Figure 3.10** The Ptolemaic and Copernican systems in their simplest representations.

Quotation 3.7

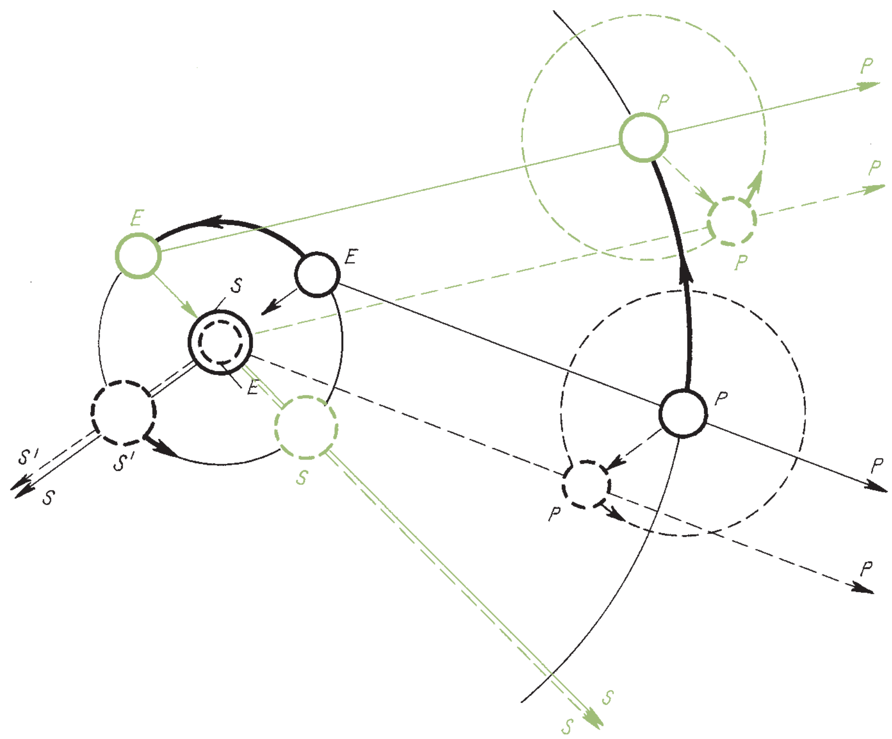
The universe is globe-shaped, either because that is the most perfect shape of all, needing no joint, an integral whole; or because that is the most capacious of shapes, which is most fitting because it is to contain and preserve all things; or because the most finished parts of the universe, I mean the Sun, Moon and stars, are observed to have that shape, or because everything tends to take on this shape, which is evident in drops of water and other liquid bodies, when they take on their natural shape. There should therefore be no doubt that this shape is assigned to the heavenly bodies. ...

The first and highest of all is the sphere of the fixed stars, which contains itself and all things, and is therefore motionless. It is the location of the universe, to which the motion and position of all the remaining stars is referred. For though some consider that it also changes in some respect, we shall assign another cause for its appearing to do so in our deduction of the Earth's motion. There follows Saturn, the first of the wandering stars, which completes its circuit in thirty years. After it comes Jupiter, which moves in a twelve-year-long revolution. Next is Mars, which goes round biennially. An annual revolution holds the fourth place, in which as we have said is contained the Earth along with the lunar sphere which is like an epicycle. In fifth place Venus returns every nine months. Lastly, Mercury holds the sixth place, making a circuit in the space of eighty days. In the middle of all is the seat of the Sun. For who in this most beautiful of temples would put this lamp in any other or better place than the one from which it can illuminate everything at the same time? Aptly indeed is he named by some the lantern of the universe, by others the mind, by others the ruler. Trismegistus called him the visible God, Sophocles' Electra, the watcher over all things. Thus indeed the Sun as if seated on a royal throne governs his household of Stars as they circle round him.

—Copernicus, *On the Revolutions of the Heavenly Spheres* [pp. 36, 49–50]



▲ **Figure 3.13** Equivalence in the case of the inner planets: The midpoint of the epicycle always lies on the line connecting Earth and the Sun. The radius of the epicycle is equal to that of the orbit of the planet, and the deferent coincides with the orbit of Earth.



▲ **Figure 3.14** For an outer planet, we show here the agreement of the two world systems when the planet moves.

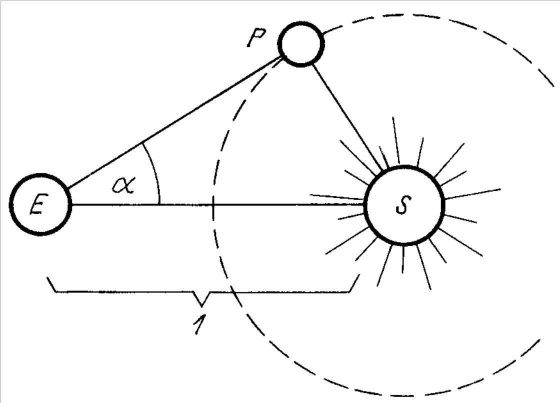
angle as before. If we also require the planet to be seen from Earth at the old angle, then it, like Earth, must be moved parallel through the same distance. We thereby obtain the configuration shown in the figure with dashed lines: the Ptolemaic view.

We now consider the situation at a later point in time and enter into the figure the configuration according to the Copernican system, again with solid lines, and that for the Ptolemaic system with dashed lines, but this time in color. We see that at this later time as well, the positions of the Sun and the planet are in the same relationship in both systems, provided the following two conditions are satisfied: in the Ptolemaic system, the Sun must orbit Earth in a circle corresponding to the orbit of Earth, and secondly the planet moves on a circular epicycle whose midpoint runs along the Copernican orbit, with the ray connecting the midpoint to the planet being at every moment parallel to the ray from Earth to the Sun. For an inner planet, the epicycle's midpoint moves in such a way that it is always on a line connecting the Sun and Earth. We saw this line in Section 1.4 (Figure 1.72), and it now can be understood what was only surmised, namely that the Sun plays some distinguished role in connection with planetary motion.

A glance at Figure 3.10 shows that the Copernican system is the simpler of the two. Furthermore, we find that in addition to the angles, the distances also acquire meaning, and it becomes a simple matter to determine the distance from each planet to the Sun. We recall here once again (Section 1.4) that in the Ptolemaic system, the radii of the deferents are chosen for the individual planets in such a way that after bringing in the epicycles, there is no overlap. Even the order of the planets was arbitrarily chosen according to the principle, later proven correct, that the more distant the planet, the smaller its mean velocity with respect to the background sphere of fixed stars.

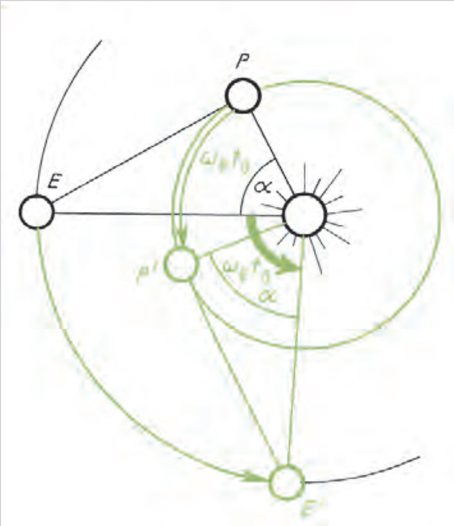
The distance to one of the inner planets can be determined in the Copernican system by using Figure 3.15. We have merely to find the maximal angle at which the planet is seen with respect to the Sun, as measured from Earth. From the illustrated triangle and from the Earth-Sun distance *ES*, the distance of the planet from the Sun can be determined using the relation

$$PS = ES \sin\alpha .$$



▲ **Figure 3.15** Determination of the orbital radius of an inner planet in terms of the unit distance from Earth to the Sun.

In the Copernican system, one can calculate a planet's orbital period about the Sun. With the help of Figure 3.16, let us investigate how this orbital period can be determined for an inner planet. We select a specific position for the planet, for example the position that we discussed above for the determination of distance, in which the planet is observed at a maximal angle with respect to the Sun. Let us now determine the time it takes for the planet to return to the same position with respect to an observer on Earth, of course. We have denoted this position of the planet by P'. We see that during this time Earth has moved in its orbit through a certain angle from its initial position while the inner planet has completed one revolution about the Sun and a part of a second revolution. Let us express the movement of Earth in its orbit by the angular velocity ω_E and that of the planet by ω_P, and let t_0 denote the time that the planet takes to achieve the same position with respect to a terrestrial observer. Then the angle through which Earth moves is $\omega_E t_0$, while that for the planet is $\omega_P t_0$. As can be seen from the figure, the two angles are connected by the relation



▲ **Figure 3.16** Determination of the orbital period of an inner planet according to Copernicus.

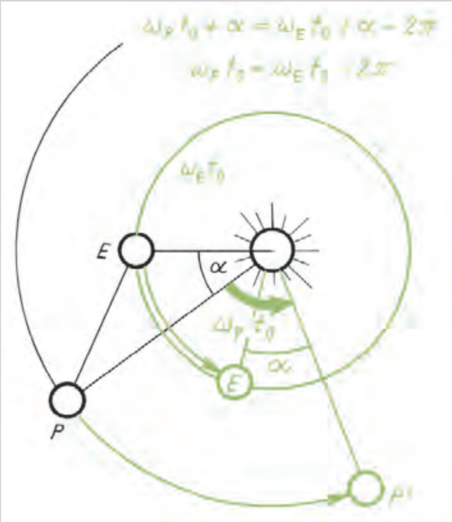
$$\omega_E t_0 = \omega_P t_0 - \alpha + \alpha - 2\pi .$$

Let us denote the orbital period of the Earth by T_E and that of the planet by T_P, then the angular velocities and periods are related as follows:

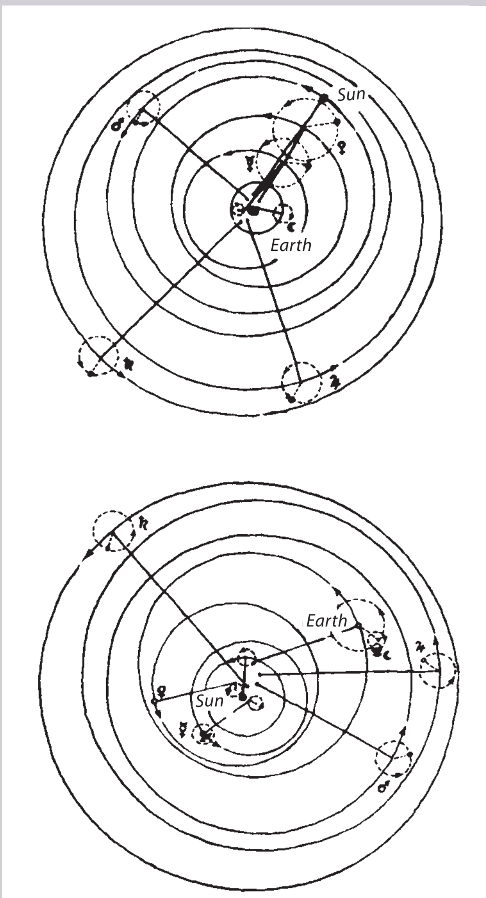
$$\omega_E = \frac{2\pi}{T_E}, \quad \omega_P = \frac{2\pi}{T_P}.$$

We now continue our observations over time intervals in which the configuration under consideration occurs N times, apply these to the first equation where

▼ **Figure 3.17** Determination of the orbital period of an outer planet.



▼ **Figure 3.18** The difference between the Ptolemaic (top) and Copernican (bottom) systems largely disappears when, in order to obtain agreement with observations, epicycles and deferents are brought in [Cohen 1960, p. 58].



we also substitute the angular velocities in terms of the orbital periods:

$$\frac{2\pi}{T_{\mathrm{E}}}(t_0 N) = \frac{2\pi}{T_{\mathrm{P}}}(t_0 N) - 2\pi N.$$

If we measure the time in years—that is, if we use the Earth's orbital period as the unit of time, thereby replacing T_{E} by 1—then from

$$T_{\mathrm{E}} = 1, \quad t_0 N = T \quad \text{(in years)},$$

we obtain the relationship

$$T = \frac{T}{T_{\mathrm{P}}} - N,$$

and finally,

$$T_{\mathrm{P}} = \frac{T}{T + N}.$$

This relationship gives the orbital period of an inner planet expressed in Earth years.

With the help of Figure 3.17, we may now, using analogous reasoning, determine the orbital period of an outer planet.

The simplicity of the pictures and the fact that one can give a physical meaning to the periods as well as the distances provide a strongly convincing argument for the validity of the Copernican system. However, it is precisely its equivalence with the Ptolemaic system that reveals the inadequacies of the Copernican picture sketched here. The simplified Copernican system is equivalent to the simplified Ptolemaic system. But we also know that for a precise description of planetary motion in the Ptolemaic system, many more epicycles and equants must be introduced, and it is therefore obvious that the Copernican cosmology as sketched above, despite its convincing simplicity and physical interpretation, cannot correctly describe the observed phenomena.

It is at this point that difficulties began to arise for Copernicus. As we know today, the planets do not move in circular orbits, but elliptical ones, and the assumption of circular trajectories was inadequate for reproducing the observations even with the precision achieved in the sixteenth century or in antiquity. This could be one of the reasons—the others are perhaps ideological—that Aristarchus rejected this whole theory in his time. True to the task that he set for himself, Copernicus wanted to use in his theory only uniform circular motion, but the result was that the beauty and the transparency of his entire theory was lost. Thus Copernicus was also forced to admit epicycles into his system, and because he wished to avoid equants, in place of the few circles he could eliminate by moving the point of reference for planetary motion from Earth to the Sun, he promptly had to employ many others due to his steadfast support of Platonic principles. In the end, to describe the motions of the planets in accord with observation, Copernicus had to use more than 30 circles in a wide variety of combinations.

Figure 3.18 shows—still with some simplifications—the Copernican and Ptolemaic systems side by side. Without reading the figure caption, at first glance it is difficult to distinguish which is which. In both systems, the planets move along epicycles whose midpoints move along a deferent circle. In Figure 3.19, the motion of Earth around the Sun is shown in detail. While we see that Earth moves in a circular orbit about the Sun, the center of this circle, however, is not the Sun but a fictive point in space that itself moves on another small circle, whose center, in turn, moves on a circular path around the Sun. The Copernican system has to be this complex in order to agree with observed facts. From the point of view of physics, the Sun here has no role other than that of an illuminating lantern for the planets. Therefore, in many works on the history of science, the Copernican system is not identified as *heliocentric*—that is, a system with the Sun at the center—but as *heliostatic*, with the Sun at rest, in contrast to the geostatic system, in which Earth is at rest.

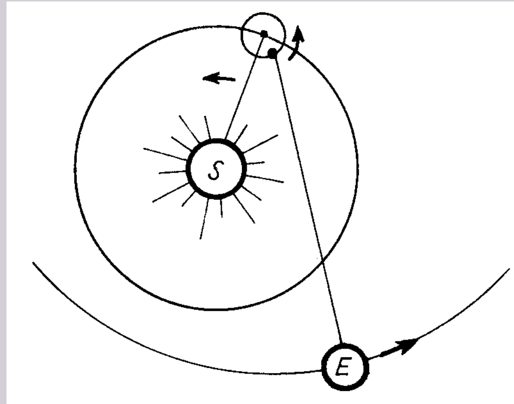
Thus, in the fully elaborated Copernican system, simplicity and aesthetics are lost. The physically distinguished role of the Sun is also lost, while the fault that is usually brought up in connection with the Ptolemaic system remains, namely that the planets travel in their epicyclic orbits about a point that exists only in our imagination as a fictive mathematical point of reference; when we seek a physical explanation, an effective force, we do not get any support from the theory for finding the origin of such a force. In the simplified Copernican system, in contrast, the Sun resides at the midpoint, and so it is obvious that the effective force is connected somehow with the Sun. But what are we to make of a Copernican system tamed to observation, in which this central position of the Sun has been obscured?

It is a much debated question, whether the foreword to Copernicus's book—which is due, according to historians, not to Copernicus himself but to Osiander—was in fact written in order to protect the book from the persecution of the clergy. In this foreword it is stated that the ideas presented in the book are nothing more than mathematical hypotheses, useful for simplifying astronomical calculation, and that they should not be taken as a representation of physical reality. But taking the book as a whole, this statement should not, in fact, be seen as a mollification directed at the Church, for the *fully elaborated* Copernican system can in fact be considered *only* as mathematical hypothesis, insofar as it admits no possible physical interpretation. Apparently, the contemporaries of Copernicus and the generation of astronomers that followed saw things this way, and perhaps this explains the fact that although the preliminary announcement of the Copernican system was received with great interest and expectation, nevertheless, after the appearance of the complete work, hardly anyone—with the exception of a few professional astronomers—took notice of it for the next several generations (Figure 3.20). This is particularly true of philosophers and clerics; the new system was not taken as a provocation or as a challenge, but merely as a variation on the Ptolemaic system with relatively few alterations.

To support this view, we cite in Figure 3.21 the title of an English translation of *De Revolutionibus* in 1576 suggesting that Copernicus had revived the old Pythagorean doctrines. At the same time, the Jesuit priest Clavius, whom the Pope had charged with reforming the calendar, used the Copernican system in his work. Many historians of science would place the Copernican system in the second or third century, rather than the sixteenth, if the judgment were to be based only on the assertions made within the system itself or—as a literary theorist would put it—if one considered only the stylistic elements.

Indeed, Copernicus was quite conservative in many respects. He spoke of the revolutions of the celestial orbits, meaning that he still believed in the crystalline spheres into which the planets were affixed like gems in their settings, so that they turned together. He also imagined the system of fixed stars as belonging to such a crystalline sphere. An interesting further development in the theory can be found in the English edition mentioned above, in which the stars are no longer arranged on the surface of a sphere, but rather in space. This is the first time that we see a picture in which the solar system is surrounded by an infinite sea of stars.

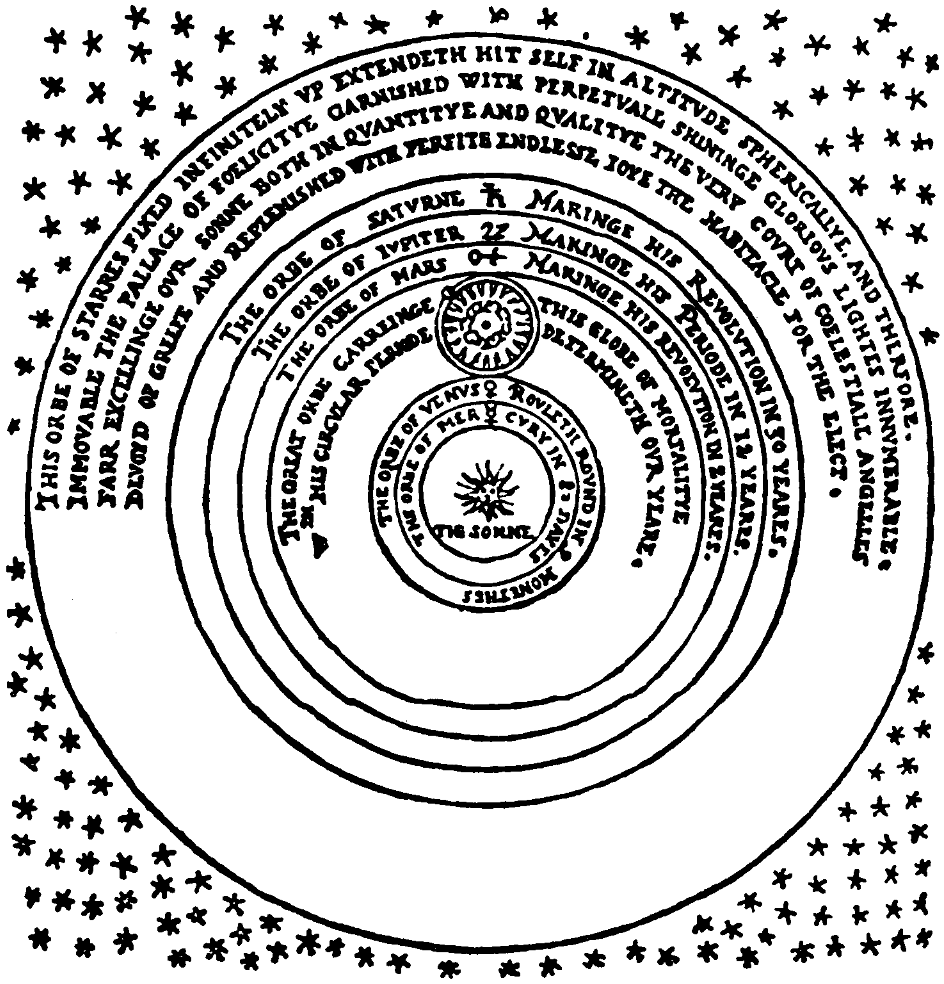
In some places in his writings, Copernicus answers arguments against the movement of Earth in a way that corresponds even to our present-day science. In other places, he still argues in the Aristotelian spirit. A good example for this is his



▲ **Figure 3.19** Copernicus did not use equants. However, to "rescue the phenomena," he had to introduce complex double epicycles. Earth's motion is also represented by such a complicated system [Hall 1965, p. 62].

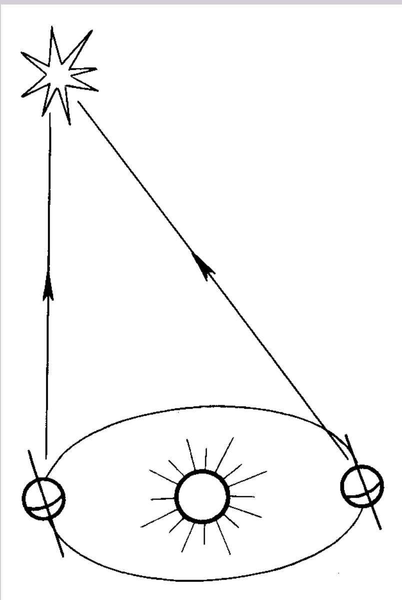
> Then Mercury runs on seven circles in all; Venus on five; the earth on three, and round it the moon on four; finally Mars, Jupiter, and Saturn on five each. Altogether, therefore, thirty-four circles suffice to explain the entire structure of the universe and the entire ballet of the planets.
>
> —Copernicus, *Commentariolus* [p. 90]

◀ **Figure 3.20** In his 1589 book, pictured here, Maginus made use of Copernicus's astronomical data but rejected the Copernican hypotheses regarding the motion of Earth as absurd. (Central library of the Benedictine order, Pannonhalma.)



▶ **Figure 3.21** A representation of the Copernican system in Digges's book. Digges accepted the Copernican system and even goes a step further: The stars are no longer arranged on crystalline spheres, but distributed in space. The text in the outer ring of the picture, in modern English, reads thus:

> This orb of stars fixed infinitely up extends itself in altitude spherically, and therefore, immovable the palace of felicity garnished with perpetual shining glorious lights innumerable, far excelling our sun both in quantity and quality the very court of celestial angels, devoid of grief and replenished with perfect endless love the dwelling place for the elect.
>
> —Thomas Digges, *Perfit Description of the Caelestiall Orbes according to the most ancienne doctrine of the Pythagoreans lately revived by Copernicus and by Geometricall Demonstrations approued,* 1576



▲ **Figure 3.22** If Earth orbits the Sun, then the stars must appear at different angles from different points on the orbit of Earth—or the stars must be very far away.

answer to the question of why bodies fall toward the center of Earth. Recall that Aristotelian physics held that all objects have their natural place, the heavy bodies below and the light above, and every body strives to assume the place assigned to it by nature. But if Earth no longer has a central, special place in the cosmos, then the notions "above" and "below" become meaningless. Copernicus explains the falling of objects as the striving of all things to unite with and make whole the place where they belong. However, we can also interpret this explanation—with a large measure of goodwill—as saying that every object has in it a center of force, or if you like, that it gravitationally attracts.

To the clever objection of why the fixed stars, in rotating about Earth in their orbits around the Sun, are not seen at different angles at different times of the year, or why—as we would put it today—no parallax is observed (Figure 3.22), Copernicus offered a clever answer: The crystalline sphere of the stars is so far away that Earth's orbit shrinks to a point by comparison. From today's point of view, such an answer is completely correct, but at that time, it did not appear convincing because it implied a size of the universe that was beyond the comprehension of that era. Moreover, the argument could be countered on considerations of parsimony, namely, that the vanishing of a logically positive phenomenon (parallax) had to rest on an additional hypothesis (the immeasurably large extent of the sphere of stars).

We summarize the significance of Copernicus's work as a negative result and two positive *possibilities*:

1. He was the first in history to give a logically complete account of the heliocentric system on the basis of Pythagorean and Platonic principles. It turned

out, however, that neither the attainable precision nor the physical interpretation was able to go significantly beyond the Ptolemaic system.

2. By placing Earth among the planets and thereby raising (or perhaps degrading) it to the rank of a celestial body, Copernicus put aside the sharp distinction between terrestrial and celestial phenomena and thus attacked Aristotelian physics in one of its fundamental theses, thus threatening to undermine the until-then well-founded hierarchical cosmology.
3. Copernicus's system assigned a special role to the Sun, if not in the fully elaborated variant, but at least in the basic system that could then serve as the starting point for the foundation of physical astronomy. It is no coincidence that every progressive proponent of the Copernican cosmology would seize on the simplified version, whether the reason was their limited understanding of mathematics and astronomy, sufficient for reading only the first chapter of *De revolutionibus* and not the other five, or a deliberate disregard of those last five chapters in order to move the basic Copernican system in another direction.

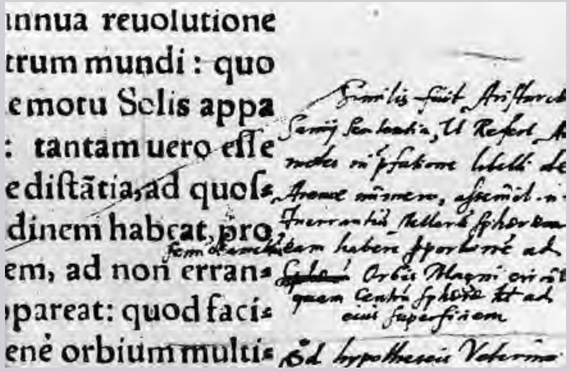
We must, of course, add that the power of any idea depends to a very great extent on—indeed, is often completely determined by—whether it is expressed at the opportune moment in history. In Copernicus's time, his system was not seen as something radically new. Figure 3.23 shows Tycho Brahe's handwritten marginal notes in a copy of *De revolutionibus*, in which he remarks that the ideas expressed there were already known to Aristarchus. However, Copernicus revived Aristarchus's ideas at the right moment and with the best mathematical tools available at the time, and he worked them out extensively, even if he did not make sufficiently critical use of the experimental data. Thus the Copernican system became an enormously powerful weapon in the hands of those who were to finally undo the Aristotelian cosmology and thereby it created the foundations for the building of a new natural science (Quotation 3.8).

Astronomy after Copernicus developed in two directions: One branch involved philosophers and physicists who were not concerned with the astronomical details and accepted the simplified Copernican variant. With the help of the theory, a new poetic vision of the world was created (Giordano Bruno), dangerous sociopolitical conclusions were drawn (Campanella), and thus with the introduction of both physical and philosophical arguments, this variant led finally to success (Galileo). In view of its immediate historical effects, this direction is the more important of the two.

Concrete physical results, however, were achieved primarily in the other branch, which led the most systematical and precise astronomical measurements in the history of physics until then (Tycho Brahe) to a refinement of the Copernican system, namely the elliptical orbits (Kepler), to which finally, although it took almost another century, a physical interpretation could be attached (Newton). The former branch will be discussed in Section 3.3, let us now follow the fate of the Copernican system in the hands of the professional astronomers.

3.2.3 *A Compromise: Tycho Brahe*

Frederick II, king of Denmark, was able to offer his court astronomer, Tycho Brahe (1546–1601), an opportunity to pursue his work in a way that was unique in the seventeenth century (Figure 3.24)—at least in Europe. It seems that only in ancient Alexandria and in the seventeenth century only outside of Europe—for example, in Samarkand at the court of Ulugh Beg—were astronomers able to work free of material want and with ample scientific equipment at their disposal.



▲ **Figure 3.23** A marginal note by Tycho Brahe in the exemplar of the book *De revolutionibus* depicted in Figure 3.9.

Quotation 3.8

Salviati: … Nor can I ever sufficiently admire the outstanding acumen of those who have taken hold of this opinion and accepted it as true; they have through sheer force of intellect done such violence to their own senses as to prefer what reason told them over that which sensible experience plainly showed them to the contrary. For the arguments against the whirling of the earth which we have already examined are very plausible, as we have seen; and the fact that the Ptolemaics and Aristotelians and all their disciples took them to be conclusive is indeed a strong argument of their effectiveness. But the experiences which overtly contradict the annual movement are indeed so much greater in their apparent force that, I repeat, there is no limit to my astonishment when I reflect that Aristarchus and Copernicus were able to make reason so conquer sense that, in defiance of the latter, the former became mistress of their belief.

—Galileo, *Dialogue Concerning the Two Chief World Systems—Ptolemaic & Copernican* [p. 328]

Newton also derived this relationship and was disappointed to learn that Huygens had already published the same results.

Huygens's train of thought is of great importance to the history of science because here it was established—contradicting the Peripatetics and even Galileo—not only that to maintain circular motion, a force is always required (which, by the way, Descartes already knew), but also that a numerical value could be calculated for this force. In this way, Huygens smoothed the way for a precise determination of acceleration in motion along curved paths.

As we have already mentioned, Huygens was no philosopher; his strength lay—as we have seen—in the establishment of simple, reasonable, but very productive fundamental physical principles. Nonetheless, Quotation 3.45, taken from the foreword to his book dedicated to problems of optics (*Traité de la lumière*), represents one of the most cogent formulations of the basic principles of natural philosophy.

3.7 Newton and the Principia: The Newtonian Worldview

3.7.1 *The Tasks Awaiting the Advent of Newton*

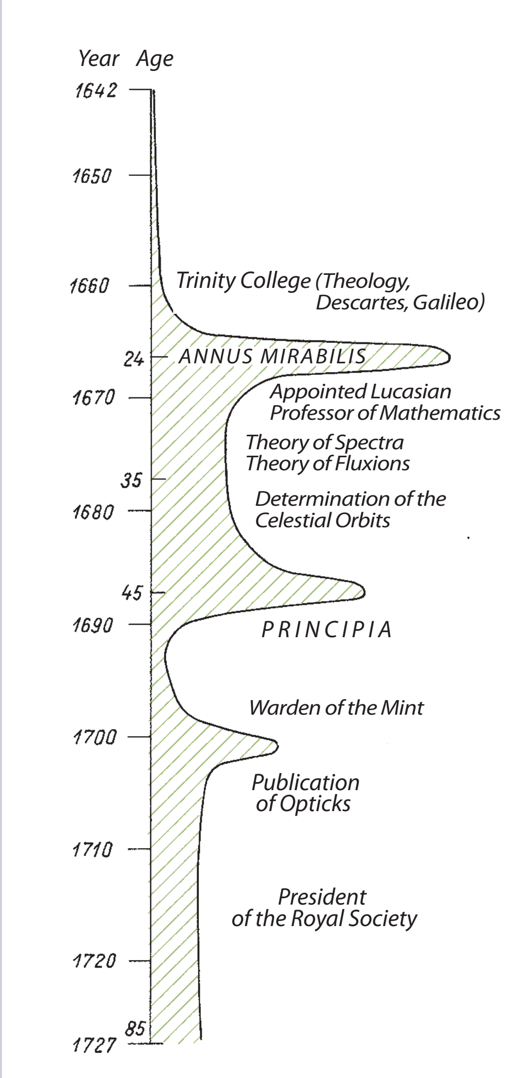
In the previous sections, we have sketched the path and followed the ideas leading to a new dynamics. Let us see—by summarizing the results of the first seven to eight decades of the seventeenth century—what was there for Newton to build on and what tasks were awaiting him.

We have spoken so far of three strands by which these ideas developed: free fall, collision, and circular motion.

- *Free fall.* The problem comprises the kinematics of bodies moving with constant acceleration, the proportionality of the distance traveled to the square of the time, and the surprising fact that every object—at least under ideal conditions—falls with the same acceleration. This fact greatly simplifies the kinematic description, but it also complicates its dynamic interpretation. Huygens's wide-ranging investigation into the problem of free fall did not bring us significantly closer to the goal, even though it was indirectly very useful because it showed that the right choice of an initial starting point—such as Huygens's principle on the center of gravity that was discussed in detail—can yield a broad multitude of concrete results.
- *Collision.* The momentum—that is, the product of the mass of the body and its velocity—as well as its change over time clearly play key roles.
- *Circular motion.* The important realization is that in order to maintain such motion, a force is necessary, contrary to the Peripatetic belief that circular motion can to some extent be seen as inertial, or naturally given, motion. More generally, it is precisely with circular motion, as the simplest form of curvilinear motion, that the vector nature of velocity and the change of velocity are the most evident and are also quantitatively accessible.

Behind all this lies a new law of inertia, recognized as final and irrevocable, according to which motion is a *state* and not a *process* and an effective cause is needed not to maintain it but to change it.

Finally, Descartes put his stamp on the worldview of physicists by requiring a unified explanation of celestial and terrestrial phenomena, and further requiring that this explanation be clearly formulated, meaning that interaction is possible only by immediately visible and perceptible contact.



▲ **Figure 3.117** Important events and creative periods in Newton's life. See also Plate XVII.

Isaac Newton (1642–1727): According to the Julian calendar then in use, born Christmas day in 1642; however, on the Continent, the new year had already begun. Newton's father had died several months before his son's birth. From 1661, Newton, with the support of his uncle, studied mathematics at Trinity College, Cambridge. During the plague epidemic in 1665, he withdrew to his estate in Woolsthorpe; this and the following year are known as Newton's "anni mirabiles" (Plate XVII). At only 24 years of age, Newton conceived the fundamental ideas for the binomial theorem, differential calculus, theory of color, centripetal force, laws of motion, and theory of gravitation. On his return to Cambridge, he dealt with problems of optics; in 1668, he completed a reflecting telescope. In 1669, he was appointed to the Lucasian Chair of Mathematics at the University of Cambridge, to succeed Isaac Barrow. In 1672, he presented his *Theory of Light and Colors* to the Royal Society; this book precipitated such dispute that he decided not to publish anything further. A summary of his work on optics was not published until

continued on next page

◀ **Table 3.4** How the great figures of the seventeenth century judged one another.

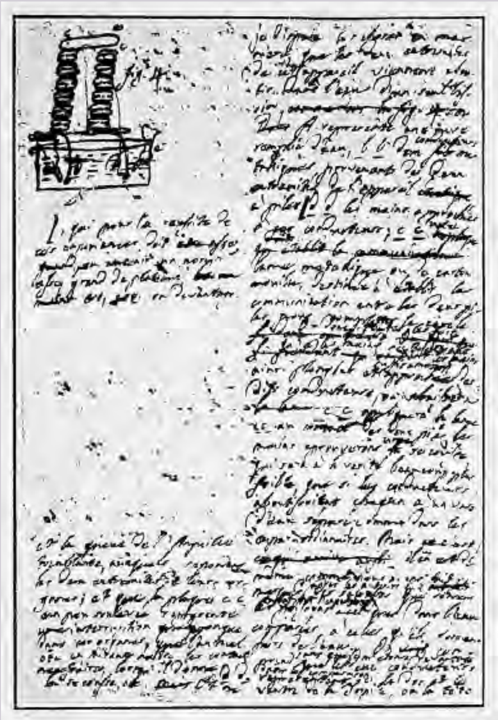
In establishing his law, Ohm could draw on two significant developments. Thomas Johann Seebeck (1770–1831) discovered thermoelectricity in 1821, and so Ohm was able to obtain a current source with constant voltage. On the theoretical front, Fourier's 1822 work on thermal conduction helped Ohm formulate analogous laws for electrical conduction. The problems that Ohm had to overcome were more conceptual than technical: for example, it was not clear whether a current along a conductor is constant or whether it may be "used up" in the process, and it was also not clear what was the relationship between the potential, as known from electrostatics, and the quantity that was measurable in the electric circuit and that was somehow analogous to the concept of temperature. It was also unknown whether current flows on the surface or through the interior of a conductor.

Ohm's simple law was extended by Gustav Kirchhoff to more complicated circuits. In 1845, Ohm worked out the two Kirchhoff laws for general circuits. Kirchhoff also made crucial progress in explaining the subject conceptually; for example, he pointed to the shared nature of the potential in the Poisson equation and the "electroscopic force" in Ohm's law.

Kirchhoff's first law, or current law, states that the sum of the currents meeting at a node in a circuit is equal to zero. In forming this sum, the currents flowing into the nodal point are considered to be negative, and those flowing out are considered positive.

Kirchhoff's second law concerns voltage: if one considers any closed loop within an electrical circuit, the sum of the "electromotive forces" (the internal voltages) is equal to the drop in voltage across the resistors. Again, the appropriate positive and negative signs must be used.

The introduction in 1894 of complex resistances, or impedances, in treating alternating-current circuits is the work of the American engineer Charles Steinmetz (1865–1923). For the quantitative treatment of phenomena in networks that are powered by generators with complex temporal voltage curves, a most original, almost magical, method was given by Oliver Heaviside (1850–1925), a method that was able to be justified mathematically only with difficulty via the methods of the Laplace transform and the theory of distributions.



▲ **Figure 4.81** The construction of the voltaic pile (from one of Volta's notebooks).

Quotation 4.28

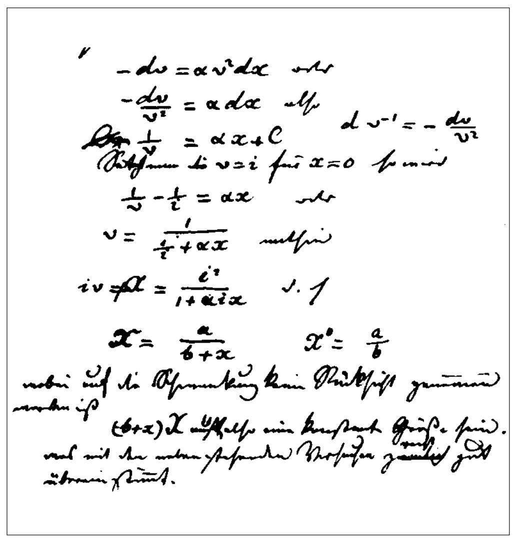
You certainly have a right to ask why it is inconceivable that no one tried the action of the voltaic pile on a magnet for twenty years. However, I believe that a cause of this is easily discovered: it simply existed in Coulomb's hypothesis on the nature of magnetic action; everyone believed this hypothesis as though it were a fact; it simply discarded every possibility of the action between electricity and so-called magnetic wires; the restriction was such that when M. Arago spoke of these new phenomena [of electromagnetism] at the Institute his remarks were rejected just as the ideas of stones falling from the heavens were rejected when M. Pictet read a memoir to the Institute on these stones. Everyone had decided that all this was impossible. ... Everyone resists changing ideas to which he is accustomed.

—Ampère, Letter to a friend, 1820 [Williams 1966, p. 60]

▶ **Figure 4.82** Georg Simon Ohm (1789–1854): Was senior teacher of mathematics and physics at the gymnasium in Cologne (1817–1828); from 1833 directed the polytechnic school in Nuremburg, and was appointed professor at the University of Munich in 1849.

In addition to his well-known discoveries in basic electrical circuits, Ohm did significant work in acoustics. He investigated the role of overtones in human hearing (1843). Helmholtz seized on Ohm's work on hearing in working out his resonance theory.

▼ **Figure 4.83** Ohm's law in its original form.



$$-dv = \alpha v^2 dx$$
$$-\frac{dv}{v^2} = \alpha\, dx$$
$$d\,v^{-1} = -\frac{dv}{v^2}$$
$$\frac{1}{v} = \alpha x + C$$
$$\frac{1}{v} - \frac{1}{i} = \alpha x$$
$$v = \frac{1}{\frac{1}{i} + \alpha x}$$
$$X' = \frac{a}{b}$$
$$X = \frac{a}{b+x}$$

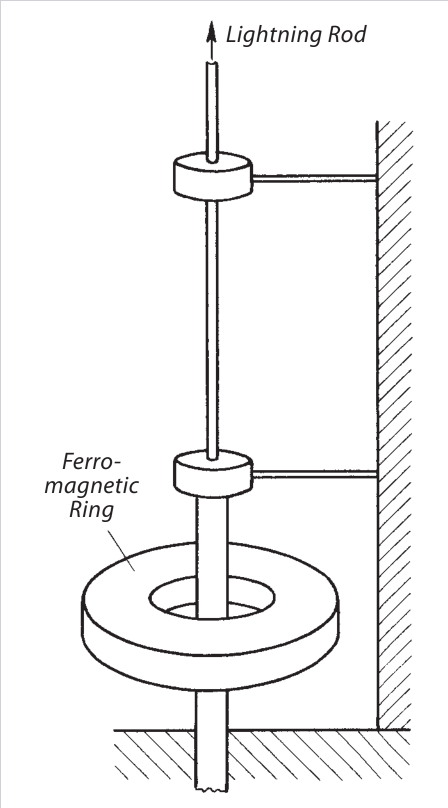
4.4.6 *The Magnetic Field of Electric Currents: Cross-Fertilization from Natural Philosophy*

Throughout the first two decades of the nineteenth century, experimenters were able to make use of equipment that could produce constant currents of suitable strength to bring conductors to incandescence and to carry out electrochemical investigations. Therefore, it seems surprising that the magnetic effects of current were only discovered in 1820.

At the beginning of the nineteenth century, a number of observations should have suggested to investigators that there is some kind of connection between magnetic fields and electrical current or, as one would have said at the time, the flow of the electric *fluidum* produces a magnetic effect in the surroundings. For instance, it was already known that in a house stuck by lightning, steel objects—knives, for example—that were close to the lightning strike became magnetized. Even today it is still a common practice to measure the very high currents (on the order of 100,000 amperes) that occur in lightning by using the magnetic effect (Figure 4.84). At that time, however, this was given little attention because no one was looking for a connection between electricity and magnetism. Coulomb's writings, as Ampère remarked in a letter (Quotation 4.28), excluded all such possibilities. Strangely, the impulse to seek such a relationship came from philosophy: The extreme mechanical materialism emanating from the rationalism of the eighteenth century was protested against by Romanticism in art, literature, and philosophy. This movement emphasized a more unified and dynamic description of nature and mankind. In Schelling's natural philosophy, all natural phenomena are represented as diverse manifestations of a single fundamental principle, in constant battle with one another, but eventually reaching equilibrium.

Ørsted embraced this philosophy; he spent years searching for a connection between electricity and magnetism. In this regard, natural philosophy exerted an immediate positive influence on the development of physics, and we have to rate this influence even more highly when we consider that Faraday was also thinking along such lines. As is clear from Ørsted's memoirs (Quotation 4.29), such a unifying natural-philosophical point of view can have disadvantages as well. Ørsted assumed at the outset that the magnetic effect should emanate from an electrical conductor like light or heat and together with light and heat. For this reason, he started by looking for the magnetic effect around conductors that glowed with current. He chose a very thin platinum wire as the conductor because that could be made to glow readily. In fact, a weak current was sufficient for heating the thin wire, but this worked against the success of the experiment.

Ørsted's discovery was of a purely qualitative character (Figure 4.85), and the theory that he proposed contributed neither an explanation of the phenomenon nor useful suggestions for further experimentation. Nevertheless, it was so completely unexpected that it received great attention in Europe. Ørsted sent his article, which was written in Latin, to all the relevant scientific societies in Europe. It is already clear from the letter of Ampère cited above (Quotation 4.28) that there was a general reluctance to believe in the correctness of the observation. However, the speed with which further theoretical and experimental results were achieved in this area proves that the leading intellects of the time had soon completely accepted this idea. Both the necessary experimental equipment and the requisite mathematical apparatus were at hand, so that within a few years, the associated theoretical description as we know it today had been completed.



▲ **Figure 4.84** Even today, the magnitude of the current in a lightning strike (up to hundreds of thousands amperes) is determined from the magnetization of a ring made of ferrous material slipped onto the grounding stake.

Quotation 4.29

Electromagnetism itself was discovered in the year 1820, by Professor Hans Christian Oersted, of the University of Copenhagen. Throughout his literary career, he adhered to the opinion, that the magnetic effects are produced by the same powers as electrical. He was not so much led to this, by the reason commonly alleged for this opinion, as by the philosophical principle, that all phenomena are produced by the same original power. ...

In the month of July 1820, he again resumed the experiment, making use of a much more considerable galvanical apparatus. The success was now evident, yet effects were still feeble in the first repetitions of the experiment, because he employed only very thin wires, supposing that the magnetical effect would not take place, when heat and light were not produced by the galvanical current; but he soon found that conductors of a greater diameter give much more effect; and he then discovered, by continued experiments during a few days, the fundamental law of electromagnetism, viz. *that the magnetical effect of the electrical current has a circular motion round it.*

—Ørsted, Article about his own discovery in *The Edinburgh Encyclopaedia* [Williams 1966, pp. 56, 58]

Quotation 4.39

Any person who reflects on the ideas which we annex to the word heat will perceive that this word is used for two meanings, or to express two different things. It either means a sensation excited in our organs, or a certain quality, affection, or condition of the bodies around us, by which they excite in us that sensation. The word is used in the first sense when we say, we feel heat; in the second when we say, there is heat in the fire, or in a hot stove. ...

We must therefore adopt, as one of the most general laws of heat, that "all bodies communicating freely with each other, and exposed to no inequality of external action, acquire the same temperature, as indicated by a thermometer." All acquire the temperature of the surrounding medium. ...

This is what has been commonly called an equal heat, or the equality of heat among different bodies; I call it the *equilibrium of heat*. The nature of this equilibrium was not well understood, until I pointed out a method of investigating it. Dr. Boerhaave imagined, that when it obtains, there is an equal quantity of heat in every equal measure of space, however filled up with different bodies, and professor Muschenbroek expresses his opinion to the same purpose: "*Est enim ignis aequaliter per omnia, non admodum magna, distributus, ita ut in pede cubico auri et aeris ut plumarum, par ignis sit quantitas*." The reason they give for this opinion is, that to whichever of these bodies the thermometer be applied, it points to the same degree.

But this is taking a very hasty view of the subject. It is confounding the quantity of heat in different bodies with its general strength or intensity, though it is plain that these are two different things, and should always be distinguished, when we are thinking of the distribution of heat.

—Joseph Black, *Lectures on the Elements of Chemistry* [pp. 21–22, 74, 75]

Quotation 4.40

It was formerly a common supposition, that the quantities of heat required to increase the heat of different bodies by the same number of degrees, were directly in proportion to the quantity of matter in each; and therefore, when the bodies were of equal size, the quantities of heat were in proportion to their density. But very soon after I began to think on this subject (anno 1760), I perceived that this opinion was a mistake, and that the quantities of heat which different kinds of matter must receive, to reduce them to an equilibrium with one another, or to raise their temperature by an equal number of degrees, are not in proportion to the quantity of

continued on next page

that the *caloricum* had some weight, though very small in comparison to the total weight of the object containing it. There were also measurements according to which a negative weight would have had to be assigned to the *caloricum*. The idea of a weightless substance—imponderable matter—would have caused no particular difficulties; physicists had already become accustomed to it in the case of light as well as that of the electric *fluidum*.

4.5.3 *Rumford: But Heat Is Still a Form of Motion!*

Declaring that heat is a form of motion, Count Rumford (Benjamin Thompson, 1753–1814) took up the fight against the substance theory of heat. In the course of an adventurous life, Rumford worked in a wide variety of fields and left behind contributions not only to science but also to other realms of human endeavor. In 1800, for example, he founded the English Royal Institution, whose first director was Davy and which later became famous through the work of Faraday. Rumford's scientific work was done in Munich, where he served as advisor to the Bavarian king and later as director of the military arsenal. He also founded social institutions and a state employment agency; and to this day, his name lives on in Rumford soup and the Rumford fireplace.

Rumford first set himself the task of verifying and completing the measurements relating to the weight of the heat substance. He noticed that latent heat was a suitable object of these measurements because, for example, a relatively large amount of heat is required for the melting of ice, and the same quantity of heat is liberated when water freezes without a change in its temperature. This method allowed for the elimination of the sources of error resulting from differences in temperature. With carefully executed experiments, in which he investigated the influence of even the smallest possible differences in temperature on the balance arm, Rumford was able to prove unambiguously that the heat substance, if indeed it existed, must have a vanishingly small weight. According to Rumford, he achieved such a degree of precision in his weighing that he would have been able to detect a deviation of one part in a million in the weight of an object. Rumford's description of his measurements can be found in Quotation 4.42, together with a cautious note that his results are almost self-evident if one considers heat not as a substance, but as motion.

The weakest point of the substance theory was its inability to provide a plausible explanation for the creation of heat through friction. Within the framework of substance theory, it was necessary to assume that friction so alters the state of a body that its heat capacity is reduced, with the result that the unchanged quantity of heat substance can raise its temperature. By examining the heat generated by the process of boring cannon barrels in great detail, Rumford intended to deal a death-blow to this theory. He was first able to prove that the specific heat of the shavings from the barrel remained unchanged. Then he was able to establish that from a given body kept warm by friction we can extract a heat quantity proportional to time; in other words, we can extract as much heat from it as we want. From these observations, Rumford drew confidently his final conclusions: Heat cannot be a substance, because if it were, then one would not be able to remove an unlimited quantity from a body. Heat can be nothing other than motion that can be continually recreated by mechanical friction, so that one can draw off heat from a body as long as this heat is created by mechanical work (Quotation 4.43). Quotation 4.44, from Rumford's article, shows that he came quite close to recognizing the equivalence of mechanical energy and heat energy. From the results of his measurements, with hindsight, we can even determine a value for the equivalence, which will play an important role later.

In saying farewell to Rumford, we must mention that he saw his investigations as basic research without immediate practical application and therefore had no expectation of material support. He writes in self-justification that the cannon barrels used in his experiments did not go to waste, but were put to use for their intended purpose.

From today's vantage point of the complete triumph of the kinetic theory, we would be inclined to see Rumford's conclusions as definitive. However, such was not the case at the beginning of the nineteenth century. Rumford's experimental results were accepted, to be sure, but the attempt was made to interpret them on the basis of heat substance. The fact, for example, that one can remove an inexhaustible quantity of heat from a body was interpreted to mean that in such cases the body serves only as a conduit; in reality, the heat substance flows into the body from the environment, which constitutes a practically inexhaustible reservoir.

To be sure, the kinetic theory also had its difficulties in the quantitative—and also qualitative—explanation of certain phenomena.

The following table summarizes the most important phenomena as well as commentary as to which of the two theories—heat-substance theory and kinetic theory—can more convincingly explain them.

	Heat conduction	Thermal radiation	Latent heat	Frictional heat	Quantitative conclusion possible?
Heat substance theory	yes	yes	yes	no	yes
Kinetic theory	yes	no	no	yes	no

To this table it must be added that the flow of heat substance (thermal conduction) could be presented as a very simple analogy to fluid flow, whereas with the kinetic theory, conduction was very difficult to describe because knowledge of the statistical nature of collision processes would have been needed. Nevertheless, in the table we state that the kinetic theory would eventually be able to accomplish this task. The *caloricum* theory can easily explain thermal radiation, that is, transmission of heat through a vacuum, as a flow of imponderable heat substance through a vacuum. The kinetic theory is helpless in the face of this phenomenon. Today we say that, in this situation, heat is transmitted from one body to another as electromagnetic radiation, that is, in a form of motion different from the usual motion of matter.

Looking at the above table, it is not difficult to understand why the great majority of scholars in the first decades of the nineteenth century still accepted the substance theory—not with full conviction, but as a useful working hypothesis.

4.5.4 *Fourier's Theory of Heat Conduction*

One of the most important successes of heat substance theory was achieved by Fourier with his mathematical theory of heat conduction.

Jean Baptiste Joseph Fourier (Figure 4.121) came from a poor family. It was thanks to the French Revolution—and, following it, Napoleon—that he had

Quotation 4.40, *continued*

matter in each, but in proportions widely different from this, and for which no general principle or reason can yet be assigned. …

Quicksilver, therefore, has less *capacity* for the matter of heat than water (if I may be allowed to use this expression) has; it requires a smaller quantity of it to raise its temperature by the same number of degrees. … We must, therefore, conclude that different bodies, although they be of the same size, or even of the same weight, when they are reduced to the same temperature or degree of heat, whatever that be, may contain very different quantities of the matter of heat; which different quantities are necessary to bring them to this level, or equilibrium, with one another.

It may have been remarked that the discoveries which have been made in this way are very unfavorable to one of the opinions which have been formed of the nature of heat. Many have supposed that heat is a tremulous, or other, motion of the particles of matter, which tremendous motion they imagined to be communicated from one body to another. But, if this were true, we must admit that the communication would be in conformity with our general experience of the communication of tremulous motion. We are not at liberty to feign laws of motion different from those already admitted, otherwise we can make any supposition account for any phenomena that we please. The denser substances ought surely to be the most powerful in communicating heat to others, or exciting it in them. The fact, however, in a great many examples, and yet not in all, is just the reverse. Such an opinion is therefore totally inconsistent with the phenomena. I do not see how this objection can be evaded.

—Joseph Black, *Lectures on the Elements of Chemistry* [pp. 76, 77, 80]

Quotation 4.41

Fluidity was universally considered as produced by a small addition to the quantity of heat which a body contains, when it is once heated up to its melting point; and the return of such a body to a solid state as depending on a very small diminution of the quantity of heat after it is cooled to the same degree; that a solid body, when it is changed into a fluid, receives no greater addition to the heat within it than what is measured by the elevation of temperature indicated after fusion by the thermometer; and that, when the melted body is again made to congeal, by a diminution of its heat, it suffers no greater loss of heat than what is indicated also by the simple application to it of the same instrument.

continued on next page

The Physics of the Twentieth Century

5.1 "Clouds on the Horizon of Nineteenth-Century Physics"

5.1.1 *A Conclusion or a New Start?*

The twentieth century will usher in the physics of the sixth decimal place, proclaimed the optimists at the turn of the century, elated at all of physics' accomplishments. By this they meant that the remaining task was simply to refine—based on the existing foundations—the measurements and calculations further in order to arrive at ever more precise numerical results (Quotations 5.1, 5.2).

However, the greatest physicists of the time saw clouds gathering on the horizon. The title of this section alludes to a lecture given by Lord Kelvin in 1900, in which he said:

> The beauty and clearness of the dynamical theory, which asserts heat and light to be modes of [mechanical] motion, is at present obscured by two clouds. The first came into existence with the undulatory theory of light... How could the Earth move through an elastic solid, such as essentially is the luminiferous ether? The second is the Maxwell–Boltzmann doctrine regarding the partition of energy.

We might conclude that both the optimism and the pessimism were prompted by a host of phenomena cropping up in the last quarter of the nineteenth century that did not fit into the classical framework. In fact, when we look at Figure 5.1, we can see a number of question marks, each signifying such a new phenomenon: the laws of spectra, the dependence on velocity of the mass of the electron, x-rays and radioactivity, to mention only a few.

A crisis in physics is never caused by a mere torrent of new phenomena, even when explanations for them have not yet been found. The real problem arises when we can find a definitive explanation based on the current theory—and "explanation" in physics naturally also means that the theory can connect the characteristic numerical values of the phenomenon in question to other already accepted values—but the predictions made by the theory do not agree with the experimentally measured values.

To put it plainly, we can speak of a crisis in a physical theory when in spite of sustained effort, a number of experimental observations cannot be reconciled with the theory.

In Figure 5.1 we have shown the division of the discipline of physics as it was generally accepted at the end of the nineteenth century. As we have already mentioned, this physics incorporates the physics of ordinary matter and the physics of the ether. To be sure, the idea of unification naturally arose as well: Many imagined the ether as a superfine material that should also have the properties of solid matter, in order for it to be able to propagate transverse electromagnetic waves. The converse idea was also proposed, that the ether is a continuous medium within which the particles of ordinary matter are formed as stable vortices in the manner of stable smoke rings in air.

Quotation 5.1

The more important fundamental laws and facts of physical science have all been discovered, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote. ... Our future discoveries must be looked for in the 6th place of decimals.

—A. A. Michelson, *Light Waves and Their Uses,* 1903 [Holton 1988, p.88]

Quotation 5.2

Now to the field of physics as it presented itself at that time. In spite of all the fruitfulness in particulars, dogmatic rigidity prevailed in matters of principles: In the beginning (if there was such a thing) God created Newton's laws of motion together with the necessary masses and forces. This is all; everything beyond this follows from the development of appropriate mathematical methods by means of deduction. What the nineteenth century achieved on the strength of this basis, especially through the application of the partial differential equations, was bound to arouse the admiration of every responsive person.

—Albert Einstein, "Autobiographical Notes" [p. 19]

Quotation 5.3

I am never content until I have constructed a mechanical model of the object that I am studying. If I succeed in making one, I understand; otherwise I do not. Hence I cannot grasp the electromagnetic theory of light. I wish to understand light as fully as possible, without introducing things that I understand still less. Therefore I hold fast to simple dynamics for there, but not in the electromagnetic theory, can I find a model.

—Lord Kelvin, 1884 [Mason 1953, pp. 391–392]

Quotation 5.4

However, after the first brilliant results of the kinetic theory of gases, its recent progress seems not to have fulfilled expectations; at every attempt to place this theory on a firmer footing, the difficulties have increased at an alarming rate. Everyone who has studied the work of the two researchers who have delved most deeply into the analysis of molecular motion, Maxwell and Boltzmann, cannot avoid the impression that in overcoming these problems, the admirable effort of acumen in physics and mathematical facility expended to date does not stand in the desired relationship to the fruitfulness of the results obtained.

—Planck [1958, Vol. 1, pp. 372–373]

Quotation 5.5

For a long time, physicists have assumed that all properties of bodies ultimately can be reduced to combinations of geometric figures and local motions; the general principles to which all physical properties are subject should thus be none other than the principles that govern local motion, principles that underlie efficient mechanics. The general principles of physics would then be encoded in efficient mechanics.

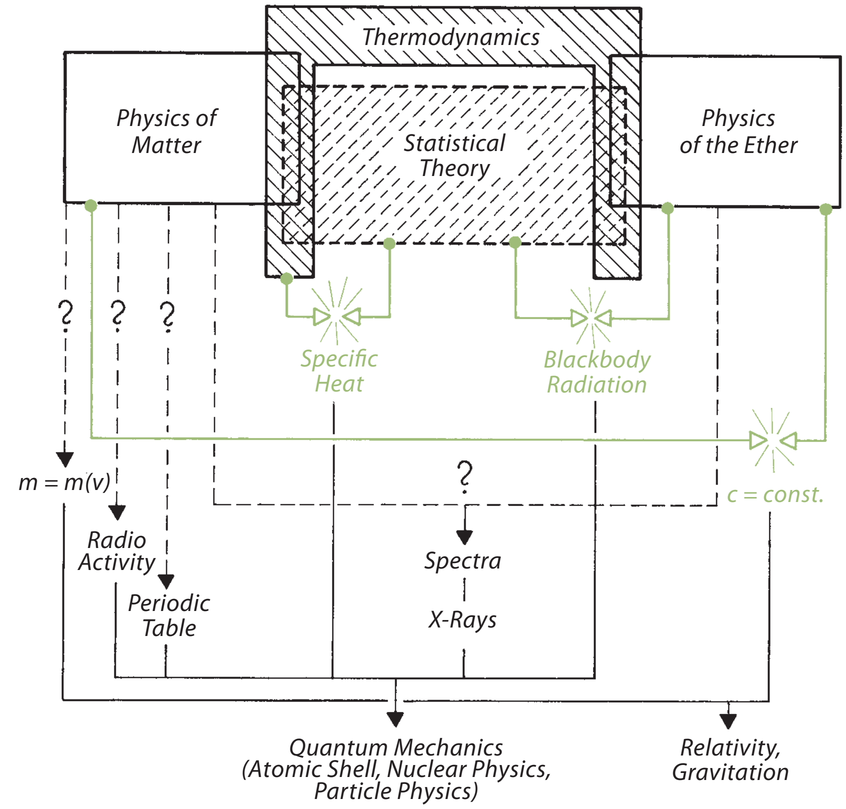
The reduction of all physical properties of combinations of geometric figures and local motions—what is usually called the *mechanical explanation* of the universe—seems today to have been refuted. And indeed, it is not to be refuted for a priori or metaphysical or mathematical reasons but because it was up to now only a project, a dream, and not a reality. Despite great efforts, physicists have not been able to devise such an arrangement of geometric figures and local motions that could provide, according to the rules of theoretical mechanics, a satisfactory representation of an only slightly expanded circle of the physical laws.

Will the attempt to reduce all of physics to theoretical mechanics, an attempt that always failed in the past, perhaps succeed in the future? Only a prophet could answer this question in a positive or negative sense.

Without giving preference to one or other of these answers, it seems much more reasonable to avoid efforts, at least provisionally, that have thus far been fruitless, such as the mechanical explanation of the universe.

We therefore attempt to formulate a system of general laws—laws that all physical properties must obey—without the a priori assumption that all these properties are reducible to geometric figures and local motions. The system of these general laws will in what follows not be reduced to the laws of efficient mechanics.

—P. Duhem, *Traité d´énergétique ou de thermodynamique générale*, 1911 [pp. 2, 3]



▲ **Figure 5.1** The structure of physics toward the end of the nineteenth century. Open problems are indicated with a question mark, and the phenomena that could not be explained within the confines of classical physics appear in color.

Thermodynamics existed as a separate discipline but it also provided a link between the two different groups of phenomena.

Finally, there was the statistical, or kinetic, theory of matter the goal of which was to reduce all physical phenomena to microphysical processes satisfying the laws of mechanics. The mechanistic explanation of the universe, proposed as a program by Descartes, remained an influence and a requirement even as late as the end of the nineteenth century (Quotation 5.2).

Earlier we described the attempts to understand the laws of electromagnetic fields and even entropy with the help of mechanical models. Even for Kelvin, the understanding of a physical phenomenon was complete only when a mechanical model for it could be provided (Quotation 5.3).

In Figure 5.1, the kinetic theory of matter is displayed with dashed borders to indicate that it was not fully accepted. Despite its rapid initial success, its weakness, which would later turn out to be of decisive import, was already evident in the pioneering works, namely, its failure to explain specific heat satisfactorily. Yet the theory of specific heat is based on a very general principle—the equipartition theorem. Maxwell formulated this theorem in 1878 in complete generality, using Lagrange's generalized coordinates with arbitrary force laws between the particles, assuming only the conservation of energy: In thermal equilibrium, energy is partitioned equally among the degrees of freedom of a particle. It is precisely a discrepancy between such a general theory and particular experimental observations that causes the most severe difficulties, for we cannot make the perhaps all too specialized assumptions of the theory responsible for the contradiction. Thus, we may understand why Planck himself (Quotation 5.4), and others as well (Quotation 5.5), looked upon the efforts in this area with a certain degree of skepticism.

Figure 5.16 *continued*

The concepts of conventionalism are illustrated by the following quotes:

> Can we maintain that certain phenomena which are possible in Euclidean space would be impossible in non-Euclidean space, so that experiment in establishing these phenomena would directly contradict the non-Euclidean hypothesis? I think that such a question cannot be seriously asked. To me it is exactly equivalent to the following, the absurdity of which is obvious: There are lengths which can be expressed in metres and centimetres, but cannot be measured in toises, feet, and inches …
>
> —Poincaré, *Science and Hypothesis* [p. 73]

> Suppose, for example, a world enclosed in a large sphere and subject to the following laws: The temperature is not uniform; it is greatest at the centre, and gradually decreases as we move towards the circumference of the sphere, where it is absolute zero. The law of this temperature is as follows: If R be the radius of the sphere, and r the distance of the point considered from the centre, the absolute temperature will be proportional to $R^2 - r^2$. Further, I shall suppose that in this world all bodies have the same co-efficient of dilatation, so that the linear dilatation of any body is proportional to its absolute temperature. Finally, I shall assume that a body transported from one point to another of different temperature is instantaneously in thermal equilibrium with its new environment. There is nothing in these hypotheses either contradictory or unimaginable. A moving object will become smaller and smaller as it approaches the circumference of the sphere. Let us observe, in the first place, that although from the point of view of our ordinary geometry this world is finite, to its inhabitants it will appear infinite. As they approach the surface of the sphere they become colder, and at the same time smaller and smaller. The steps they take are therefore also smaller and smaller, so that they can never reach the boundary of the sphere. If to us geometry is only the study of the laws according to which invariable solids move, to these imaginary beings it will be the study of the laws of motion of solids *deformed by the differences of temperature* alluded to. …
>
> Let me make another hypothesis: suppose that light passes through media of different refractive indices, such that the index of refraction is inversely proportional to $R^2 - r^2$. Under these conditions it is clear that the rays of light will no longer be rectilinear but circular.
>
> —Poincaré, *Science and Hypothesis* [pp. 65–66]

▶ **Figure 5.17** Some facsimile pages from EINSTEIN's first article on the theory of relativity. The titles of all three protagonists' articles indicate that the theory of relativity arose from problems in the field of electrodynamics of moving bodies. LORENTZ wrote his article in English (Figure 4.115): "Electromagnetic Phenomena in a System Moving with Any Velocity Smaller than That of Light"; POINCARÉ's was, of course, written in French: *Sur la dynamique de l'électron*; and finally, EINSTEIN's work bore the title *Zur Elektrodynamik bewegter Körper*.

continued on next page

3. *Zur Elektrodynamik bewegter Körper;* *von A. Einstein.*

Daß die Elektrodynamik Maxwells — wie dieselbe gegenwärtig aufgefaßt zu werden pflegt — in ihrer Anwendung auf bewegte Körper zu Asymmetrien führt, welche den Phänomenen nicht anzuhaften scheinen, ist bekannt. Man denke z. B. an die elektrodynamische Wechselwirkung zwischen einem Magneten und einem Leiter. Das beobachtbare Phänomen hängt hier nur ab von der Relativbewegung von Leiter und Magnet, während nach der üblichen Auffassung die beiden Fälle, daß der eine oder der andere dieser Körper der bewegte sei, streng voneinander zu trennen sind. Bewegt sich nämlich der Magnet und ruht der Leiter, so entsteht in der Umgebung des Magneten ein elektrisches Feld von gewissem Energiewerte, welches an den Orten, wo sich Teile des Leiters befinden, einen Strom erzeugt. Ruht aber der Magnet und bewegt sich der Leiter, so entsteht in der Umgebung des Magneten kein elektrisches Feld, dagegen im Leiter eine elektromotorische Kraft, welcher an sich keine Energie entspricht, die aber — Gleichheit der Relativbewegung bei den beiden ins Auge gefaßten Fällen vorausgesetzt — zu elektrischen Strömen von derselben Größe und demselben Verlaufe Veranlassung gibt, wie im ersten Falle die elektrischen Kräfte.

Beispiele ähnlicher Art, sowie die mißlungenen Versuche, eine Bewegung der Erde relativ zum „Lichtmedium" zu konstatieren, führen zu der Vermutung, daß dem Begriffe der absoluten Ruhe nicht nur in der Mechanik, sondern auch in der Elektrodynamik keine Eigenschaften der Erscheinungen entsprechen, sondern daß vielmehr für alle Koordinatensysteme, für welche die mechanischen Gleichungen gelten, auch die gleichen elektrodynamischen und optischen Gesetze gelten, wie dies für die Größen erster Ordnung bereits erwiesen ist. Wir wollen diese Vermutung (deren Inhalt im folgenden „Prinzip der Relativität" genannt werden wird) zur Voraussetzung erheben und außerdem die mit ihm nur scheinbar unverträgliche

892 *A. Einstein.*

Voraussetzung einführen, daß sich das Licht im leeren Raume stets mit einer bestimmten, vom Bewegungszustande des emittierenden Körpers unabhängigen Geschwindigkeit V fortpflanze. Diese beiden Voraussetzungen genügen, um zu einer einfachen und widerspruchsfreien Elektrodynamik bewegter Körper zu gelangen unter Zugrundelegung der Maxwellschen Theorie für ruhende Körper. Die Einführung eines „Lichtäthers" wird sich insofern als überflüssig erweisen, als nach der zu entwickelnden Auffassung weder ein mit besonderen Eigenschaften ausgestatteter „absolut ruhender Raum" eingeführt, noch einem Punkte des leeren Raumes, in welchem elektromagnetische Prozesse stattfinden, ein Geschwindigkeitsvektor zugeordnet wird.

Die zu entwickelnde Theorie stützt sich — wie jede andere Elektrodynamik — auf die Kinematik des starren Körpers, da die Aussagen einer jeden Theorie Beziehungen zwischen starren Körpern (Koordinatensystemen), Uhren und elektromagnetischen Prozessen betreffen. Die nicht genügende Berücksichtigung dieses Umstandes ist die Wurzel der Schwierigkeiten, mit denen die Elektrodynamik bewegter Körper gegenwärtig zu kämpfen hat.

I. Kinematischer Teil.

§ 1. **Definition der Gleichzeitigkeit.**

Es liege ein Koordinatensystem vor, in welchem die Newtonschen mechanischen Gleichungen gelten. Wir nennen dies Koordinatensystem zur sprachlichen Unterscheidung von später einzuführenden Koordinatensystemen und zur Präzisierung der Vorstellung das „ruhende System".

Ruht ein materieller Punkt relativ zu diesem Koordinatensystem, so kann seine Lage relativ zu letzterem durch starre Maßstäbe unter Benutzung der Methoden der euklidischen Geometrie bestimmt und in kartesischen Koordinaten ausgedrückt werden.

Wollen wir die *Bewegung* eines materiellen Punktes beschreiben, so geben wir die Werte seiner Koordinaten in Funktion der Zeit. Es ist nun wohl im Auge zu behalten, daß eine derartige mathematische Beschreibung erst dann einen physikalischen Sinn hat, wenn man sich vorher darüber klar geworden ist, was hier unter „Zeit" verstanden wird.

Zur Elektrodynamik bewegter Körper. 893

Wir haben zu berücksichtigen, daß alle unsere Urteile, in welchen die Zeit eine Rolle spielt, immer Urteile über *gleichzeitige Ereignisse* sind. Wenn ich z. B. sage: „Jener Zug kommt hier um 7 Uhr an," so heißt dies etwa: „Das Zeigen des kleinen Zeigers meiner Uhr auf 7 und das Ankommen des Zuges sind gleichzeitige Ereignisse."[1])

Es könnte scheinen, daß alle die Definition der „Zeit" betreffenden Schwierigkeiten dadurch überwunden werden könnten, daß ich an Stelle der „Zeit" die „Stellung des kleinen Zeigers meiner Uhr" setze. Eine solche Definition genügt in der Tat, wenn es sich darum handelt, eine Zeit zu definieren ausschließlich für den Ort, an welchem sich die Uhr eben befindet; die Definition genügt aber nicht mehr, sobald es sich darum handelt, an verschiedenen Orten stattfindende Ereignisreihen miteinander zeitlich zu verknüpfen, oder — was auf dasselbe hinausläuft — Ereignisse zeitlich zu werten, welche in von der Uhr entfernten Orten stattfinden.

Wir könnten uns allerdings damit begnügen, die Ereignisse dadurch zeitlich zu werten, daß ein samt der Uhr im Koordinatenursprung befindlicher Beobachter jedem von einem zu wertenden Ereignis Zeugnis gebenden, durch den leeren Raum zu ihm gelangenden Lichtzeichen die entsprechende Uhrzeigerstellung zuordnet. Eine solche Zuordnung bringt aber den Übelstand mit sich, daß sie vom Standpunkte des mit der Uhr versehenen Beobachters nicht unabhängig ist, wie wir durch die Erfahrung wissen. Zu einer weit praktischeren Festsetzung gelangen wir durch folgende Betrachtung.

Befindet sich im Punkte A des Raumes eine Uhr, so kann ein in A befindlicher Beobachter die Ereignisse in der unmittelbaren Umgebung von A zeitlich werten durch Aufsuchen der mit diesen Ereignissen gleichzeitigen Uhrzeigerstellungen. Befindet sich auch im Punkte B des Raumes eine Uhr — wir wollen hinzufügen, „eine Uhr von genau derselben Beschaffenheit wie die in A befindliche" — so ist auch eine zeitliche Wertung der Ereignisse in der unmittelbaren Umgebung von

894 *A. Einstein.*

B durch einen in B befindlichen Beobachter möglich. Es ist aber ohne weitere Festsetzung nicht möglich, ein Ereignis in A mit einem Ereignis in B zeitlich zu vergleichen; wir haben bisher nur eine „A-Zeit" und eine „B-Zeit", aber keine für A und B gemeinsame „Zeit" definiert. Die letztere Zeit kann nun definiert werden, indem man *durch Definition* festsetzt, daß die „Zeit", welche das Licht braucht, um von A nach B zu gelangen, gleich ist der „Zeit", welche es braucht, um von B nach A zu gelangen. Es gehe nämlich ein Lichtstrahl zur „A-Zeit" t_A von A nach B ab, werde zur „B-Zeit" t_B in B gegen A zu reflektiert und gelange zur „A-Zeit" t'_A nach A zurück. Die beiden Uhren laufen definitionsgemäß synchron, wenn

$$t_B - t_A = t'_A - t_B.$$

Wir nehmen an, daß diese Definition des Synchronismus in widerspruchsfreier Weise möglich sei, und zwar für beliebig viele Punkte, daß also allgemein die Beziehungen gelten:

1. Wenn die Uhr in B synchron mit der Uhr in A läuft, so läuft die Uhr in A synchron mit der Uhr in B.

2. Wenn die Uhr in A sowohl mit der Uhr in B als auch mit der Uhr in C synchron läuft, so laufen auch die Uhren in B und C synchron relativ zueinander.

Wir haben so unter Zuhilfenahme gewisser (gedachter) physikalischer Erfahrungen festgelegt, was unter synchron laufenden, an verschiedenen Orten befindlichen, ruhenden Uhren zu verstehen ist und damit offenbar eine Definition von „gleichzeitig" und „Zeit" gewonnen. Die „Zeit" eines Ereignisses ist die mit dem Ereignis gleichzeitige Angabe einer am Orte des Ereignisses befindlichen, ruhenden Uhr, welche mit einer bestimmten, ruhenden Uhr, und zwar für alle Zeitbestimmungen mit der nämlichen Uhr, synchron läuft.

Wir setzen noch der Erfahrung gemäß fest, daß die Größe

$$\frac{2\,\overline{AB}}{t'_A - t_A} = V$$

eine universelle Konstante (die Lichtgeschwindigkeit im leeren Raume) sei.

Wesentlich ist, daß wir die Zeit mittels im ruhenden System

918 *A. Einstein.*

sprung befinde und sich längs der X-Achse des Systems K mit der Geschwindigkeit v bewege. Es ist dann einleuchtend, daß das Elektron im genannten Momente ($t = 0$) relativ zu einem längs der X-Achse mit der konstanten Geschwindigkeit v parallelbewegten Koordinatensystem k ruht.

Aus der oben gemachten Voraussetzung in Verbindung mit dem Relativitätsprinzip ist klar, daß sich das Elektron in der unmittelbar folgenden Zeit (für kleine Werte von t) vom System k aus betrachtet nach den Gleichungen bewegt:

$$\mu \frac{d^2 \xi}{d\tau^2} = \varepsilon X',$$
$$\mu \frac{d^2 \eta}{d\tau^2} = \varepsilon Y',$$
$$\mu \frac{d^2 \zeta}{d\tau^2} = \varepsilon Z',$$

wobei die Zeichen ξ, η, ζ, τ, X', Y', Z' sich auf das System k beziehen. Setzen wir noch fest, daß für $t = x = y = z = 0$ $\tau = \xi = \eta = \zeta = 0$ sein soll, so gelten die Transformationsgleichungen der §§ 3 und 6, so daß gilt:

$$\tau = \beta\left(t - \frac{v}{V^2}x\right),$$
$$\xi = \beta(x - vt), \qquad X' = X,$$
$$\eta = y, \qquad Y' = \beta\left(Y - \frac{v}{V}N\right),$$
$$\zeta = z, \qquad Z' = \beta\left(Z + \frac{v}{V}M\right).$$

Mit Hilfe dieser Gleichungen transformieren wir die obigen Bewegungsgleichungen vom System k auf das System K und erhalten:

$$\text{(A)} \qquad \left\{\begin{aligned} \frac{d^2 x}{dt^2} &= \frac{\varepsilon}{\mu}\frac{1}{\beta^3}X, \\ \frac{d^2 y}{dt^2} &= \frac{\varepsilon}{\mu}\frac{1}{\beta}\left(Y - \frac{v}{V}N\right), \\ \frac{d^2 z}{dt^2} &= \frac{\varepsilon}{\mu}\frac{1}{\beta}\left(Z + \frac{v}{V}M\right). \end{aligned}\right.$$

Wir fragen nun in Anlehnung an die übliche Betrachtungsweise nach der „longitudinalen" und „transversalen" Masse

Zur Elektrodynamik bewegter Körper. 919

des bewegten Elektrons. Wir schreiben die Gleichungen (A) in der Form

$$\mu\beta^3 \frac{d^2 x}{dt^2} = \varepsilon X = \varepsilon X',$$
$$\mu\beta^2 \frac{d^2 y}{dt^2} = \varepsilon\beta\left(Y - \frac{v}{V}N\right) = \varepsilon Y',$$
$$\mu\beta^2 \frac{d^2 z}{dt^2} = \varepsilon\beta\left(Z + \frac{v}{V}M\right) = \varepsilon Z'$$

und bemerken zunächst, daß $\varepsilon X'$, $\varepsilon Y'$, $\varepsilon Z'$ die Komponenten der auf das Elektron wirkenden ponderomotorischen Kraft sind, und zwar in einem in diesem Moment mit dem Elektron mit gleicher Geschwindigkeit wie dieses bewegten System betrachtet. (Diese Kraft könnte beispielsweise mit einer im letzten System ruhenden Federwage gemessen werden.) Wenn wir nun diese Kraft schlechtweg „die auf das Elektron wirkende Kraft" nennen und die Gleichung

Massenzahl × Beschleunigungszahl = Kraftzahl

aufrechterhalten, und wenn wir ferner festsetzen, daß die Beschleunigungen im ruhenden System K gemessen werden sollen, so erhalten wir aus obigen Gleichungen:

$$\text{Longitudinale Masse} = \frac{\mu}{\left(\sqrt{1 - \left(\frac{v}{V}\right)^2}\right)^3},$$

$$\text{Transversale Masse} = \frac{\mu}{1 - \left(\frac{v}{V}\right)^2}.$$

Natürlich würde man bei anderer Definition der Kraft und der Beschleunigung andere Zahlen für die Massen erhalten; man ersieht daraus, daß man bei der Vergleichung verschiedener Theorien der Bewegung des Elektrons sehr vorsichtig verfahren muß.

Wir bemerken, daß diese Resultate über die Masse auch für die ponderabeln materiellen Punkte gilt; denn ein ponderabler materieller Punkt kann durch Zufügen einer *beliebig kleinen* elektrischen Ladung zu einem Elektron (in unserem Sinne) gemacht werden.

Wir bestimmen die kinetische Energie des Elektrons. Bewegt sich ein Elektron vom Koordinatenursprung des Systems K aus mit der Anfangsgeschwindigkeit 0 beständig auf der accomplished it." Indeed, EINSTEIN must share the renown for establishing the special theory of relativity among notable predecessors and contemporaries, particularly with LORENTZ and POINCARÉ. In working out the details and in the further development of the theory, PLANCK and MINKOWSKI also made important contributions.

5.2.4 *The Measurement of Distance and Time*

Next we shall examine briefly the consequences of the relativity principle as clearly enunciated by both POINCARÉ and EINSTEIN.

The universal principle of the theory of special relativity is contained in the following postulate: Physical laws are invariant with respect to the Lorentz transformations if we switch from one inertial system to another arbitrary inertial system. From this, it follows directly that the speed of light (in vacuum) has a constant value independent of the coordinate system.

How this fact inevitably leads to the overthrow of the classical notion of simultaneity is shown clearly in the following thought experiment, advanced by EINSTEIN:

Imagine a train, as shown in Figure 5.20, moving with constant speed past an observer standing by the track. A second observer is located at the precise midpoint of the passing train. At exactly the time at which the observer in the train passes the observer standing by the track, both observers independently note the simultaneous flashes of two light pulses sent from the front and back of the train. What conclusions do the two observers draw with regard to the time at which the light pulses from the front and back of the train were sent? The observer on the train—taking into account that by the measurements taken with his ruler, he is standing in the middle of the train, and also that the velocity of light is independent of the state of motion—can conclude from the fact that the two pulses arrived simultaneously that they must have started at the same time, in other words, that the flashes must have been sent at the same time from the front and back of the train.

The observer standing alongside the track also knows that the speed of light is constant and that light signals require a finite amount of time to traverse a finite distance. From the simultaneity of the arrival of the two signals he concludes that the signal from the back end of the train must have been sent first because when the signals were sent, the back end of the train was farther from him than the front. The light pulse leaving the front of the train and propagating with constant speed can arrive at the same time as the pulse leaving the back of the train only if the former was emitted at a later time. The stationary observer thus concludes that the two flashes must have been sent at different times.

In the theory of relativity, we imagine that at every point in both coordinate systems we place a corresponding clock, which we can compare with the clock of the momentarily coinciding point of the other coordinate system. But we also synchronize the clocks in any given coordinate system so that they will run together. How can we do this? The simplest way is to exploit the constancy of the speed of light and send a light signal from the origin of the coordinate system at time $t = 0$. On receiving the signal, an observer standing at distance r from the coordinate origin sets his clock to time r/c, and assuming identical physical construction, the clocks will now run synchronously. The formulas of the Lorentz transformation are derived from the case in which the clocks in the coordinate systems K and K' are all synchronized with a light pulse that was emitted when the origins of the two coordinate systems coincided.

As we have seen, the most surprising consequence of the Lorentz transformation is that simultaneity is a relative notion. Directly related to this are the contraction

Figure 5.17 *continued*

As his starting point, LORENTZ chooses the negative result of the MICHELSON experiment and emphasizes the ad hoc character of the solutions given thus far by himself and FITZGERALD. He cites the experiment by TROUTON and NOBLE from the previous year (1903) and refers to an opinion expressed by POINCARÉ already in 1900:

> It would be more satisfactory if it were possible to show by means of certain fundamental assumptions and without neglecting terms of one order of magnitude or another, that many electromagnetic actions are entirely independent of the motion of the system. Some years ago, I already sought to frame a theory of this kind. I believe it is now possible to treat the subject with a better result. The only restriction as regards the velocity will be that it be less than that of light.
>
> I shall start from the fundamental equations of the theory of electrons. [pp. 12–13]

As is typical for him, EINSTEIN begins by emphasizing the asymmetry of the MAXWELL equations for the case of moving bodies. It is clear that only the relative motion of a magnet and a conductor determines the observable phenomena, but we still interpret differently what happens when the magnet moves and the conductor is stationary (here there will be an electric field and the current is induced) versus when the magnet is stationary and the conductor moves (there is no electric field but a force will act on the electrons in the conductor and the current will be the same as in the first case). Then EINSTEIN mentions generally—without reference to concrete cases—the unsuccessful experimental efforts to determine the motion of Earth relative to the absolutely stationary "light medium." Then comes the critical insight; the conjecture that there is no distinguished inertial system is raised to the level of an axiom together with a second underlying assumption: The velocity of light is independent of the state of motion of the light source and has the same value for all inertial systems. The article continues in a radically new path: the definition of simultaneity followed by a derivation of the LORENTZ transformation by interpreting what it means to measure time and length.

This is perhaps what excited physicists more than anything else. Even among the leading physicists, there were only a few who were truly comfortable with the electrodynamics of MAXWELL and LORENTZ, and even fewer were capable of recognizing the epoch-making significance of a transformation that leaves the MAXWELL equations invariant. And now, with EINSTEIN, all one had to do was pay careful attention to how clocks are synchronized, and one could not escape the conclusion that all of physics had to be reconsidered. After all, even a high school physics book starts with the discussion of how to measure time, distance, and mass.

The article further discusses the addition theorem of velocities, the transformation rules for electromagnetic field quantities, the DOPPLER effect, the theory of aberration, and the transformation rules for the energy of light rays; this is especially important because the later article on the equivalence of energy and mass continues from this point.

continued on next page

Figure 5.17 *continued*

What is *not* to be found in the article: Even though the dynamics of the electron are discussed, the establishment of the equations of motion had to wait for Planck. Einstein still speaks of longitudinal and transversal mass, like Lorentz. However, the formula

$$m_0 c^2\left[\left(1-v^2/c^2\right)^{-1/2}-1\right]$$

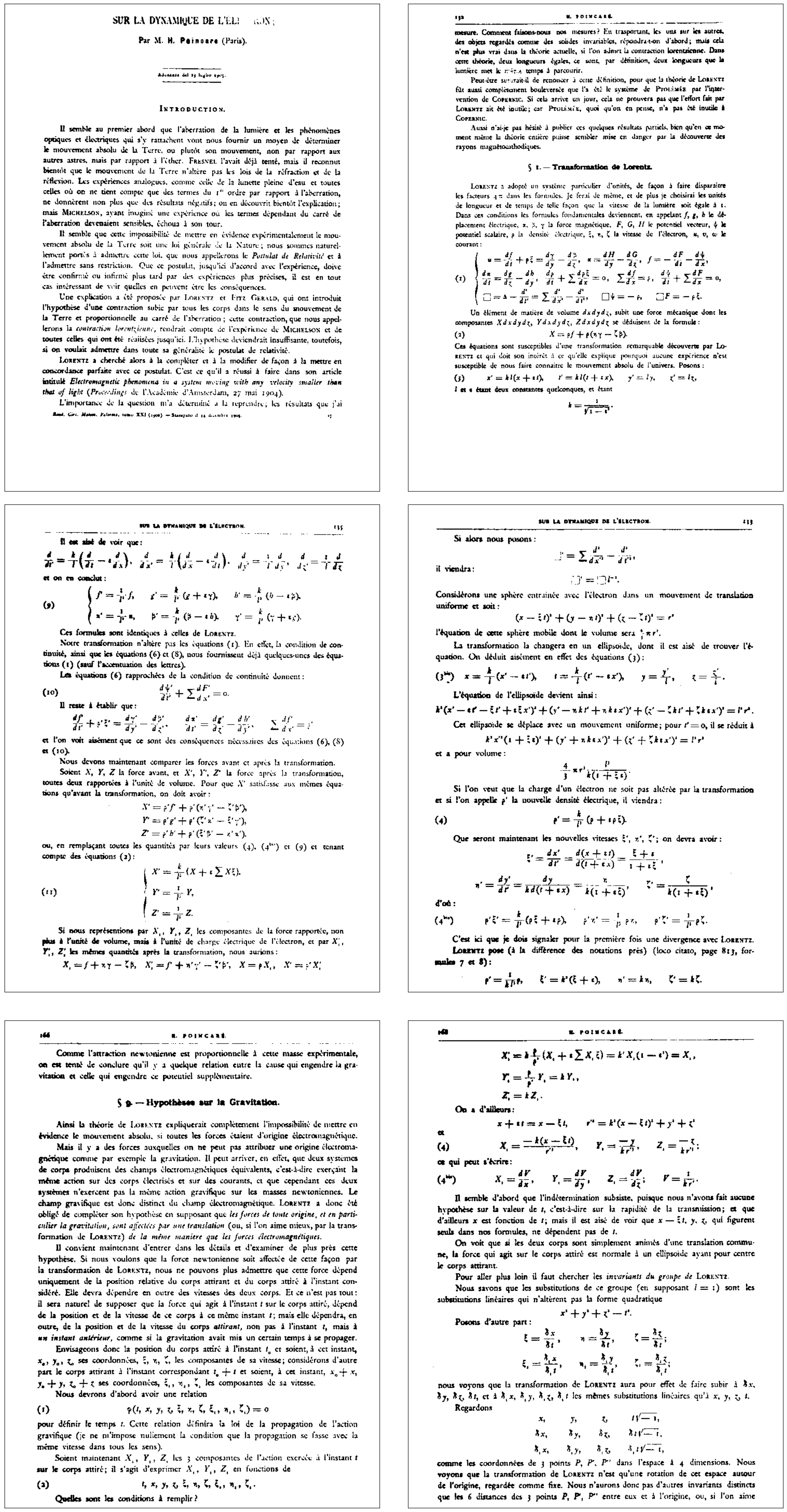
for the kinetic energy is derived here.

The derivation of the formula for the change of mass,

$$m=m_0\left(1-v^2/c^2\right)^{-1/2},$$

on the basis of mechanical considerations, that is, from the example of collision processes—observed in two inertial systems and on the assumption of conservation of energy and momentum, just as it was done by Huygens in the classical case—is the contribution of Lewis and Tolman (1908).

We have mentioned in the main text a characteristic feature of Einstein's article: Not a single name, not a single earlier publication, is mentioned, other than the name M. Besso, a friend and colleague who is thanked for his assistance.



SUR LA DYNAMIQUE DE L'ÉLECTRON;

Par M. H. Poincaré (Paris).

Introduction.

§ 1. — Transformation de Lorentz.

§ 9. — Hypothèses sur la Gravitation.

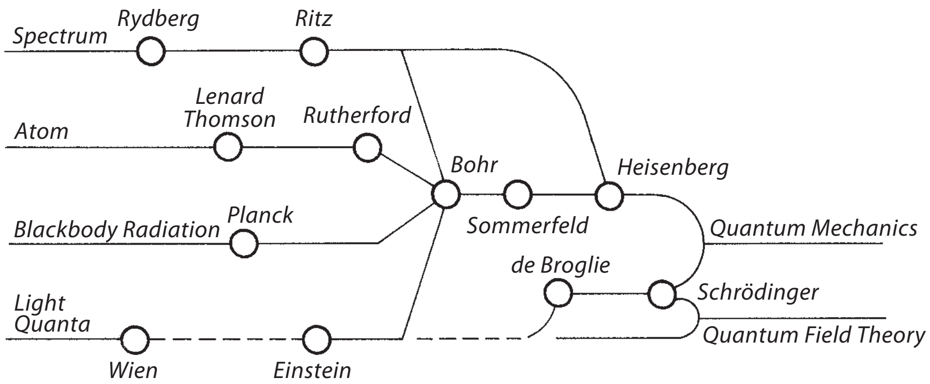
▶ **Figure 5.18** Some facsimile pages from Poincaré's article. It was submitted on July 28, 1905 and appeared in 1906 (*Rendiconti del Circolo Matematico di Palermo* 23, p. 129). In his monograph, Pauli writes:

> The formal gaps left by Lorentz's work were filled by Poincaré. He stated the relativity principle to be generally and rigorously valid. [1981, p. 3]

In addition to results already mentioned in the main text, we would emphasize the following conclusions of the article: The Lorentz transformation can be interpreted as a rotation in four-dimensional space x, y, z, ict; other quadruples of numbers could be formed that obey the same transformation rules as x, y, z, t. This yields a simple method for finding Lorentz-invariant quantities. Ivanenko refers emphatically to a fact that had essentially been forgotten: Poincaré was the first to apply the theory of relativity to the problem of gravitation; it was the first realistic and correct step in the direction of the modification of Newton's law of gravitation. Poincaré recognized the finite speed of the gravitational effect and attempted to find a relativistic correction to Newton's law.

The question is still raised from time to time as to why the discovery of the theory of relativity is ascribed *solely* to Einstein. We have offered some explanations in the main text but here is another: Einstein published in one of the leading journals of physics, while Poincaré, in contrast, wrote for mathematicians, so to speak, in a relatively obscure Italian journal. Poincaré's abstract style and especially the fact that he tended to undervalue his own work may also have played a role:

> The importance of this question induced me to investigate it recently; the results that I obtained agree on all major points with those of Lorentz; only in some isolated questions I feel compelled to modify or supplement them; in the future, their differences will come to light; they are of only secondary significance.



▲ **Figure 5.40** The main steps on the path to understanding the quantum world (after[Hund 1974]).

experiment that would let heat flow from a cooler body to a warmer body, in violation of the second law of thermodynamics.

It is here that the unique significance of blackbodies becomes clear. By a blackbody we mean a body that absorbs all the radiation striking it, and therefore its absorptivity is $a = 1$. Thus, the relationship given above yields

$$\frac{e_1}{a_1} = \frac{e_2}{a_2} = \cdots = \frac{e_{\text{black}}}{1} = e_{\text{black}},$$

which means that the ratio of emissivity to absorptivity of an arbitrary body is equal to the emissivity of a blackbody. From what we have just said, the quotients e/a are *independent of any material constant* of the body under investigation, so this law is a *universal law of nature.* This universal character gives the radiation law for blackbodies its fundamental significance. PLANCK himself was intrigued by this universal character (Quotation 5.20). It was soon recognized that blackbody radiation can be realized in a cavity with metallic walls (of platinum–iridium). If the walls of the enclosure are kept at a fixed temperature, then within the cavity, the radiation reaches a state of equilibrium, which is the blackbody radiation. If now an opening is made so small that the thermal equilibrium is not disturbed, then the radiation emitted through this opening can be taken as equal to the blackbody radiation to a very good approximation (Figure 5.42). A very simple and geometrically clearly understandable relationship exists between the energy density of the radiation in the cavity and the intensity of the radiation emitted from the opening in the wall of the enclosure. They are proportional to each other, and it is easy to see that the constant of proportionality contains the velocity c with which the energy propagates. We therefore have

$$B_v = \frac{c}{4\pi} u_v,$$

where the factor $1/4p$ comes from geometric considerations. In this formula, $u_v = u_v(v, T)$ is the energy within a unit volume of the cavity in a unit frequency range, and $B_v(v, T)$ is the radiant power emitted perpendicularly per unit area of the cavity opening per unit time into a unit solid angle.

The next significant step forward in the understanding of the laws of blackbody radiation came with the Stefan–Boltzmann law. In 1879, while analyzing measurements taken by TYNDALL, STEFAN had the following insight: According to those measurements, a particular test body at a temperature of 1473 K radiated 11.7

Figure 5.39 *continued*

The year 1911 was also a signal year for KAMERLINGH-ONNES, for in that year, he discovered the phenomenon of superconductivity (Plate XXII) in his already world-renowned low-temperature laboratory. Today, we have unjustifiably forgotten such experimental physicists as KNUDSEN (1871–1948) and EMIL WARBURG (1846–1931). KNUDSEN invented the manometer now named for him and investigated gas flow at very low pressures. WARBURG discovered the phenomena of hysteresis in ferromagnetic materials and established the relationship between hysteresis loss and the area of the hysteresis loop. Finally, we have PAUL LANGEVIN (1872–1946), whose contributions to the development of French and even European physics went far beyond his concrete results (properties of ionized gases; relationship between mobility and recombination, the theory of paramagnets). For example, the twin paradox is due to him. His role is comparable to that of PAUL EHRENFEST, who also failed to achieve the kinds of outstanding individual results that might have brought him the greatest international recognition: the Nobel Prize.

Quotation 5.20

My original decision to devote myself to science was a direct result of the discovery which has never ceased to fill me with enthusiasm since my early youth—the comprehension of the far from obvious fact that the laws of human reasoning coincide with the laws governing the sequences of the impressions we receive from the world about us; that, therefore, pure reasoning can enable man to gain an insight into the mechanism of the latter. In this connection, it is of paramount importance that the outside world is something independent from man, something absolute, and the quest for the laws which apply to this absolute appeared to me as the most sublime scientific pursuit of life.

—MAX PLANCK, *Scientific Autobiography*... [p. 13]

Born speaks thus of his work in his Nobel lecture:

> It appeared to me that it was not possible to arrive at a clear interpretation of the Ψ-function by considering bound electrons. I had therefore been at pains, as early as the end of 1925, to extend the matrix method, which obviously covered only oscillatory processes, in such a way as to be applicable to aperiodic processes. I was at that time the guest of the Massachusetts Institute of Technology in the U.S.A., and there I found in Norbert Wiener a distinguished collaborator. In our joint paper we replaced the matrix by the general concept of the operator and, in this way, made possible the description of aperiodic processes. Yet we missed the true approach, which was reserved for Schrödinger; and I immediately took up his method, since it promised to lead to an interpretation of the ψ-function. Once more an idea of Einstein's gave the lead. He had sought to make the duality of particles (light quanta or photons) and waves comprehensible by interpreting the square of the optical wave amplitudes as probability density for the occurrence of photons. This idea could at once be extended to the Ψ-function: Ψ^2 must represent the probability density for electrons (or other particles). To assert this was easy; but how was it to be proved? ...
>
> But the factor that contributed more than these successes to the speedy acceptance of the statistical interpretation of the Ψ-function was a paper by Heisenberg that contained his celebrated uncertainty relationship, through which the revolutionary character of the new conception was first made clear.
>
> —Max Born, "Statistical Interpretation of Quantum Mechanics," Nobel Lecture

Even though the formalisms of Heisenberg's and Schrödinger's theories were so fundamentally different, Schrödinger himself pointed out that they are mathematically equivalent, despite the initial aversion the two scientists had to each other's ideas. Heisenberg's opinion:

> The more I work with the physical parts of the Schrödinger theory, the more disgusting I find it.

Schrödinger, in turn, wrote thus:

> I found the complicated methods of transcendental algebra, which make any visualization impossible, annoying, almost repulsive.

In their philosophical conclusions they differed as well: Schrödinger—like Einstein (Quotations 5.30, 5.31)—did not want to accept the fact that a return to a description of natural phenomena based on causal space-time relations is untenable even as an eventual future hope. However, the majority of physicists accepted the "Copenhagen interpretation" (Figure 5.64) worked out by Heisenberg and Bohr. See also Figures 5.65 through 5.70 for further illustrations of the times and the issues.

5.3.10 *Heisenberg: The Copenhagen Interpretation of Quantum Theory*

> The Copenhagen interpretation of quantum theory starts from a paradox. Any experiment in physics, whether it refers to the phenomena of daily life or to atomic events, is to be described in the terms of classical physics. The concepts of classical physics form the language by which we describe the arrangements of our experiments and state the results. We cannot and should

Quotation 5.29, ***continued***

the number of degrees of freedom of the system, there can be only one single quantum equation for each system. In course of time the configuration point of classical theory describes a definite curve; on the other hand, the configuration point of the material wave fills at any given time the whole of infinite space, including those parts of space where potential energy is greater than the total energy, so that according to the classical theory, kinetic energy would become negative in these parts of space, and the momentum imaginary. ...

From the discrete characteristic energy values, discrete characteristic values of the period of oscillation may be derived. The latter are determined according to the quantum postulate, in a similar manner to that of a stretched cord with fixed ends; with this distinction that the latter quantization is determined by an external condition, viz. the length of the cord, whereas in the present instance it depends upon the quantum of action, which in turn depends directly upon the differential equation.

To each characteristic vibration there corresponds a particular wave function (ψ); this is the solution of the wave equation; and all these different characteristic functions form the component elements for the description of any movement in terms of wave mechanics.

—Planck, *The Universe in the Light of Modern Physics* [pp. 28–30]

Quotation 5.30

The generation to which Einstein, Bohr and I belong, was taught that there exists an objective physical world, which unfolds itself according to immutable laws independent of us; we are watching this process as the audience watches a play in a theatre. Einstein still believes that this should be the relation between the scientific observer and his subject. Quantum mechanics, however, interprets the experience gained in atomic physics in a different way. We may compare the observer of a physical phenomenon not with the audience of a theatrical performance, but with that of a football game where the act of watching, accompanied by applauding or hissing, has a marked influence on the speed and concentration of the players, and thus on what is watched. In fact, a better simile is life itself, where audience and actors are the same persons.

—Born, "Physics and Relativity" [pp. 104–105]

Figure 5.64 The symbol of Copenhagen is the mermaid, a figure from one of Andersen's fairy tales; the physicist, however, associates Copenhagen primarily with Bohr and his school, to which we may also count Heisenberg, Pauli, Dirac, Ehrenfest, Gamow, Landau, Kramers, and Klein. The atmosphere was familiar, but opponents were not spared. Heisenberg reports on a visit by Schrödinger in *Physics and Beyond* [pp. 73–76]:

> [A]lthough Bohr was normally most considerate and friendly in his dealings with people, he now struck me as an almost remorseless fanatic, one who was not prepared to make the least concession or grant that he could ever be mistaken.

On this occasion, Schrödinger offered the following bitter, and frequently quoted, opinion:

> If all this damned quantum jumping were really here to stay, I should be sorry I ever got involved with quantum theory.

Heisenberg recalls that the discussion became more and more violent:

> And so discussions continued day and night. After a few days Schrödinger fell ill, perhaps as a result of his enormous effort; in any case, he was forced to keep to his bed with a feverish cold. While Mrs. Bohr nursed him and brought in tea and cake, Niels Bohr kept sitting on the edge of the bed talking to Schrödinger: "But you must surely admit that…" No real understanding could be expected since, at the time, neither side was able to offer a complete and coherent interpretation of quantum mechanics. For all that, we in Copenhagen felt convinced toward the end of Schrödinger's visit that we were on the right track, though we fully realized how difficult it would be to convince even leading physicists that they must abandon all attempts to construct perceptual models of atomic processes.

Some significant elements of the Copenhagen interpretation may have come from Bohr's upbringing. Jammer (1974) in his analysis of Bohr's philosophical background highlights Kierkegaard, whose student Høffding was a university colleague of Bohr's father. According to Kierkegaard, the creator of a philosophical system is himself a part of that system that he wishes to explain:

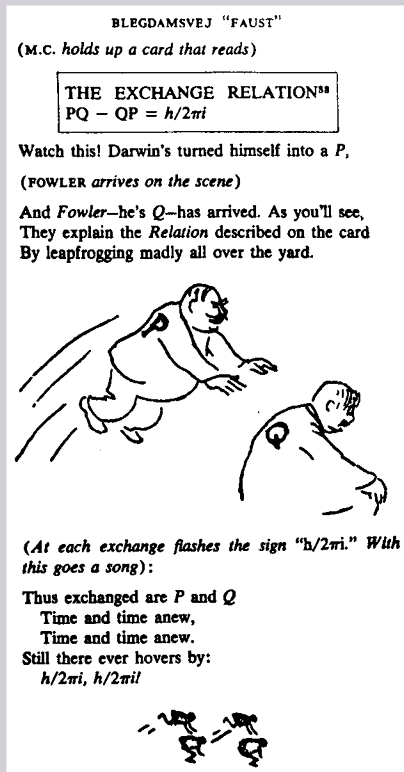
> One cannot view oneself, without self-deception, as an indifferent onlooker or impersonal observer; one is necessarily always a participant. The determination of the boundary between the objective and the subjective is an arbitrary act, and human life consists in a series of decisions. Science is nothing other than a well-determined action; and truth: a work of man, and indeed, not only because it is man who created knowledge, but because the significant object of knowledge is not something that has been standing complete since the beginning of time.

The psychology of William James also emphasizes the arbitrariness in demarcation and the uncontrollable influence of observation on the observed phenomenon. Finally, the philosophers of the Viennese School, who were greatly influenced by Mach, had similar ideas ("an assertion makes sense only if it can be empirically verified"). The motto of Wittgenstein, who came from this circle, was this: "Whereof one cannot speak thereof one must be silent."

with high accuracy we cannot know the other with high accuracy; still we must know both for determining the behavior of the system. The space-time distribution of the atomic events is complementary to their deterministic description. The probability function obeys an equation of motion as the co-ordinates did in Newtonian mechanics; its change in the course of time is completely determined by the quantum mechanical equation, but it does not allow a description in space and time. The observation, on the other hand, enforces the description in space and time but breaks the determined continuity of the probability function by changing our knowledge of the system. ...

*

A real difficulty in the understanding of this interpretation arises, however, when one asks the famous question: But what happens "really" in an atomic event? It has been said before that the mechanism and the results of an observation can always be stated in terms of the classical concepts. But what one deduces from an observation is a probability function, a mathematical expression that combines statements about possibilities or tendencies with statements about our knowledge of facts. So we cannot completely objectify the result of an observation, we cannot describe what "happens" between this observation and the next. This looks as if we had introduced an element of subjectivism into the theory, as if we meant to say: what happens depends



BLEGDAMSVEJ "FAUST"

(M.C. *holds up a card that reads*)

THE EXCHANGE RELATION[38]
$PQ - QP = h/2\pi i$

Watch this! Darwin's turned himself into a *P*,

(FOWLER *arrives on the scene*)

And *Fowler*—he's *Q*—has arrived. As you'll see,
They explain the *Relation* described on the card
By leapfrogging madly all over the yard.

(*At each exchange flashes the sign* "$h/2\pi i$." *With this goes a song*):

Thus exchanged are *P* and *Q*
Time and time anew,
Time and time anew.
Still there ever hovers by:
$h/2\pi i$, $h/2\pi i$!

Figure 5.65 The collaborators in Bohr's school could not free themselves of science even in their amusements. We show here a facsimile page of a parody of Faust in which the distribution of roles is telling: Faust is Paul Ehrenfest; Mephisto, Wolfgang Pauli; and God, Niels Bohr.

Paul Ehrenfest (1880–1933): Student of Boltzmann in Vienna; 1912: successor to Lorentz in the chair of theoretical physics in Leyden. The adiabatic principle established by him in 1913 and worked out in detail in subsequent years bears his name. Ehrenfest showed in 1927 that the equations of motion of classical mechanics follow from wave mechanics as a limiting case. With his critical and pedagogically valuable contributions to discussions, he contributed to the development of physics far beyond his concrete results. This contradiction between his important position and his creative capacity may have contributed to his depression and suicide.

continued on next page

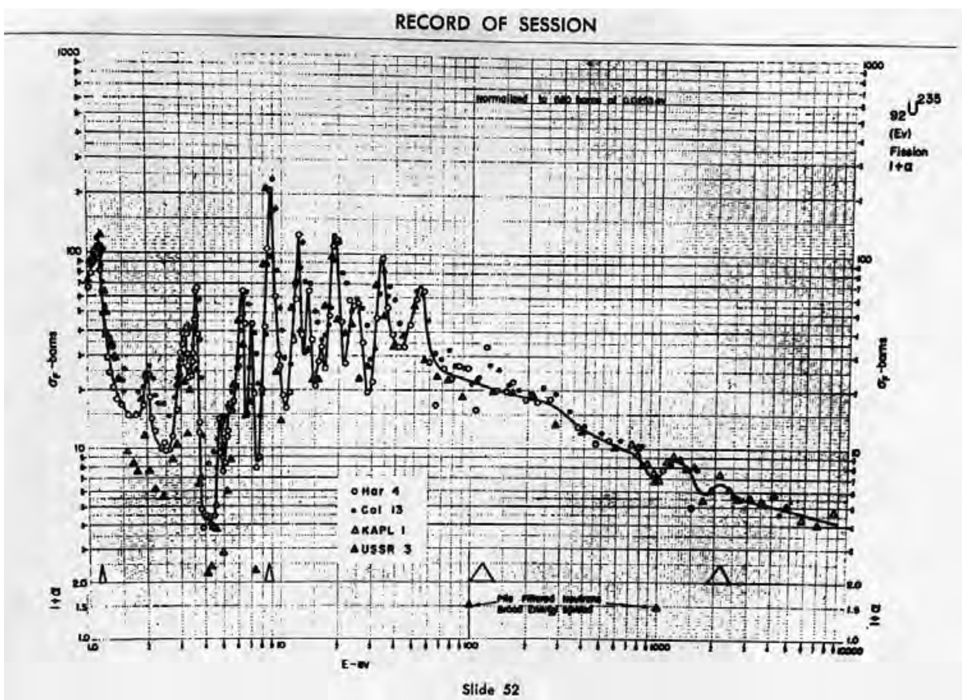
The liquid drop model had its greatest success in the interpretation of nuclear fission. But more about that later.

Because both the independent-particle model—the shell model—and the liquid drop model were able to correctly describe some of the observed phenomena but completely failed in other cases, there was understandably a drive to create a unified model combining the advantages of both. This problem was solved in 1952 by Bohr and Mottelson with their collective model. We must add here that it is Aage Bohr, Niels Bohr's son, to whom we are referring. In the history of physics, five families have produced more than one Nobel Laureate: Marie and Pierre Curie, as well as their daughter and son-in-law; father and son Bragg; the two Bohrs, father and son; the two Thomsons, also father and son; and finally, the Siegbahns, father and son.

Among nuclear models, we must also mention the optical model, offered in 1954 by Feshbach, Porter, and Weisskopf, which is designed primarily for quantitative descriptions of nuclear reactions. Also called the crystal ball model, it likens the nucleus to a sphere composed of a material with a determined index of refraction, but this index also has an imaginary part, so the sphere not only scatters the incident waves, but absorbs them as well. This absorption corresponds to the capture of particles.

5.4.10 *Nuclear Fission: Experimental Evidence, Theoretical Doubt*

The most significant discovery of the 1930s—nuclear fission—merits a separate discussion. Here we are again witnessing a curious turn of events occasioned by the splitting of a heavy atomic nucleus. This was such an unexpected phenomenon that after its discovery, it became clear only in hindsight that it had already been observed five years earlier, but had been given a completely different interpretation. We saw something similar in the discovery of the neutron, but while Chadwick, a member of Rutherford's school, was chomping at the bit, so to speak, to meet the theoretically predicted particle in experimental reality, in the case of fission researchers practically had to be forced into recognizing the reality of the phenomenon by the persuasive power of experiments that excluded the possibility of any other inter-



(a) $_1H^1 + {}_3Li^7 = {}_2He^4 + {}_2He^4 + 17.5\ \text{MeV}$

(b) $N^{14} + n = C^{14} + p$

$C^{14} \rightarrow N^{14} + e^- + 0.156\ \text{MeV}$

(c) $_2He^4 + {}_{13}Al^{27} = {}_{15}P^{30} + {}_0n^1$

$_{15}P^{30} \rightarrow {}_{14}Si^{30} + e^+$

(d) $_{10}Ne^{22} + {}_{94}Pu^{242} = {}_{103}Lr^{260} + {}_1H^1 + 3\,{}_0n^1$

▲ **Figure 5.115** **(a)** The first nuclear reaction that was accomplished with artificially accelerated particles (Cockcroft and Walton, 1932).

(b) Due to cosmic radiation, some nitrogen atoms in the air are transformed into radioactive carbon, which decays with a half-life of 5730 ± 40 years. The activity of radioactive carbon incorporated into plant life, and thereafter into animals, decays after the death of the organisms according to the law of exponential decay. By comparing the amount of radioactive carbon left with what is in the atmosphere, one can determine the approximate date of the organism's death (Willard Frank Libby [1908–1980], radiocarbon dating, 1948).

(c) A current physics problem: Up to what atomic number can transuranic elements be created? In laboratories under the directorship of G. Seaborg and A. Ghiorso, and of G. N. Flyorov, the number 106 was achieved at the beginning of the 1970s.

Some transuranic elements can be found in nature. Plutonium-244, the one with the longest half-life ($T_{1/2} = 8 \times 10^7$ years), occurs in trace amounts in minerals. Neptunium-237 ($T_{1/2} = 2.14 \times 10^6$ years) and plutonium-239 ($T_{1/2} = 2.4 \times 10^4$ years) can be found in uranium ore.

Through neutron-capture reactions one can get as far as fermium ($Z = 100$); by bombarding heavy elements with light or medium-heavy ions, it has been possible to create super-heavy atoms well above atomic number $Z = 115$, but these are very short lived due to spontaneous alpha decay and spontaneous fission. Theoretically, there is still a possibility that an island of increased stability will be found in the neighborhood of certain higher "magic" numbers.

▶ **Figure 5.116** A historic document: The fission cross section of the U-235 nucleus as a function of the energy of the bombarding neutrons. The figure plots the values that were measured independently in three countries: USSR, Great Britain (labeled Har in the figure), and the USA (labeled Col and KAPL). These results were top secret until 1955 because knowledge of this information is essential for designing atomic bombs as well as for nuclear power plants [United Nations 1955, p. 285].

The cross section of a reaction is defined in a way that represents the measurement method: From the incident beam, N particles per second fall on a unit area of the target material of density n atoms per cm^3. While passing through the distance dx, the beam encounters 1·n dx target atoms. Due to nuclear (or other) reactions, the intensity of the beam will decrease. The value of this decrease is −dN =

continued on next page

pretation. Even then they yielded to the evidence only reluctantly. However, Bohr senior, upon hearing of nuclear fission, slapped his forehead and exclaimed, "Oh, what idiots we all have been! Oh, but this is wonderful! This is just as it must be!"

After the discovery of the neutron, a worldwide search for nuclear reactions triggered by neutrons began. Fermi's laboratory in Rome quickly acquired a strong international reputation in the field (Figure 5.121). The other major center of neutron physics research during these years was in Paris, where Joliot-Curie's group was working. By bombarding heavy atomic nuclei, especially uranium, the heaviest nucleus occurring in nature, they expected to get interesting results, specifically the creation of new elements that do not appear in nature, the so-called transuranium elements. Adding a neutron to a uranium nucleus would produce a nucleus with an extra neutron, and one could expect the nucleus to free itself of the redundant neutron via beta decay. But beta decay creates an additional proton, which entails the shifting of the element one place to the right in the periodic table, and so from the element with atomic number 92 (uranium), one would end up with an element with atomic number 93. In 1934, Fermi reported that he had been able to produce an element with atomic number greater than 92. Although he formulated his claim very cautiously, the Italian press jumped in to report that Fermi had presented the queen with a bottle full of this new material created by man. The news was coolly received by the scientific community. In the very same year, 1934, a German chemist, Ida Noddack, sharply attacked Fermi's paper with the argument that Fermi had failed to investigate the associated radioactivity thoroughly and had ignored a whole host of other factors as well. For us, however, this is not the important part. The interesting lines in Noddack's article are the following—and let us bear in mind that we are in the year 1934:

> One may just as well assume that in this new form of nuclear fission by neutrons, considerably more additional "nuclear reactions" take place than have thus far been observed from the action of proton and α rays on nuclei. With the latter type of rays one finds only nuclear transformations giving off electrons, protons, and helium nuclei, which in the case of heavy elements changes the mass of the bombarded nucleus only a little, since the elements that arise are close neighbors. It is conceivable that in bombarding heavy nuclei with neutrons, these nuclei would break up into several *larger* pieces, which would be isotopes of known elements but not neighbors of the bombarded elements.
>
> —Ida Noddack, "Über das Element 93" (On the Element 93) [p. 654]

Here for the first time we encounter the idea of nuclear fission, and it is perhaps not an accident that this idea was broached by a chemist and not by a physicist. We met an analogous phenomenon in our discussion of naturally occurring radioactivity, except that there the possibility of the transmutation of an element was considered first by a physicist rather than by a chemist.

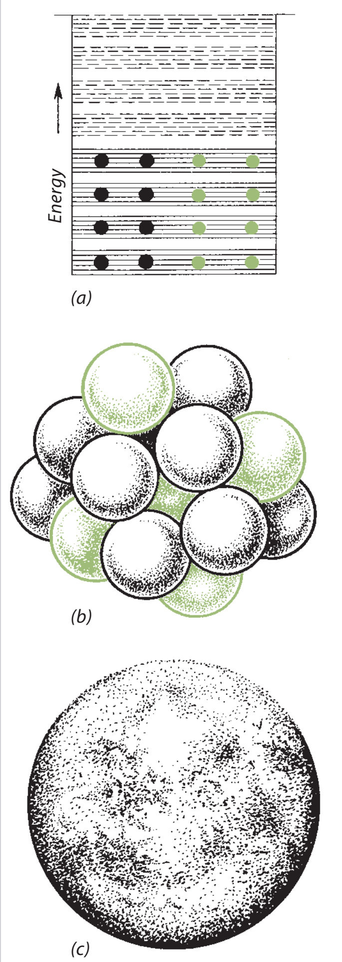
A correct interpretation of new observations requires both genius and scientific knowledge, but scientific knowledge can also be a shackle that someone working in a neighboring discipline might be able to discard. In the case of nuclear fission, it was the chemists who were in such a favored position. The physicists already had very definite ideas—perhaps not in detail, but in a qualitative form—regarding the processes of nuclear reactions. To a physicist it seemed completely impossible that a particle with a charge greater than that of a helium nucleus could be ejected from an atom via the tunnel effect. Therefore, it is understandable that Noddack's ideas had absolutely no influence among physicists.

Figure 5.116 *continued*

$N\sigma n$ dx, where the constant of proportionality σ is the cross section of a single target atom with respect to the given reaction (or the net total of other interactions). We can interpret this equation as meaning that each target atom appears as an area σ for each incident particle. Every 1 cm^2 of the incident beam, sees the "effective" target area (n dx)σ, and this is also the probability that one beam particle will react with one target atom in the volume (1·dx). Therefore, the total number of reactions will be N (n·1·dx)σ. The unit of the cross section: 1 barn = 10^{-24} cm^2.

$$
\begin{aligned}
&{}_1H^1 + {}_3Li^7 \\
&\quad = 1.007825 + 7.016005 \\
&\quad = {}_2He^4 + {}_2He^4 + 17.5\ \text{MeV} \\
&\quad = 4.002604 + 4.002604 + 0.018622
\end{aligned}
$$

▲ **Figure 5.117** Energy balance of a nuclear transformation.



◀ **Figure 5.118** Models of the nucleus. **(a)** Simple shell model. **(b)** Liquid drop model. **(c)** Optical model (after Peierls).

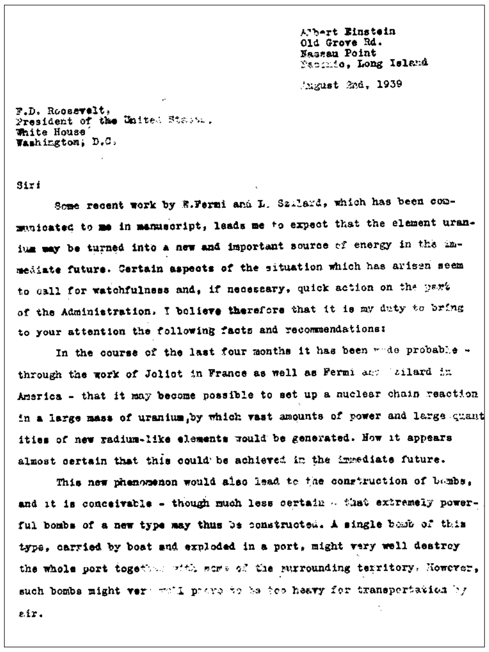
of energy from the system. That it is indeed possible to release energy in huge quantities is evidenced by the existence of the hydrogen bomb, in which fusion reactions take place when the bomb is set off. The controlled release of fusion energy has yet to be realized, but if success were ever achieved in this area, mankind would be liberated from all the oppressive shortages of energy now being faced (Figure 5.133).

5.4.13 *The Responsibility of Physicists*

The fact that from a practical viewpoint most significant discoveries of the twentieth century have been primarily put in the service of mass destruction raises the question of the responsibilities of science, especially physics, or more to the point, of physicists. Countless articles, studies, books, novels, poems, plays, and films have been devoted to this topic (Quotations 5.44, 5.45). We would merely like to observe that a physicist is a member of human society just like any other human being, with neither greater nor lesser responsibilities. Most people do their work with dedication and joy, especially in case of creative work, and frequently give no thought at all to future consequences. It is well worth reading the recollections of Weisskopf about the years in which the atomic bomb was being built (Quotation 5.46).

We can see that physicists were willing and will most likely continue to be willing to make themselves useful to governments for the fabrication of ever more destructive weapons (Figure 5.134, Figure 2.69), while in peacetime participating in peace conferences.

Anyone interested in studying the attitude of physicists regarding the societal consequences of their scientific discoveries should be aware of the fact that the first



Albert Einstein
Old Grove Rd.
Nassau Point
Peconic, Long Island

August 2nd, 1939

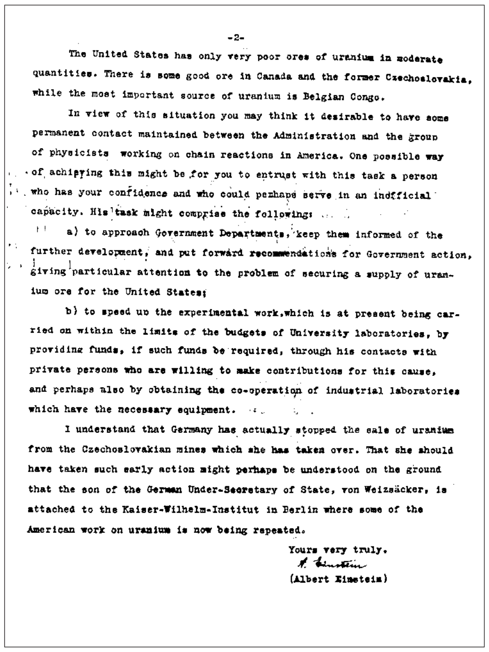
F.D. Roosevelt,
President of the United States,
White House
Washington, D.C.

Sir:

Some recent work by E.Fermi and L. Szilard, which has been communicated to me in manuscript, leads me to expect that the element uranium may be turned into a new and important source of energy in the immediate future. Certain aspects of the situation which has arisen seem to call for watchfulness and, if necessary, quick action on the part of the Administration. I believe therefore that it is my duty to bring to your attention the following facts and recommendations:

In the course of the last four months it has been made probable - through the work of Joliot in France as well as Fermi and Szilard in America - that it may become possible to set up a nuclear chain reaction in a large mass of uranium, by which vast amounts of power and large quantities of new radium-like elements would be generated. Now it appears almost certain that this could be achieved in the immediate future.

This new phenomenon would also lead to the construction of bombs, and it is conceivable - though much less certain - that extremely powerful bombs of a new type may thus be constructed. A single bomb of this type, carried by boat and exploded in a port, might very well destroy the whole port together with some of the surrounding territory. However, such bombs might very well prove to be too heavy for transportation by air.



-2-

The United States has only very poor ores of uranium in moderate quantities. There is some good ore in Canada and the former Czechoslovakia, while the most important source of uranium is Belgian Congo.

In view of this situation you may think it desirable to have some permanent contact maintained between the Administration and the group of physicists working on chain reactions in America. One possible way of achieving this might be for you to entrust with this task a person who has your confidence and who could perhaps serve in an inofficial capacity. His task might comprise the following:

a) to approach Government Departments, keep them informed of the further development, and put forward recommendations for Government action, giving particular attention to the problem of securing a supply of uranium ore for the United States;

b) to speed up the experimental work, which is at present being carried on within the limits of the budgets of University laboratories, by providing funds, if such funds be required, through his contacts with private persons who are willing to make contributions for this cause, and perhaps also by obtaining the co-operation of industrial laboratories which have the necessary equipment.

I understand that Germany has actually stopped the sale of uranium from the Czechoslovakian mines which she has taken over. That she should have taken such early action might perhaps be understood on the ground that the son of the German Under-Secretary of State, von Weizsäcker, is attached to the Kaiser-Wilhelm-Institut in Berlin where some of the American work on uranium is now being repeated.

Yours very truly.
A. Einstein
(Albert Einstein)

Figure 5.134 Einstein's letter to F. D. Roosevelt, president of the United States, in which he called the president's attention to the possibility of the creation of an atomic bomb. (See also Figure 2.69.)

My action concerning the atomic bomb and Roosevelt consisted merely in the fact that, because of the danger that Hitler might be the first to have the bomb, I signed a letter to the President which had been drafted by Szilard. Had I known that that fear was not justified, I, no more than Szilard, would not have participated in opening this Pandora's box. For my distrust of governments was not limited to Germany. Unfortunately, I had no share in the warning made against using the bomb against Japan. Credit for this must go to James Franck. If they had only listened to him!

—Einstein, Letter to Laue, March 19, 1955 [Schweber 2008, p.61]

Quotation 5.46

It is very difficult to describe—let alone to judge—one's feelings and one's decisions after 30 years. There are many now who say that a physicist should devote his time to the search for truth and should not devote his abilities to produce weapons of destruction. It is easy to say, and it may even be right. There were very few who actually followed it. Pauli had to leave Europe at that time and was in Princeton and he never even thought of joining any of these war projects. But for a man in my position, and for so many others, not to join would have been a very difficult path to follow. I cannot tell you why I went to Los Alamos. The fear that Hitler would make the bomb had much to do with it. If someone suggests I went just because everybody else did, he may be right. The significance of physics is a very difficult thing to describe. Physics is not only the search for truth, it is also potential power over nature; the two aspects cannot be separated. One may say that a physicist should search only for truth and should leave the power over nature to somebody else; but this attitude actually skirts the subject and does not look at reality. The important point about physics—and most of science—is not only that it represents natural philosophy but that it also is deeply involved in action—in life, in death, in tragedy, in abuse, in the human predicament. Whether this is good or bad, who is to judge? Both sides can be argued. Some terrible things have happened since man made use of fission. However, the first bomb may have ended the war. At least, that is what we thought; we thought we had saved a million live; maybe we were right the second bomb was much harder to defend. We did participate in all that and I don't want to condemn or to justify it.

I cannot deny that those four years in Los Alamos were a great experience, from a human as well as from a scientific point of view, in spite of the fact that they were devoted to the development of the most murderous device ever created by man. Such are the contradictions of life. From the human point of view, to live together, intellectually and otherwise, with the best physicists from the whole world (such as Niels Bohr, Enrico Fermi, J. Chadwick, R. Peierls, E. Segrè, and many more) was quite an experience. The discussions we had on philosophy, art, politics, physics, and on the future world under the shadow of a super-weapon remain unforgettable. But also from the purely professional level, we had to face tasks that never were faced before. It was a remarkable experience to deal with matter under unusual conditions. We attempted to predict the behavior of matter and make experiments about it under conditions that were by factors of thousands

continued on next page

experimentally the violation of mirror symmetry. One could point to the fact that well-known symbols of Western culture such as the cross and five-pointed star are mirror-symmetric, whereas the yin–yang symbol, which is of importance in Chinese culture and, like the European symbols, appears on national flags, does not possess mirror symmetry.

If we assume that *CPT* symmetry is strictly satisfied, then it follows from the violation of *CP* symmetry that there is also a violation of time-reversal symmetry. And indeed, there exist experimental indications that time-reversal symmetry is violated.

The fact that mirror symmetry is not strictly valid does not mean at all that the symmetry principles have lost their significance for particle physics. As was shown in the course of later investigations, using abstract symmetries, which are no longer accessible to intuition and can be described only with the help of group theory (SU_2 and SU_3 symmetries), the elementary particles have been systematized so successfully that with their help, new phenomena have been accurately predicted.

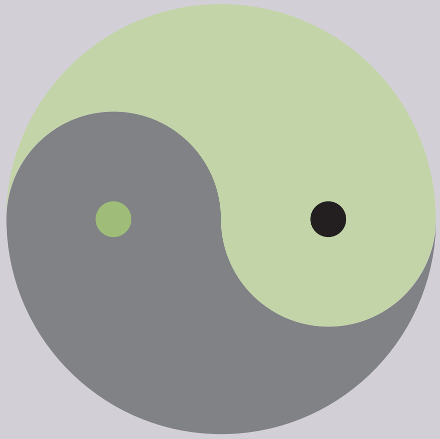
In 1960–1961, Murray Gell-Mann and Yuval Neeman proposed the "eightfold way" model. According to this principle of systemization—the name refers to the teachings of the Buddha—hadrons, mesons, and baryons, whose particles form families with eight members, can be grouped into multiplets: Six particles are located at the vertices of a regular hexagon, and two additional particles are located at the center. Figure 5.167 shows the octet of baryon with half-integer spin: Even the neutron and proton have their places here. The quantum numbers for strangeness (S), charge (Q), hypercharge ($Y = B + S$), and isospin projection (I_3) are identified.

This eightfold way can be enlarged. Figure 5.168 shows an arrangement of 10 hyperons with spin 3/2 and parity +1 (the $3/2^+$ decuplet). Beginning with this arrangement, Gell-Mann and Nishijima predicted the existence of the Ω^- particle. Contrary to the usual depiction, we have pointed the apex of the triangle upward in order to emphasize the similarity of the figure to the "holy" Pythagorean tetractys (Figure 1.35). The subsequent experimental detection of the Ω^- particle strengthened belief in the entire concept.

Following this line of argument, we select the triangle as the basic element of the geometric ordering in our I_3-Y coordinate system and obtain three particles at the vertices (Figure 5.169). The most striking and unexpected—and until the later experimental proof, almost unacceptable—property of these particles is their electric charges: Expressed in units of the elementary charge, they are the fractions ±⅓ and ±⅔.

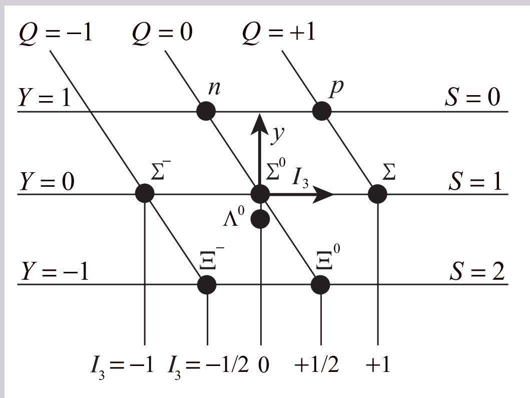
Thus, in 1964 Gell-Mann and George Zweig arrived at—for the time at least—the fundamental building blocks of matter, the quarks. The name was proposed by Gell-Mann and refers—perhaps reflecting slightly his own doubts—to a sentence in James Joyce's novel *Finnegans Wake*. Every now and then, a drunken innkeeper calls to the bartender, "Three quarks for Muster Mark."

Figure 5.170 shows how the most important elementary particles are constructed from quarks based on this hypothesis. At first glance, we are astonished at the classical simplicity and clarity of the model. An engineer could practically call the workshop with a work order: Build a neutron from quarks that are forged, milled, and welded together. Boltzmann and Lord Kelvin would have been pleased to finally understand the underlying principle of all things, because a mechanical model seems to be at hand. But all of that is just appearance. If we wish to compare this figure with anything at all, then we should not compare it with the mechanical



▲ **Figure 5.166** An important symbol in the Orient, the yin–yang symbol, is not mirror-symmetric, and perhaps it is therefore not completely by chance that the violation of mirror symmetry was discovered by Chinese scientists. In the guest book of the Department of Atomic Physics at the University of Budapest, we find Heisenberg quoting Plato, while Tung-Dao Lee, in contrast, wrote the following few lines of a poem by Lao Tzu (sixth century BCE):

> The Tao that can be told
> is not the universal Tao.
> The name that can be named
> is not the universal name.
>
> In the infancy of the universe
> there were no names.
> Naming fragments the mysteries of life
> into ten thousand things
> and their manifestations.
>
> —Lao Tzu, *The Tao Te Ching*



▲ **Figure 5.167** With the help of the SU-3 symmetry, the elementary particles can be organized into "multiplets." The figure shows the octet of baryons with half-integer spin.

models of Boltzmann and Kelvin or even of Maxwell; instead, we need to go back two thousand years, for this figure is much more reminiscent of the Platonic ideals (Quotation 5.53).

5.5.10 *Back to the Apeiron?*

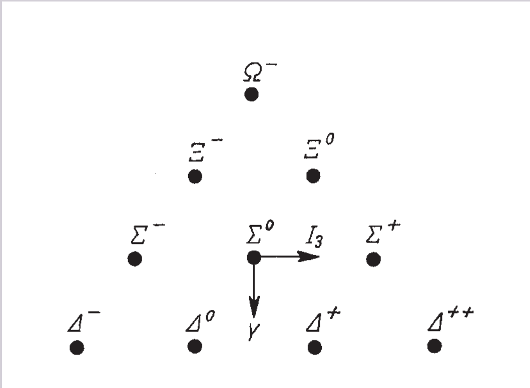
In the foregoing we have followed the attempts within particle physics to answer questions of the form: “What is something composed of?” The method used in the search had proved itself very successful in the investigation into the structure of the atom and the atomic nucleus: One transfers energy to the entity that is thought to be complex, and with that, it is broken up into its components. To separate the parts of the atomic shell, it sufficed to bombard the atom with electrons or protons having an energy of a few electron volts. In the case of the nucleus, the projectile had to have several million electron volts of energy in order to break off from the nucleus one or more nuclear building blocks, the nucleons. For the investigation of elementary particles, literally gigantic energies are required because only with energies in the giga-electron-volt range can one expect new results. But is this method really the right one? Will it actually answer the question that was posed? Heisenberg’s reply was a resounding no:

> If we speak of protons, pions, hyperons, and so on as consisting of smaller, as yet unobserved, particles, of quarks, partons, then we are forgetting that the sentence “they consist of…” has an acceptably clear sense only if we succeed in decomposing these protons and so on into parts with a small expenditure of energy, where the rest masses of the particles thus arising are much greater than the expended energy.

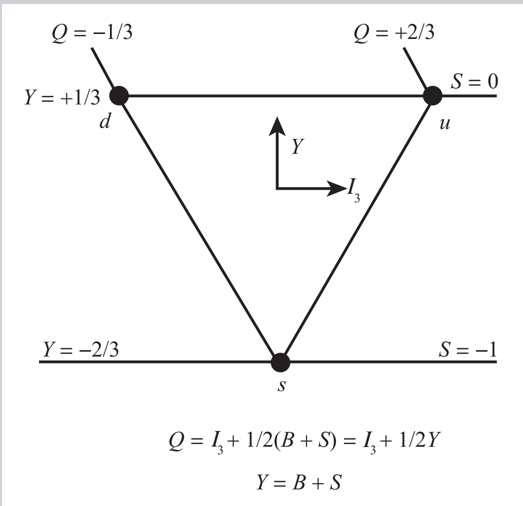
Heisenberg thus arrived at the idea that the elementary particles are to be seen as different manifestations, different quantum states, of one and the same “primordial substance.” The elementary particles, it would follow, are the only possible manifestations of matter. Because of its similarity to the primordial substance hypothesized by Anaximander, Born called this substance *apeiron*.

The various elementary particles come into existence under the influence of the primordial substance on itself. It is because of this self-interaction that a fundamental equation of Heisenberg proposed that unified field theory has to be nonlinear. From the solution to this equation, the properties of the elementary particles, including their masses, should follow, and the theory should also provide an answer to the question of why it is precisely these particles with these properties that exist.

> The final equation of motion for matter will probably be some quantized nonlinear wave equation for a wave field of operators that simply represents matter, not any specified kind of waves or particles. This wave equation will probably be equivalent to rather complicated sets of integral equations, which have “eigenvalues” and “eigensolutions,” as physicists call it. These eigensolutions will finally represent the elementary particles; they are the mathematical forms which shall replace the regular solids of the Pythagoreans. We might mention here that these “eigensolutions” will follow from the fundamental equation for matter by much the same mathematical process by which the harmonic vibrations of the Pythagorean string follow from the differential equation of the string. But, as has been said, these problems are not yet solved.
>
> If we follow the Pythagorean line of thought we may hope that the fundamental law of motion will turn out as a mathematically simple law, even if



▲ **Figure 5.168** The $(3/2)^+$ decuplet (spin 3/2, parity +1). This arrangement led to the prediction of the Ω^- hyperon. One hundred years earlier they would have said that a hole in the periodic table would have to be filled.



▲ **Figure 5.169** If we place a triangle, the basic element of the hexagon of the octet in Figure 5.167, in our coordinate system (I_3, Y), we represent the basic elements of physical matter: the three quarks, *u* (up), *d* (down), and *s* (strange); their quantum numbers are listed in Figure 5.170. The antiquarks could also be found in an upward pointing triangle.

Quotation 5.53

I too play with symbols, and have planned a little work, *Geometric Cabala*, which is about the Ideas of natural things in geometry; but I play in such a way that I do not forget that I am playing. For nothing is proved by symbols, nothing hidden is discovered in natural philosophy through geometric symbols; things already known are merely fitted [to them]; unless by sure reasons it can be demonstrated that they are not merely symbolic but are descriptions of the ways in which the two things are connected and of the causes of this connection.

—Kepler, Letter to Joachim Tanckius, 1608 [Vickers 1984, p. 155]

continued on next page

its evaluation with respect to the eigenstates may be very complicated. It is difficult to give any good argument for this hope for simplicity—except the fact that it has hitherto always been possible to write the fundamental equations in physics in simple mathematical forms. This fact fits in with the Pythagorean religion, and many physicists share their belief in this respect, but no convincing argument has yet been given to show that it must be so.

—Heisenberg, *Physics and Philosophy* [pp. 72–73]

To give the reader a taste of what such a universal equation looks like, we write it down explicitly, although without attempting an explanation:

$$\gamma_\nu \frac{\partial \Psi}{\partial x_\nu} \pm l^2 \gamma_\mu \gamma_s \Psi \left(\Psi^* \gamma_\mu \gamma_s \Psi \right) = 0.$$

After very promising initial successes, Heisenberg was unable during the remainder of his life to set this theory on a sufficiently firm foundation so that it could displace the theories that rely on the structural model.

Among the "thought structures" of our mind, the theory of relativity called into question the a priori existence of space and time; quantum mechanics brought new problems to the idea of causality; and finally, particle physics shed a new light on the category of substance. We are not going to explore, even superficially, the philosophical arguments surrounding the category of substance—that is, the idea of matter—as we did with causality. Here also, we find the anthropomorphic beginnings as well as the thesis and antithesis of Hume and Kant (Quotations 5.54, 5.55, 5.56). We note here only that the primordial substance with its various manifestations—the elementary particles representable by symmetry groups—can be compared with the matter of Aristotelian physics. We refer again to Weyl:

Aristotelian philosophy considers matter as the determinable, in contrast to the determining form. Matter is [the] possibility of becoming formed. In a production process of several stages its matter appears "more formed" at each step, and thereby the range of possibilities for further forming becomes more restricted. And at the same time matter, the component of merely potential rather than actual being, shrinks more and more. Substantiality is ascribed to the forms rather than to matter. The forms push matter from potentiality to actuality ....

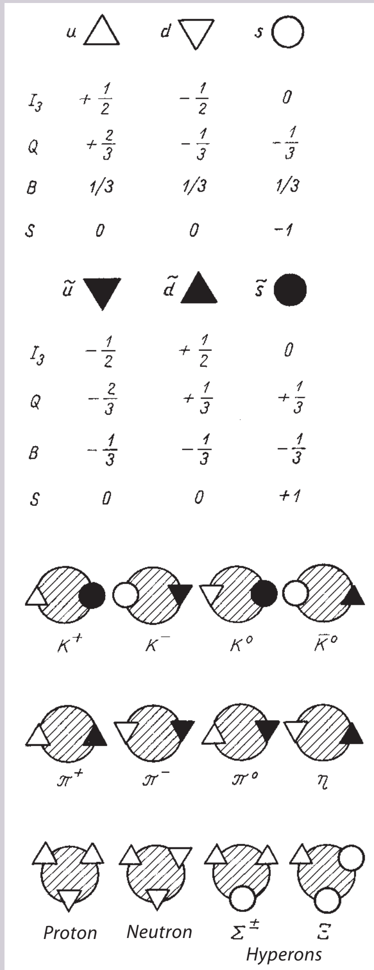
—Hermann Weyl, *Philosophy of Mathematics and Natural Science* [p. 178]

Even if we do not view the primordial substance as a "possibility," that is, "brought to life" only through form, the permanent matter structures that we perceive within the manifold diversity of the real world are secured—or more modestly and precisely put, described—by the form-giving laws of quantum mechanics. So, for instance, in measurement practices of sufficiently high precision, we exploit the fact that all atoms of an element are identical. Moreover, even after they are destroyed, they can be identically reproduced. As we see in Quotation 5.57, Newton thinks that this is possible only because the smallest building blocks of matter are "indestructible." In the end, these building blocks are an embodiment of the classical notion of substances, the invariable carriers of particular properties, the *accidentia*. But what makes it possible that, after the interaction of two systems, the original state can be recovered? Just imagine how different the situation would be if, say, two solar systems collided. Following Weisskopf, we can emphasize

Quotation 5.53, ***continued***

I am convinced that we can discover by means of purely mathematical construction the concepts and the laws connecting them with each other, which furnish the key to understanding of natural phenomena. Experience may suggest the appropriate mathematical concepts, but they most certainly cannot be deduced from it. Experience remains, of course the sole criterion of the physical utility of a mathematical construction. But the creative principle resides in mathematics. In a certain sense, therefore, I hold it true that pure thought can grasp reality, as the ancients dreamed.

—Einstein. *Ideas and Opinions*, 1954

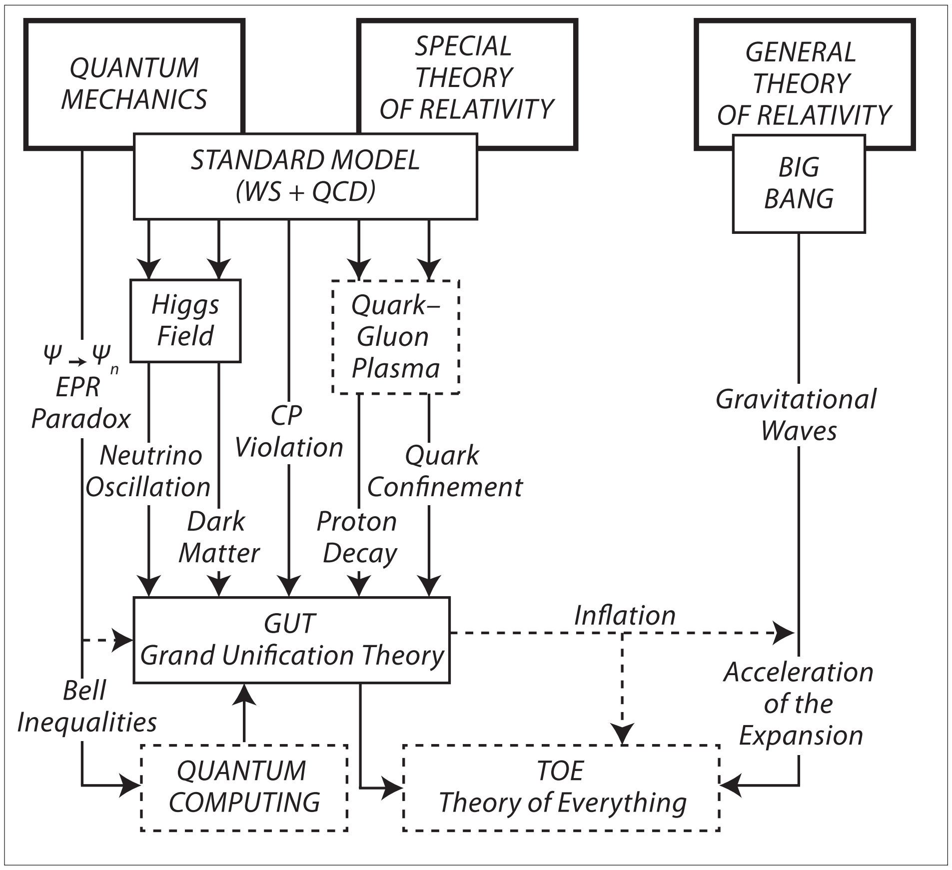


◀ **Figure 5.170** Top: Quantum numbers of the three quarks, *u* (up), *d* (down), and *s* (strange), and the three antiquarks. Bottom: the quark models of some elementary particles (Gell-Mann and George Zweig, 1964).

Quotation 5.54

And since I conceive that other beings can also have the right to say "I", or that it can be said for them, it is through this that I conceive what is called substance in general.

—Leibniz, Letter to Queen Sophie Charlotte [p. 188]



◀ **Figure 5.198** If we compare this diagram with Figure 5.1, we do not find here any clashing arrows that would indicate known contradictions (in color in Figure 5.1). The Standard Model is unable to give answers to a number of important questions but its assertions are not in contradiction of any experimental facts. (Diagram is in part after G. Vesztergombi.)

A summary of this sort presents even greater difficulties at the turn of this millennium than at the turn of the previous century. In preparing the earlier figure, we had knowledge of all the new disciplines that would be established over the century ahead. Thus we could define the questions to be answered and problems to be solved. In the leading journals, such as *Annalen der Physik* and *Physical Review*, hundreds of articles have been published in which new and newer problems are continually solved that in turn, however, raise a new set of problems. It is easy to decide what the relevant problems were after the fact, the answers to which led to the establishment of relativity theory and quantum mechanics. However, we don't know for certain—we only suspect or fantasize—about the syntheses to take place in the coming century; we can therefore not maintain that the solution of the selected questions in fact represents the correct path to the establishment of newer fundamental laws.

The twentieth century consigns to the current a fundamental problem that it struggled over for decades: the measurement process itself and the evaluation of results or, formulated quite generally, the "interface" between mankind and nature.

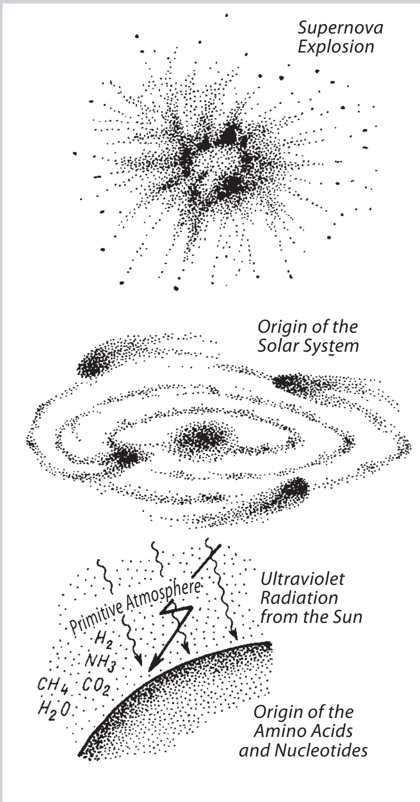
with reality, can nonetheless be used to deal adequately with problems relating to the big bang. By this we mean that they hope to arrive at statements that in fact refer to the real world and are thereby verifiable through experiment.

It is not at all surprising that abstract concepts and theories cannot be expressed in colloquial language. It is much more surprising that one can speak of such things at all (see Bohr's thoughts in this direction, Quotation 0.9 and Figure 5.197).

We need only recall that the conceptual system of Maxwell's theory, the electromagnetic field, made very great demands on the abstraction capacity of the best thinkers of the nineteenth century. The consequences of this theory, electromagnetic waves, have nevertheless long been generally accepted—if more on trust than understanding.

5.7.6 *Questions and Doubts Multiply*

If someday a TOE (theory of everything) is born out of a synthesis of superstring theory and inflation theory, to what degree can it be viewed as the realization of a dream, the dream of a final theory that many physicists desire and even express in the titles of their books (for example, *Dreams of a Final Theory*)? If we compare Figure 5.1 with Figure 5.198, we see that the final result of the former figure represents the starting point for the latter figure. Will the creation of an all-encompassing theory bring an end to this continuity? Or will science be able to make a similar sketch at the beginning of the twenty-second century, where the starting point is given by TOE? There are many who shrink from the word "final." They consider it unacceptable, indeed logically false, that a principle does not assume another, lying at a deeper level, on which it can be based. Others believe that a final theory exists that would be capable of providing a complete explanation of the in-



◀ **Figure 5.199** Critical steps in cosmic evolution that eventually led to the most highly organized form of matter: life.

The heavy elements were created (perhaps) during a supernova explosion. The physical conditions—the narrow temperature and pressure range, appropriate liquid, gaseous, and solid phases of materials—conducive to the *continued existence* of the sensitive, fragile, and extremely complex protein molecules, which combine reproducible stability with the necessary variability, were ensured by our solar system. For the *initial formation* of the building blocks, electrical phenomena in the primitive atmosphere may have been responsible. Once self-reproducing units were formed, the tempo of evolution was dictated by the laws of biology.

the "decoherence" of the quantum state, resulting in loss of information, due to the quantum system's interaction with its environment. Irrespective of whether new practical applications might be successfully implemented, these techniques and the accompanying new experimental facts will create momentum in the investigations of basic quantum-mechanical problems such as the riddle of the measurement process (Figure 5.77) or that of the EPR paradox with Bell's inequalities (Figure 5.78).

5.7.7 *"Between Nothing and Infinity"*

The eternal and unchanging Aristotelian world encompassing the Sun, the Moon, five planets, and the stars embedded in a crystalline sphere was forced to cede its place to a dynamic universe resembling a giant laboratory full of exquisite objects that change in exquisite ways.

From a smallish planet orbiting an average star located at the edge of a galaxy of average size, mankind observes the divine drama of cosmic events. We can confidently say that we belong in the flow of these cosmic processes with every drop of our blood. Biologists trace the origins of life back to protein molecules as initial building blocks; but the hydrogen contained in our bodies also took part in the primordial processes of the universe, and every iron nucleus in human blood originated within a massive star, went through a supernova explosion before it could become, via the development of a new star system, a component of our solid earth and now play an important role our biological function (Figure 5.199).

The grandeur of all of human history is dwarfed, shrivels to nothing, and is lost in the enormous currents of the cosmos (Quotation 5.63), and yet this terrestrial world is not insignificant, for alongside all the marvelous objects in the universe, next to pulsars, quasars, and black holes, the great cosmic creation brought forth in this place the human brain and human consciousness with its capacity to be aware of both the infinitely small and the infinitely large (Figure 5.200).

> Here is where natural knowledge leads us: if it is not true, there is no truth in man; and if it is true, he finds in it a great source of humiliation, forced to humble himself one way or another.
>
> And since he cannot subsist without believing this knowledge, before entering into greater explorations of nature, I want him to consider nature both seriously and at leisure just once, and also to reflect upon himself and to judge, in a comparison of these two objects, whether any proportion holds between them.
>
> Let man then contemplate the whole of nature in its lofty and full majesty, and let him avert his view from the lowly objects around him. Let him behold that brilliant light set like an eternal lamp to illuminate the universe. Let the earth seem to him like a point in comparison with the vast orbit described by that star. And let him be amazed that this vast orbit is itself but a very small point in comparison with the one described by the stars rolling around the firmament. But if our gaze stops here, let our imagination pass beyond. It will sooner tire of conceiving things than nature of producing them. This whole visible world is only an imperceptible trace in the amplitude to nature. No idea approaches it. However much we may inflate our conceptions beyond these imaginable spaces, we give birth only to atoms with respect to the reality of things. It is an infinite sphere whose center is everywhere and circumference nowhere. ...

Let man, returning to himself, consider what he is with respect to what exists. Let him regard himself as lost in this remote corner of nature, and from the little cell in which he finds himself lodged, I mean the universe, let him learn to estimate the just value of the earth, kingdoms, cities, and himself.

What is a man in the infinite?

But to present him with another equally astonishing prodigy, let him examine the most delicate things he knows. ... Let him lose himself in wonders as astonishing in their minuteness as the others are in their extent! For who will not marvel that our body, imperceptible a little while ago in the universe, itself imperceptible inside the totality, should now be a colossus, a world, or rather a whole, with respect to the nothingness beyond our reach? ...

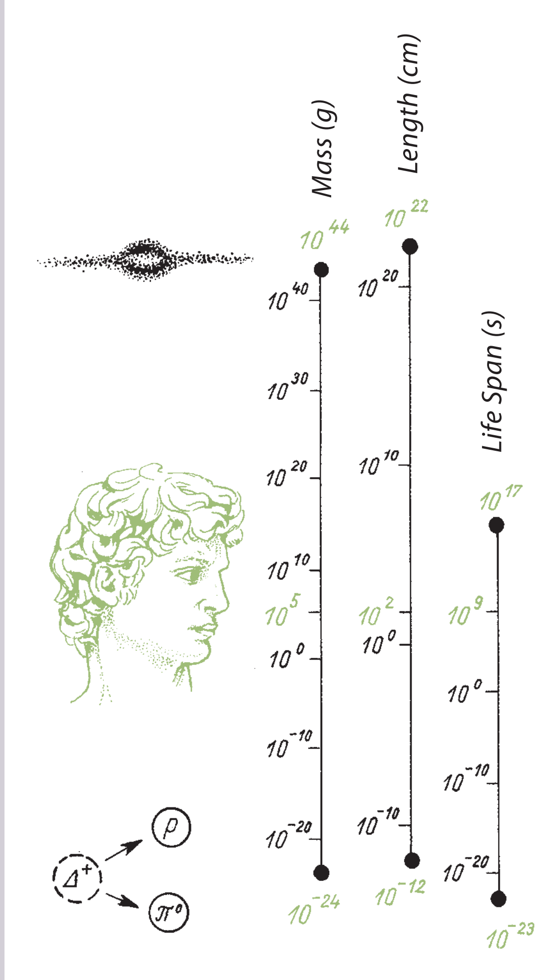
For what, in the end, is man in nature? A nothing compared with the infinite, an everything compared to the nothing, a midpoint between nothing and everything. ...

This is our true state. It is what makes us incapable of certain knowledge or absolute ignorance. We float on a vast ocean, ever uncertain and adrift, blown this way and that. Whenever we think we have some point to which we can cling and fasten ourselves, it shakes free and leaves us behind. And if we follow it, it eludes our grasp, slides away, and escapes forever. Nothing stays still for us. ...

All things, then, are caused and causing, supporting and dependent, mediate and immediate; and all support one another in a natural, though imperceptible chain linking together things most distant and different. So, I hold it is as impossible to know the parts without knowing the whole as to know the whole without knowing the particular parts. ...

Man is to himself the most prodigious object of nature, for he cannot conceive what body is, still less what mind is, and least of all how a body can be unified to a mind. This is the culmination of his difficulties, and yet it is his very being. *The way the spirit is united to the body cannot be understood by man, and yet it is man.* [*Modus quo corporibus adhaerent spiritus comprehendi ab hominibus non potest, et hoc tamen homo est;* Saint Augustine, *City of God*, XXI.10.]

—Blaise Pascal, *Pensées* [pp. 58–62]



▲ **Figure 5.200** The place of mankind between "nothing" and the "infinite."