The Fascination of PHYSICS

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To Kevin and Kim

who are never afraid to ask another question.

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Preface
to the Instructor

The students for whom this book has been written typically have one exposure to physics—this course. Given the enormous breadth of interesting material, a major challenge facing any instructor is the selection of topics. As the twentieth century draws to a close, it seems appropriate that the enormous strides taken in modern physics be meaningfully integrated into the intellectual traditions of the past. Consequently, this book presents a somewhat different approach to the topics and concepts typically included in a course at this level.

ORGANIZATION

The book is divided into five major units. Each unit begins with a concept in classical physics and builds toward a topic that generally falls into the category of modern physics. The first, *Space and Time,* begins with a fairly traditional presentation of position and motion, continues with classical relativity, and concludes with an introduction to the special theory of relativity. The care we have taken to integrate the concept of reference frame into descriptions of position and motion lays a strong foundation for the results of special relativity. Unit 2, *Interaction and Force,* begins by describing interactions and how we know they occur, next looks carefully at forces and Newton's Laws, and closes with a discussion of the four fundamental interactions in nature and current attempts to build a unified theory. Students often find the concept of force to be one of the more elusive ideas in physics. We have taken special care in developing the concept of force carefully. Unit 3, *Energy,* uses the concepts of kinetic and gravitational potential energy to introduce energy conservation and the various forms of energy that have emerged from our commitment to the principle of energy conservation. The discussion then moves to thermal energy and the laws of thermodynamics. We conclude with a look at the atomic and molecular view of matter and how kinetic energy is related to thermal phenomena on the atomic scale. Wave motion, classical and quantum, is the topic of Unit 4, *Waves and Particles.* It begins with mechanical waves, presents diffraction and interference, and then shows how experimental results led to wave-particle duality and quantum mechanics. The final section, *From Electricity to the Nucleus,* starts with the ideas of a circuit and electrical energy, looks at electromagnetism and methods of generating electrical energy, and then concludes with discussions of converting nuclear energy into electricity. Throughout the book, in an attempt to show both the unity and continuity of physics, modern ideas are integrated with the ideas that preceded them in the logical development of physical concepts.

Philosophical, social, and historical discussions are included in the development of the concepts when it seems appropriate. In addition, four interludes and an epilogue treat these aspects of physics in some detail.

OUR AUDIENCE

In this text, we make a few assumptions. First, we assume that many of the students' prior experiences can help them learn physics. So, we employ an inductive approach, and try to start each major section with some common experiences and move to generalizations and concepts. Our second assumption is that the students in this course have limited proficiency with mathematics. However, we cannot completely separate mathematics from physics. (One cannot understand a conservation law unless one sees that a value does not change.) Thus we expect the students to use arithmetic to evaluate some algebraic expressions but not to perform algebraic manipulations. Our final assumption is that the students must do in order to learn. Three different levels of written exercises and a set of activities conclude every chapter. In addition, Self-Checks (with answers at the ends of the chapters) are scattered throughout the book. (See *Preface to the Student*.)

Throughout the book we have used metric units. SI units are used almost exclusively. The only exceptions are for pedagogical reasons. (For example, N/m^2 seems to emphasize the meaning of pressure better than pascals.) Our experience has been that essentially all 18–25-year-old students have been taught the metric system and have a reasonably good feeling for the sizes of units such as the meter and kilogram. (Few have a good idea of the size of a joule, but they have no better feeling for a calorie or BTU.) Older students may not have any formal training in the metric system, but they seem to have picked it up from interactions with younger people, usually their children. Thus we have used only metric units and presented conversions with traditional U.S. units only in an appendix.

ACKNOWLEDGMENTS

We received help from a variety of people as we wrote this book. First and foremost we owe a special thanks to all the students (approximately 1000 of them) who used preliminary editions of the manuscript and were always more than willing to tell us when something was not quite presented in the clearest possible way. In addition, we relied heavily on the reviews of Murray Alexander, Milo V. Anderson, Claire Chapin, Russell Coverdale, James R. Crawford, Dewey Dykstra, Jr., David J. Ernst, John Giles, John S. King, Bernard Kramer, James A. Lock, Bernard F. Long, John E. Maling, Kaye Martin, Allan Miller, Fernando B. Morinigo, Carl J. Naegele, Barton Palatnik, Paul Phillipson, D. L. Rutledge, Lawrence C. Shepley, Jack White, and S. J. Yarosewick. Our colleagues at Kansas State University and Marymount College were seemingly infinite sources of helpful suggestions. One of us (D. Z.) also enjoyed the hospitality of the University of Utah for a sabbatical leave during which time part of this text was written. At Benjamin/Cummings, Andy Crowley provided the editorial guidance to bring this book to a successful completion, and Robin Fox's careful reading of the entire manuscript helped us tighten the final version. Sue Harrington and Mimi Hills directed the manuscript through production. Finally, we have been greatly influenced by discussions with many of our colleagues on subjects ranging from how students think to the principles of physics. We thank all of them and especially acknowledge the influences of Bob Fuller, Paul Hewitt, and Bob Karplus.

No set of acknowledgments would be complete without paying special tribute to our spouses, who only occasionally complained about the amount of time we spent on this project.

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Preface
to the Student

As you begin your study of physics you probably have two questions.

What do I need to know before I start?
How can I learn physics most effectively?

Because students' learning styles vary, no unique answers can be given to these questions. However, our students have found some general guidelines to be useful.

We assume that you have not taken a formal physics course before starting this one. However, we also believe that you already know a lot of physics. You have learned this physics just by living and doing your normal, everyday activities. What you probably do not know are the underlying concepts that connect and explain your many observations and experiences. So, the main items you need to bring to your study are your experiences and observations.

Physicists use two languages—ordinary speech with some specialized vocabulary and mathematics. As you study physics, you will pick up the vocabulary. We have tried to keep new words, as well as familiar words with new meanings, to a minimum. Thus the vocabulary of physics should not hinder your learning.

We have also kept the mathematics at a level with which you should feel comfortable. We do not expect you to solve algebraic equations. We do expect you to be able to use arithmetic to evaluate an algebraic expression. (For example, speed = distance/time; if distance = 10 meters and time = 5 seconds, what is the speed?) Most evaluations involve simple expressions, which you can do in your head. A few may require pencil and paper or an inexpensive calculator. Nothing fancy is required; anything that adds, subtracts, multiplies, and divides will do. Armed with your paper and pencil or your calculator, you will be more than adequately prepared for the mathematics in this book.

As you study physics, your first introduction to new concepts will come from reading and listening. But, that is only the start. Understanding comes from using these ideas to explain observations and problems. An effective way to acquire this understanding involves several steps.

Before each new concept is introduced, we present some common experiences or observations related to the concept. After you have read a description of the new concept, think back on the opening. Try to relate in your own words how the concept explains and ties together the experiences and observations. Also think about your own experiences. Can some of them be explained with your new knowledge? After the introduction of a concept we present some of its applications. Again, read these carefully to follow the reasoning in applying your new knowledge.

Within the text are Self-Checks. These short exercises give you a chance to see how well you have understood the material which you have just studied. Each Self-Check is also a warning. You will need to know this material to understand future concepts. So, complete the Self-Checks and compare your answers with those at the end of the chapter. Only after you have written out the answers to the Self-Checks completely and understood the correct answers are you ready to continue your study of physics.

Your learning becomes more active when you apply your newly acquired knowledge. Exercises at the end of each chapter are designed for this purpose. We have divided the exercises into four groups: Reviewing Chapter Material, Applying the Chapter Material, Extensions to New Situations, and Activities. You cannot learn physics effectively unless you complete at least some of these exercises.

The first exercises, Reviewing Chapter Material, are labeled with a prefix of A and are a series of questions taken directly from the material in the text. The questions ask you to state the ideas of the chapter in your own words. You should be able to complete all the questions for every chapter that you study.

Applying the Chapter Material, with a prefix of B, gives you the opportunity to practice using the concepts in situations that are very similar to the ones presented in the text. Sometimes these exercises involve using a general idea and some logic; other times they will require a calculation or two. In both cases your understanding will improve as you complete the exercises.

Extensions to New Situations, with a prefix of C, enables you to take an idea from the chapter, follow some logical steps, and reach a conclusion that is not stated in the chapter. We do not expect you to do this entirely on your own, so we provide some help. These exercises are where the fun can really begin. You know enough to start with one idea and see where it takes you.

Finally, the Activities present some things you can do—short experiments you can complete at home, books or articles you can read, essays you can write, and so on. They can frequently help more than anything else. Doing is one of the best ways of learning.

Whenever you are working on any of the exercises, you should remember that the underlying question is always: How do the concepts of physics explain this situation? You should not simply state the answer but give an explanation in terms of what you have learned. In physics, Yes is never a correct answer; Yes, because . . . may be correct.

In general, learning physics effectively involves not only reading and listening but also doing exercises and reflecting on your experiences. Next winter when you slip on some ice, do not think “Oh darn, I almost broke my leg,” but “Let’s see, what forces didn’t I consider while walking on the ice?”

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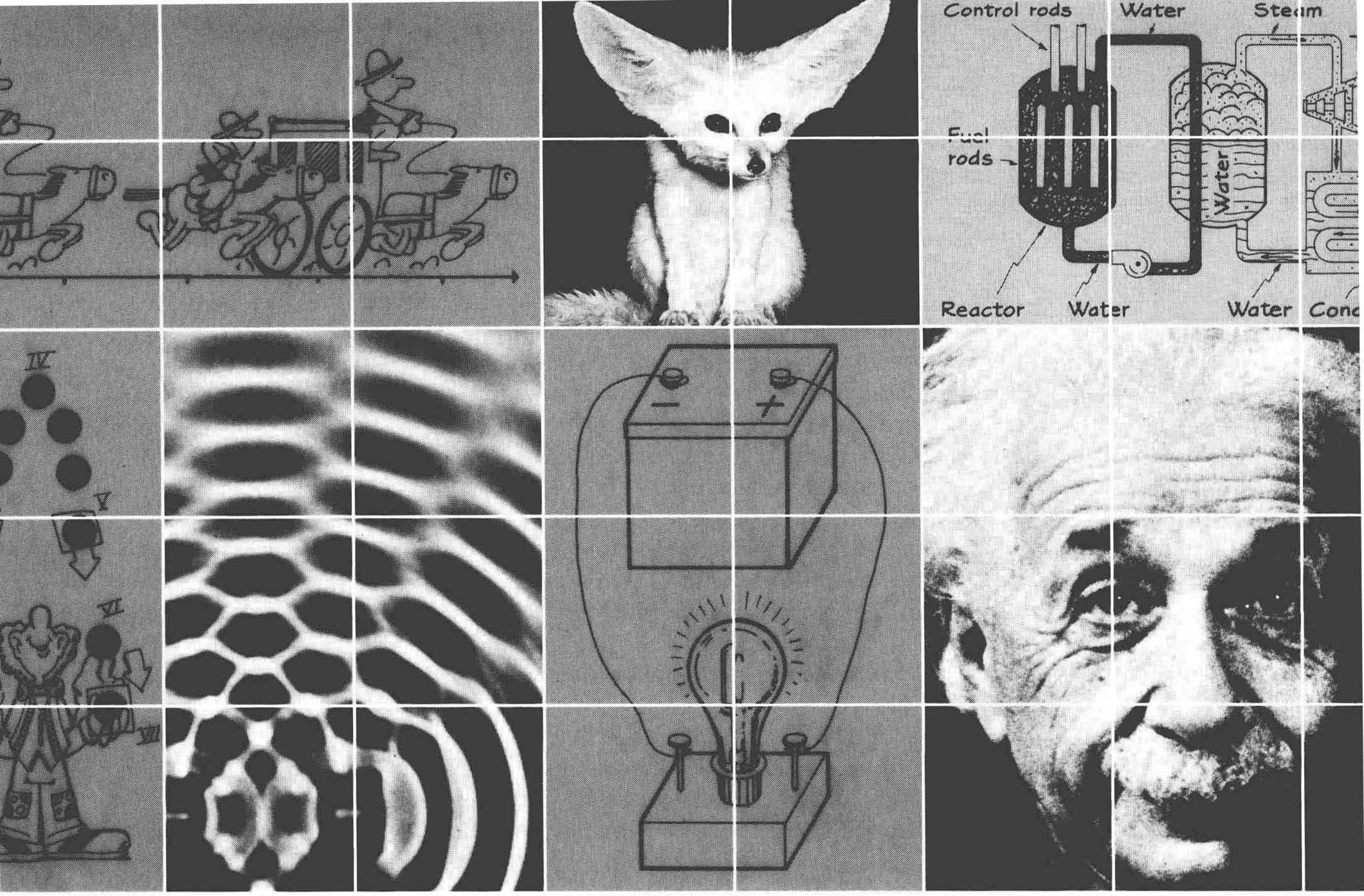

Introduction

Our children, Kevin and Kim, ask lots of questions:

> Why do things fall down?
> Why won't my sled work on the sidewalk?
> What is a star?
> Why did the cat scratch me?
> Why aren't all people treated fairly?
> How do we know about atoms?

You no doubt asked many of the same questions. In a lifetime, we ask literally thousands of questions—questions to gain information about ourselves and our world. Each question is an attempt to understand, to organize better the experiences we have had. They become the basis for the knowledge that we hand down from generation to generation.

Scientists ask only questions that have specific characteristics. First, the questions must deal with concepts upon which we can agree. Why aren't all people treated fairly? is not a scientific question because its answer depends on different definitions of *fair*—definitions that depend on the values and emotional response of the person asked. On the other hand, How do we know about atoms? is a scientific question. Knowledge accumulated during centuries of investigation has resulted in a definition of the atom upon which everyone agrees. A second characteristic of a scientific question is that it must be able to be answered by experimentation. Normally, Why did the cat scratch me? cannot be answered experimentally because we cannot duplicate the event. If we could, we could vary the circumstances and discover what combination motivates the cat to scratch. The requirement that we be able to answer a question by experimentation helps assure us that we can agree upon the answer, that the answers will become part of the knowledge base.

Asking questions that can be answered by experimentation allows scientists to agree upon the answers and describe their observations in common terms. However, the answers to many questions change over a span of centuries, sometimes even over a span of a few months. How, you might ask, can the answers change? Because the experiments we can perform change. As we develop more-sophisticated ways of observing nature, we gain new perspectives. Our concepts of space, time, and matter have changed as we have been able to explore the space beyond our earth, to observe objects moving at incredibly high speeds, and to "see" smaller and smaller pieces of matter. Each new perspective adds new answers, answers that modify our view of nature.

When Kevin asks, "Why doesn't my sled work on the sidewalk?" he is beginning to be a scientist. His question can be answered by experimentation. But he needs to ask and answer other questions—questions that enable him to see patterns: "Will it work on the lawn? On a wet lawn? On snow covered with dirt?"

You may have done puzzles in which you are given a sequence of numbers and asked to predict the next one: 2, 4, 6, ?. To solve such a puzzle, you look for a pattern. Once you find a pattern, you can use it to predict the next number. Kevin has to do much the same thing with his answers. He looks for a pattern as he tries the sled on various surfaces.

Were patterns all that concerned us, we could be content with a list of patterns—a list of observations, so to speak. But science tries to place a series of patterns within a broader pattern, several broader patterns within still broader patterns, and so forth. In short, scientists try to understand the patterns. In the process they build theories.

We can illustrate the increased power of theories with an everyday example. In a letter to Ann Landers, a woman complained about her mother-in-law, who would habitually arrive an hour ahead of the prescribed time for dinner. The daughter-in-law recognized the pattern and responded by inviting her an hour later than she really wished her to arrive. At this point she observed a single pattern. The immediate problem is solved but not really understood. What if the two women were to meet for a concert? Should the daughter-in-law add an hour to the starting time? Without understanding the overall problem—looking for broader patterns and developing a theory—the daughter-in-law cannot answer this question. Only when she looks at other situations can she build a theory of her mother-in-law's behavior. Is her mother-in-law habitually early for all invitations or only for the daughter-in-law's? Is she early for movie invitations as well as for dinner invitations? Broader and broader patterns lead to a theory that is ultimately more useful.

Asking questions, recognizing patterns, and building theories help define science. Physics is one of several disciplines that share this approach to knowing. As you study physics in the chapters that follow, you will share the knowledge accumulated by thousands of physicists over a span of the last 400 years. As you tackle the task of learning about the theories of intellectual giants like Galileo, Newton, Maxwell, Einstein, and Curie, please bear in mind the words of Didacus Stella, a Roman general:

> *Pygmies placed on the shoulders of giants can see more than the giants themselves.*

Compared to Newton and Einstein, we are all intellectual pygmies. Yet their knowledge can become ours, granting us an even broader and richer understanding of our world. This gift is, after all, what makes us human.

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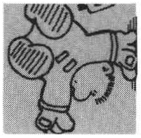
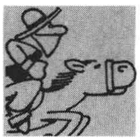
Space and Time



CHAPTER 1
Position and Change

CHAPTER 2
Describing Motion



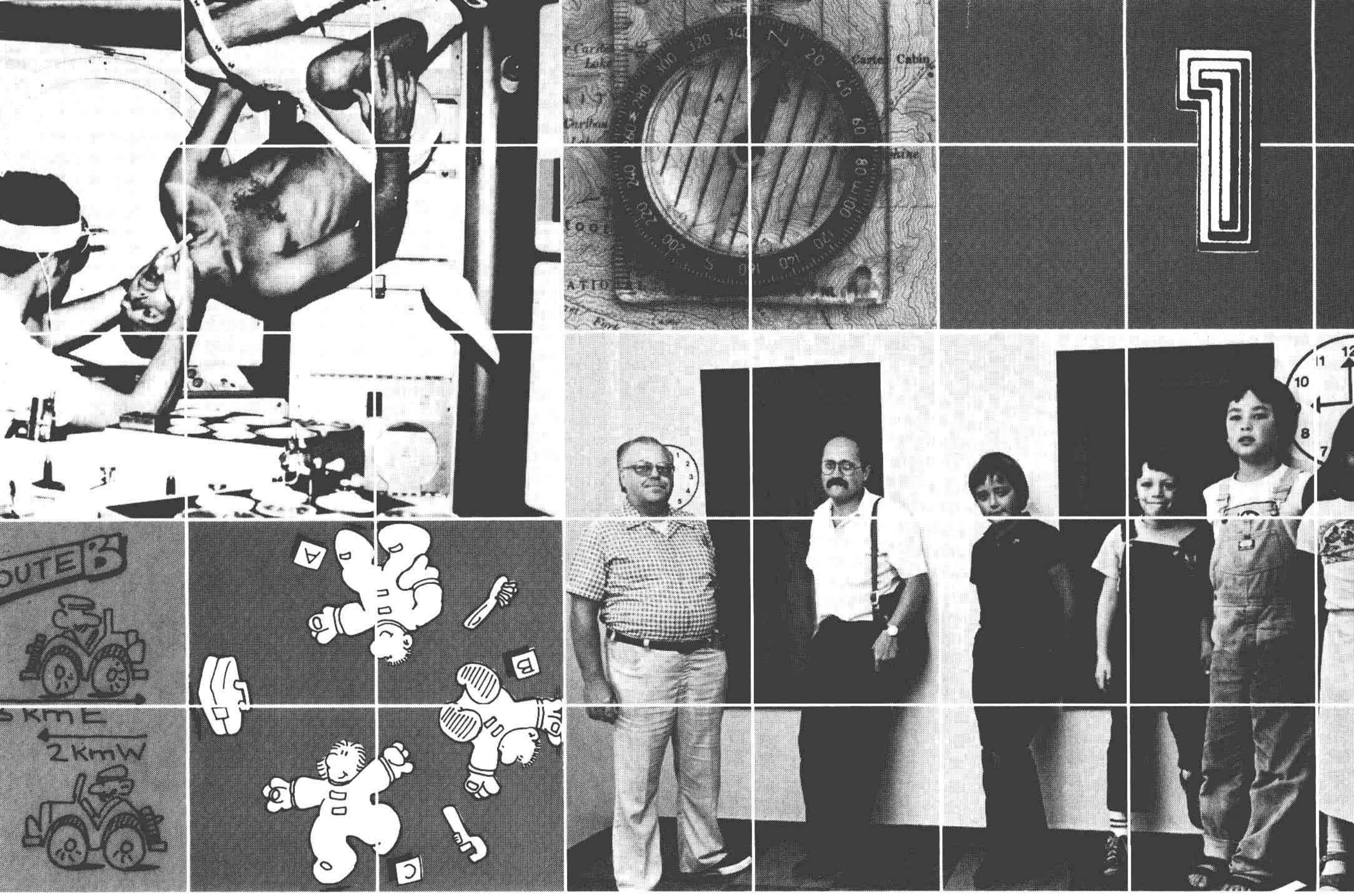
CHAPTER 3
Relative Motion at Low Speeds

CHAPTER 4
Special Theory of Relativity

We think nothing of our differing points of view as we rate the latest movie or last week's bestsellers. In many respects, each of us sees something different. So it is with the concepts of position and motion. A book is on my left but your right. We say we're standing still, yet the earth upon which we stand rotates once every twenty-four hours, carrying us past the sun at a rate of 1670 kilometers per hour. Descriptions of position and motion do indeed depend upon our point of view.

In 1905 Albert Einstein added two more quantities—length and time—to our list of relative concepts. Objects are shorter and time moves more slowly to observers moving past at speeds near the speed of light. These ideas seem absurd, partly because our thoughts are dominated by low-speed experiences. However, the relativity of length and time has been verified experimentally.

Position, motion, length and time—our descriptions of space and time depend on our separate points of view. Physics offers a process by which separate points of view can be merged—a common reference frame from which descriptions can agree.



Position and Change

The question of different points of view is a very basic one. Some people like modern art; others call it scribbling. Some like the latest movie; others find it mediocre. When we deal with opinions, it is rare that we ever share completely another's point of view. When we describe position, however, we can agree. All the Wizard (Figure 1-1) had to do to avoid confusion was turn around and face the two baskets in the same direction as the unfortunate citizen. Scientists consciously choose concepts that enable them to share points of view—to agree upon what they observe.

We begin studying motion by defining position and change in position. This chapter will show how *reference objects* combined with *reference directions* provide us with a *reference frame* with which to agree upon the position of an object. In order to be more precise, we will introduce *coordinate systems,* which incorporate the process of measurement into reference frames. *Distance* and *displacement* describe the change in position of a moving object. These last two concepts are the foundation for our later descriptions of motion.