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# Preface

*The Birth of a New Physics* has been written for the general reader, for students in high schools or colleges (studying science, philosophy, or history), for historians and philosophers, and for anyone who may wish to understand the dynamic, adventurous quality of science. I hope that scientists themselves may also find pleasure and profit in learning about the stages that led to the climax of the Scientific Revolution, the production of Newtonian mechanics and celestial mechanics.

The purpose of this book is not primarily to present a popular history of science, nor even to display for the general reader some of the recent results of research in the history of science. Rather, the intention is to explore one aspect of that great Scientific Revolution that occurred during the sixteenth and seventeenth centuries, to clarify certain fundamental aspects of the nature and development of modern science. One important theme is the effect of the closely knit structure of the physical sciences on the formation of a science of motion. Since the seventeenth century, again and again we have seen that a major modification in any one part of the physical sciences must eventually produce changes throughout; another consequence is the general impossibility of testing or proving a scientific statement in isolation or fully by itself, each test being rather a verification of the particular proposition under discussion plus the whole system of physical science.

The chief, and perhaps unique, quality of modern science is its dynamic aspect, the way in which changes constantly occur. Unfortunately, the needs of logical presentation in elementary text-books and general works on science prevent the student and reader from gaining a true idea of this particular dynamic property. Hence another of the major aims of this book is to try to indicate the penetrating force and deep effect that a single idea may have in altering the whole structure of science.

Because this book is not a history of science, but rather a historical essay on a major episode in the development of science, it does not deal fully with every aspect of the rise of modern dynamics or astronomy. For example, Tycho Brahe's reform of observational astronomy is mentioned only in passing, as is Kepler's concept of motion and the causes of motion. A topic not treated at all is the system of Cartesian thought, including the concept of a vortex-based cosmological system. In many ways, Cartesian science represents the most revolutionary part of the new science of the seventeenth century. Other major figures whose work would have to be included in a full history are Christiaan Huygens and Robert Hooke.

I should like to acknowledge my intellectual debt to Alexandre Koyré of the Ecole Pratique des Hautes Etudes (Paris) and the Institute for Advanced Study (Princeton), our master in the scholarly art of historical conceptual analysis. Majorie Hope Nicolson (Columbia University) has made us aware of the vast intellectual significance of the "new astronomy" and particularly Galileo's telescopic discoveries. For more than a decade, to my great joy and profit, I was able to discuss many of the problems of medieval science with Marshall Clagett (University of Wisconsin; the Institute for Advanced Study), and more recently with John E. Murdoch (Harvard University) and Edward Grant (Indiana University). For almost four decades I have profited from the criticisms of Edward Rosen (City University of New York) along with his scholarly contributions. More recently, I have gained new insight into Copernican science from Noel Swerdlow (University of Chicago). I have learned much about the history and early use of the telescope from Albert Van Helden (Rice University). I have a special obligation to Stillman Drake, who over the years has been more than ordinarily generous in permitting me to see his unpublished Galilean studies and in answering

questions, and who has given the typescript of this book a critical reading, first in the original edition twenty-five years ago and now once again in its revision.

The first edition of *The Birth of a New Physics,* dedicated to my daughter Dr. Frances B. Cohen, was written for the Science Study Series, part of a fresh approach to the teaching, study, and understanding of physics created by the Physical Science Study Committee, headed by Jerrold Zacharias and the late Francis L. Friedman of M.I.T. The preparation of that edition was facilitated in every imaginable way by the staff of the P.S.S.C. (notably Bruce Kingsbury); in particular I found in John H. Durston a sympathetic editor who helped me to reduce my labor to manageable proportions. I continue to be especially pleased that the photographs reproduced as plates VI and VII were specially made for this book by my old teacher and quondam student Berenice Abbott, one of America's great photographers.

The first edition has been printed and reprinted many times and has appeared in translation in Danish, Finnish, French, German, Hebrew, Italian, Japanese, Polish, Spanish, Swedish, and Turkish. The most recent of these versions, in Italian, is considerably revised and emended (including some corrections brought to my attention by Edward Rosen). Now, after an interval of some twenty-five years, the book has been updated to take account of developments and discoveries in the history of science, primarily with respect to Galileo, but also Newton. Many of the emendations and new materials have been inserted into the text, but others would have produced serious imbalances and would have destroyed the narrative pace of the original. Accordingly, the latter have been incorporated into a series of numbered supplements, referred to in the text, which amplify certain crucial issues of scholarship and understanding and which are essential to a balanced judgment concerning some of the most significant episodes in the coming-into-being of modern physical science.

Apart from the supplements, the most notable difference between the first edition and the present one is in the treatment of Galileo. During the interval between editions, we have learned (thanks initially to Thomas B. Settle's bold reproduction of one of Galileo's most famous experiments) that the experiments described by Galileo actually can give the results he claimed. Hence there has been a considerable shift of scholarly opinion. No longer is it believed that Galileo tended to describe only "thought experiments," which he either did not ever perform or could not have performed in the way he described. Rather, we have come to see Galileo as a master of the experimental art. Secondly, thanks in the greatest measure to the scholarly efforts of Stillman Drake, we have learned of the crucial importance of experiments in Galileo's formulation and testing (and even his discovery) of basic ideas on principles of motion.

I am very happy that this new edition is being published by W. W. Norton & Company. I am grateful to Edwin Barber, a vice-president, for his interest in my work. It is good to know that the world of book-making and book-selling still has a place for a real "old-time" publisher who likes books and authors.

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# THE BIRTH OF A NEW PHYSICS

CHAPTER 1

# The Physics of a Moving Earth

Odd as it may seem, most people's views about motion are part of a system of physics that was proposed more than 2000 years ago and was experimentally shown to be inadequate at least 1400 years ago. It is a fact that presumably well-educated men and women tend even today to think about the physical world as if the earth were at rest, rather than in motion. By this I do not mean that such people "really" believe the earth is at rest; if questioned, they will reply that of course they "know" that the earth rotates once a day about its axis and at the same time moves in a great yearly orbit around the sun. Yet when it comes to explaining certain common physical events, these same people are not able to tell you how it is that these everyday phenomena can happen, as we see they do, on a moving earth. In particular, these misunderstandings of physics tend to center on the problem of falling objects, on the general concept of motion. Thus we may see exemplified the old precept, "To be ignorant of motion is to be ignorant of nature."

## WHERE WILL IT FALL?

In the inability to deal with questions of motion in relation to a moving earth, the average person is in the same position as some of the greatest scientists of the past, which may be a source of considerable comfort. The major difference is, however, that for the scientist of the past the inability to resolve these questions was a sign of the times, whereas for us moderns such inability is, alas, a badge of ignorance. Characteristic of these problems is a print of the seventeenth century (Plate 1) showing a cannon pointing up in the air. Observe the question that is asked, "*Retombera-t-il?*" (Will it fall back down again?) If the earth is at rest, there is no doubt that the cannon ball fired straight up in the air should eventually come straight down again into the cannon. But will it on a moving earth? And if it will, why? The plate actually illustrates an even more complex problem of motion. Here we need only note that the nature of the path of a body or projectile hurled straight upward or dropped straight downward was very early seen to be one of the intellectual hurdles in accepting the concept that the earth moves.

Suppose the earth is in motion. Then, an arrow shot up into the air must move along with the earth while it ascends and later descends; otherwise, it would strike the earth far from the archer. A ready traditional answer is that the air must move along with the earth and hence the ascending and descending arrow is carried along. But the opponents had a ready reply: Even if the air could be supposed to move—a difficult supposition since there is no apparent cause for the air to move with the earth—would not the air move very much more slowly than the earth, since it is so very different in substance and in quality? Hence, in any case, would not the arrow be left behind? And what of the high winds that a man in a tower should feel if the earth was rushing through space?

In order to see these problems in sharper relief, we can for a moment ignore the earth itself. After all, the average man and woman may very well reply: I may not be able to explain *how* a ball dropped from a tower will strike the ground at the foot of the tower even though the earth is moving. But I *do know* that a dropped ball descends vertically, and I *do know* that the earth is in motion. So there *must* be some explanation, even if I am not aware of what it is.

Let us, then, deal with another situation altogether. Simply assume that we are able to construct some kind of vehicle which will move very quickly—so quickly indeed that its speed will be approximately 20 miles per second. An experimenter stands at the end of this vehicle, on an observation platform of the last car if it happens to be a train. While the train is rushing ahead at a speed of 20 miles a second, he takes an iron ball weighing about a pound from his pocket and throws it vertically into the air to a height of 16 feet. The ascent takes about one second, and it takes another second for the ball to come down. How far has the man at the end of the train moved? Since his speed is 20 miles per second, he will have traveled 40 miles from the spot where he threw the ball into the air.

We are in a position somewhat like the man who drew the picture of a cannon firing a ball up into the air. We ask: Where will it fall? Will the ball come down to strike the track at or very near the place from which it was thrown? Or, will the ball somehow or other manage to come down so near the hands of the man who threw it that he will be able to catch it, even though his train is moving at a speed of 20 miles per second? If you reply that the ball will strike the track some miles behind the train, then you clearly do not understand the physics of the earth in motion. But, if you believe that the man at the back of the train will catch the ball, you will then have to face the question: What "force" makes the ball move forward with a speed of 20 miles a second even though the man throwing the ball gave it an upward force and not a force along the track? (Those who may be concerned about the possibilities of air friction can imagine the experiment to be conducted inside a sealed car of the train.)

The belief that a ball thrown straight upward from the moving train will continue to move along a straight line straight up and straight down, so as to strike the track at a point far behind the train, is closely related to another belief about moving objects. Both are part of the system of physics of about 2000 years ago. Let us examine this second problem for a moment, because it happens that the same people who do not understand how objects can appear to fall vertically downward on a moving earth are also not entirely sure what happens when objects of different weight fall. Everyone is aware, of course, that the falling of a body in air depends upon its shape. This can be easily demonstrated if you make a parachute of a handkerchief, knotting the four corners of the handkerchief to four pieces of string and then tying all four pieces of string together to a small weight. Roll this parachute into a ball and throw it up into the air and you will observe that it will float gently downward. But now make it into a ball again, take a piece of silk thread and tie it around the handkerchief and weight so that the handkerchief cannot open in the air, and, as you will observe, the same object will now plummet to earth. Bodies of the same weight but of different shape fall with different speeds. But what of objects of the same shape but of different weight? Suppose you were to go to the top of a high tower, or to the third story of a house, and that you were to drop from that height two objects of identical shape, spherical balls, one weighing 10 pounds and the other 1 pound. Which would strike the ground first? And how much sooner would it strike? If the relation between the two weights, in this case a factor of ten to one, makes a difference, would the same difference in time of fall be observed if the weights were respectively 10 pounds and 100 pounds? And what if they were 1 milligram and 10 milligrams?

### ALTERNATIVE ANSWERS

The usual progression of knowledge of physics goes something like this: First, there is a belief that if 1- and 10-pound balls are dropped simultaneously, the 10-pound ball will strike the ground first, and that the 1-pound ball will take ten times as long to reach the ground as the 10-pound ball. Then follows a stage of greater sophistication, in which the student presumably has learned from an elementary textbook that the previous conclusion is unwarranted, that the "true" answer is that they will both strike at the same time no matter what their respective weights. The first answer may be called "Aristotelian," because it accords with the principles that the Greek philosopher Aristotle formulated in physics about 350 years before the beginning of the Christian era. The second exemplifies the "elementary textbook" view, because it is to be found in many such books. Sometimes it is even said that this second view was "proved" in the seventeenth century by the Italian scientist Galileo Galilei. A typical version of this story is that Galileo "caused balls of different sizes and materials to be dropped at the same instant from the top of the Leaning Tower of Pisa. They [his friends and associates] saw the balls start together and fall together, and heard them strike the ground together. Some were convinced; others returned to their rooms to consult the books of Aristotle, discussing the evidence."

Both the Aristotelian and the "elementary textbook" views are wrong, as has been known by experiment for at least 1400 years. Let us go back to the sixth century when Joannes Philoponus (or John the Grammarian), a Byzantine scholar, was studying this question. Philoponus argued that experience contradicts the commonly held views of falling. Adopting what we would call a rather "modern" attitude, he said that an argument based on "actual observation" is much more effective than "any sort of verbal argument." Here is his argument based on experiment:

> For if you let fall from the same height two weights of which one is many times as heavy as the other, you will see that the ratio of the times required for the motion does not depend on the ratio of the weights, but that the difference in time is a very small one. And so, if the difference in the weights is not considerable, that is, if one is, let us say, double the other, there will be no difference, or else an imperceptible difference, in time, though the difference in weight is by no means negligible, with one body weighing twice as much as the other.

In this statement, we find experimental evidence that the "Aristotelian" view is wrong because objects differing greatly in weight, or those that differ in weight by a factor of two, will strike the ground at almost the same time. But observe that Philoponus also suggests that the "elementary textbook" view may be incorrect, because he has found that bodies of different weight may fall from the same height in slightly different times. Such differences may be so small as to be "imperceptible." One millennium later the Flemish engineer, physicist, and mathematician Simon Stevin performed a similar experiment. His account reads:

> The experience against Aristotle is the following: Let us take (as the very learned Mr. Jan Cornets de Groot, most industrious investigator of the secrets of Nature, and myself have done) two spheres of lead, the one ten times larger and heavier than the other, and drop them together from a height of 30 feet onto a board or something on which they give a perceptible sound. Then it will be found that the lighter