A FIRST COURSE IN PHYSICAL SCIENCE

ROBERT P. BAUMAN

A FIRST COURSE IN PHYSICAL SCIENCE

ROBERT P. BAUMAN
University of Alabama at Birmingham

JOHN WILEY & SONS,
New York • Chichester • Brisbane • Toronto • Singapore

Library of Congress Cataloging in Publication Data:

Bauman, Robert P.
A first course in physical science.

Includes indexes.
1. Physics. 2. Chemistry, Physical and theoretical.
I. Title.

QC23.B338 1987 530 86-28143
ISBN 0-471-83074-7

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1
Cover photo © 1986 Sheila Granda
Cover inset A.G.E. Fotostock/© Peter Arnold, Inc.
Text design Michael Jung

PREFACE

Even casual inspection of this textbook will reveal significant differences from other physical science texts. The differences, which have been developed from experience in teaching and in studies of how students learn, are founded on a basic premise.

Premise: Reading, or being told, is not the same as learning.

Many parts of science are highly structured, so that one concept relies on another. Modern biology requires a grasp of fundamental chemistry. Understanding the notation of chemical equations requires knowledge of molecules and the mole. Acceleration and momentum can have little meaning until velocity has been understood, including its directional properties. Force, and its influence on motion, can scarcely be understood without an understanding of acceleration. Such understandings do not occur instantaneously on reading an explanation or hearing a lecture!

Traditional textbook formats present a fundamental concept and its higher-order applications at the same time (that is, within a few pages or within the same lecture). Indeed, the less sophisticated the targeted audience is in science and mathematics, the more condensed the presentation is likely to be. Since the student has not had an opportunity to digest and understand the first concept before the others appear, the student is forced to memorize. Then, the student is criticized for poor study habits and may be dismissed as incapable of learning science and mathematics.

Several studies undertaken in recent years on how students learn physical science concepts agree in the conclusion that mathematics serves as a valuable crutch. Before students have grasped the ideas that we consider most fundamental, they learn to calculate answers. This mathematical facility then enables them to check their models of physical behavior, gradually reshaping their interpretations of elementary physical processes, such as free fall and acceleration due to an impulse. There is good evidence that others before them have followed the same path, at least as far back as Galileo.

Elementary mathematics is an important ingredient of modern life. Typical students entering physical science courses lack the necessary facility with algebra but not the ability to acquire some facility. They simply require a slower and more carefully structured approach, with opportunity to practice the skills as they are learned. Teachers of physical science have both the opportunity and the obligation to help students learn elementary quantitative methods.

This textbook offers the appropriate alternative approach to conventional design. A fundamental idea (e.g., speed or displacement) is presented and the student is given an opportunity to try homework, laboratory, and quiz problems before the next layer of sophistication (e.g., the velocity vector) is introduced. In the meantime, other topics, not dependent on the same development, can be introduced and considered.

Students are accustomed to moving between subjects—from English to science to history to mathematics—without requiring that each subject be serially related to the others. The new format more than compensates for the lack of immediate continuity by allowing time for the digestion of material. Homework assignments are designed to offer repeated refreshers and opportunities for polishing skills on earlier material. At least some of the compartmentalization of topics is avoided. As the student learns the early material, recurring examples offer relatively easy points on homework and quizzes. If the material has not been mastered, the point is quickly made that it should be given more attention until it is well in hand. Experience with this technique in the classroom has shown it to be effective.

Robert P. Bauman

ACKNOWLEDGMENTS

Many people have contributed, in small ways and large, to the creation of this textbook. Foremost among them have been the students, who provide the ultimate test of which explanations are adequate and which must be revised. These and many other contributors of ideas and criticisms must remain unnamed here, but their assistance is deeply appreciated. Thanks are also due to Carol-Lee Goodman, who typed the early draft into the computer; to Drs. Lee Summerlin, Rolf Schwaneberg, and Mario Iona, who read portions of the manuscript and helped in clarification; and to my wife, whose critique of readability for the nonscientist was invaluable and whose patience with my preoccupation was essential. The cheerful efforts of Safra Nimrod and Pamela Pelton, of John Wiley, helped greatly in the final steps of converting the manuscript to a bound volume.

R. P. B.

NOTE TO THE STUDENT

It does not matter who is right, but what is right.

I. M. KOLTHOFF

Welcome to the science explorers' club. This is a very informal group that includes all those who are making an effort to learn something about the world and universe around them. (Actually, you have been a member for a long time, but welcome to a chapter meeting of the club.)

Most of you who will read this book will be enrolled in an introductory physical science course offered to college freshmen to satisfy a science requirement. We assume you are not a science major or a math whiz, but you do have some curiosity about the world around you, and perhaps some curiosity about why you should be taking a physical science course.

The most important thing to remember about science is that it is *not* a collection of information. Science is a search for truth, and you are a partner in that search. It is true that a lot of information has been accumulated already (more than any of us now knows or ever will know). But that is not the part of science that scientists find most interesting. The fascination of science lies in the part we *do not* know.

Science is a search for truth, but more specifically, it is a method of searching. It is a method that has proved extremely effective over a period of several centuries. And it is a method that is applicable to learning in other fields, as well.

The basic principles of the method of science are the following:

1. A belief that we can find answers to questions about the universe.
2. A belief that those answers can be obtained by different people, so that no one person is more inherently believable than any other person, except insofar as one person may have more experience or may be a more accurate observer of nature than another. It is the logic and the experimental evidence that are to be examined, not the authority of the person advancing the argument.
3. A recognition that the only questions worth asking (in science) are those that can, at least in principle, be subjected to test. Thus we may ask *how* the universe was created, because there are many tests of any theory of creation, some found on or in the earth and some found in observations of outer space. But it is not science to ask *why* the universe was created. That belongs to philosophers and students of religion, for there are no experimental tests of the answers that are proposed.
4. As we will discover, good science must be quantitative. It is easy to be fooled by incorrect theories that do not make quantitative predictions.

This book does *not* assume that you are skilled in mathematics. Furthermore, the most important part of science is the qualitative understanding of what will happen and why. You may ask why, then, there are mathematical symbols and equations and numerical problems. There are several reasons.

First, science is actually easier with some mathematics. The best, and easiest, way to check a concept is very often to express it quantitatively. Many studies of how students learn have shown that even the best science students start out relying on mathematics as a crutch to learn the science concepts. It would not be fair to ask you to learn the same concepts without that aid.

Second, although we do not assume that you are familiar with algebra or any other mathematics beyond arithmetic, we believe that you, like other students, can learn elementary mathematics if you are given a reasonable chance. Considering the extreme importance of quantitative skills in almost all professions today, as well as for personal economics, it would not be fair to avoid what is probably the best opportunity you will have to learn and practice those skills.

You probably recognize that you cannot learn to play tennis well by reading about tennis or by watching others play. There is no substitute for playing the game, preferably while you have a coach available to point out what you are doing right and wrong. Similarly, you cannot learn science by reading about it or by watching someone else describe it. You must try the problems yourself, struggle with putting ideas into your own words, make your own observations, and seek to put those observations into a framework that makes sense to you.

Good science is fun. Welcome to the fellowship of science explorers. Participate and enjoy the adventure.

R. P. B.

CONTENTS

CHAPTER 1

Introduction: What, Why, and How of Physical Science

. . . how "very contrary to my expectation" the result of it had turned out; but I soon after found that I had been too hasty . . . . I had learned from my own experience how very dangerous it is in philosophical investigations to draw conclusions from single experiments.

BENJAMIN THOMPSON, COUNT RUMFORD

An industrial training expert has suggested that academic instructors often fail to communicate effectively with students because they do not tell the students the most basic information:

What the students are to learn.

Why it should be learned.

How it will be learned.

The challenge seems appropriate. The what, why, and how of this course (subject to some modification by your instructor) can be summarized as follows.

WHAT:

1. You will learn the fundamental rules of the universe and a few new facts.
2. You will learn applied mathematical skills.
3. You will learn observation skills.
4. You will learn skills of logical thinking and analysis.

WHY:

1. Only if you understand how the universe works, will you be able to take advantage of the benefits. There are only a few really fun-

damental, demonstrable rules by which the universe operates. (We are not counting the important, but nonprovable, rules of morality and religion.) There are, in addition, results that flow from those demonstrable truths. The core of this course is the few basic principles and some of the more important practical results that come from those principles. You will find ways of moving objects with less effort; you will find that some things you might want to do are impossible and not worth spending your time on; you will find out how to connect wires to switches and bulbs and how to combine lenses to make things appear larger or smaller. This is the only universe around. If you are going to live in it, it will pay for you to know the rules.

2. Unless you are able to make numbers work for you easily and effectively, you will not be able to analyze budgets, taxes, recipes, and investments; and you will not be able to understand the basic rules by which the universe operates.

3. Only by observation, will you be able to add to the knowledge acquired in school and keep up to date with new information. (An important part of observation is acquiring information on your own from all sources, including books and magazines.) You will find that you have been getting far less information from your observations than you should have. Improving your observation skills will save you time, and observation is usually the cheapest way of learning.

4. Only people who have learned to think are able to move into most better-paying jobs. Business and industry tell the schools, "Teach people to think. We can tell them the specific information they need for the job." Job information changes rapidly. Thinking skills are good for all time and all jobs.

1. HOW TO LEARN SCIENCE

There are a few specific things you, and your instructor, can do to help you learn.

The textbook, lectures, and laboratories will provide more information than you will be able to remember. Put most of your effort into learning how and why things work. Do not spend much time on memorizing details or incidental facts or special cases. *What you know determines what you can learn.* If you come to class prepared, you will learn more.

Homework, quizzes, classroom recitations, laboratory exercises, and examinations will all give you practice in seeing how mathematics can work for you. Listen carefully, and you will discover simple tricks you may not have been aware of that will make the mathematics easier. Good mathematical skills, in turn, will help you learn other things.

Specific homework assignments and laboratory exercises will provide opportunities to sharpen your observation skills. Once you begin to notice things, you will discover that you can get more information from what you see than many of your companions do. You will learn more, with less effort.

The discussions in the textbook and in the classroom will emphasize new ways to look at old information and ways to analyze problems that avoid mistakes. New relationships will be pointed out. Simpler ways to deal with complex and detailed subjects will be demonstrated. But the only way to learn to think is to practice.

Suppose for a moment that you had all of the information in this textbook and your other textbooks stored in a pocket-sized computer, so you could call up any piece of information you needed with a few keystrokes. (That might not be an unreasonable assumption in the near future.) Would the purchase of such a storage computer take the place of a college education?

One of the secrets of education that is too often kept from students is that acquiring information is a small part of acquiring an education. Computers, videodisks, and even books are generally much better at storing and retaining information than humans. The point is often made, "If you can be replaced by a computer, you should be!" What is it that makes a human so much more versatile, and therefore valuable, than a computer?

The key difference between humans and computers is that, except within very narrow confines, computers do not know how to learn. By contrast, the first computers were built by people who had never seen a computer. New designs for computers, automobiles, art, clothing, and textbooks are generated by people who have seen the old designs and have deduced that, if it can be done the old way, then it could also be done in this new, different way.

A trap many students fall into is trying to imitate a book or a computer by memorizing problems. They program themselves so that when they see something that looks or sounds like a problem they have seen before, they go through the same motions to solve the problem. Unless there is a good understanding of why a problem is solved in a particular way, the result is too often disappointment and frustration. Learning involves primarily understanding ideas, so that *new* problems can be solved.

Most people change jobs every few years and change fields of work several times. How can you prepare now for a job that may not exist yet and that will almost certainly rely on technology that has not yet been developed? That is the rest of the secret. Education is not primarily acquiring information. *Education is learning how to learn.*

The most valuable employee is one who can be told, "There is a problem here. Find out what the problem is and how it can be solved." Such problem solving always involves a set of similar steps:

1. You must learn the terminology and what it really means.
2. You must learn the rules.
3. You must ascertain the facts of the particular case.
4. You must fit the facts and rules together to draw conclusions.

Steps 1 and 2 require memorization, but a memorization of ideas or concepts, not simply of words. Step 3 requires the ability to sort through the information available and determine what is relevant, what is not, and how the relevant facts fit with the rules for the problem type. Step 4 is the problem solution step, which is possible only when the first steps have been performed properly. Practice identifying these four steps as you read the textbook and learn to solve sample problems in this course.

Remember that your primary purpose in college is learning how to learn.

The classroom is a very small slice of the real world. What you do in the classroom is an indication of what you will do outside the classroom. If you spend your efforts trying to avoid learning (this takes much more work, but some students try it), you will be learning how to avoid accomplishing your goals on the outside. If you try to improve your skills every day—acquiring a few new facts and another mathematical skill or two, seeing things you have overlooked before, and learning how to get from the information you already have to the information you need—this can be the most enjoyable and valuable course you will take.

2. WHAT IS SCIENCE

The twentieth century has been characterized in many ways, but most of them, for better or worse, involve the development of science and technology in their many forms. Airplanes and space travel, movies, radio and television, plastics, and synthetic fabrics are just a few of the innovations of this century that have arisen from science. We could not ignore science or its products even if we wanted to, but neither can one person understand all of what is known today.

The world "science" means knowledge or to understand. It is often contrasted with "art," denoting skill or technique. Philosophy originally meant the love and pursuit of knowledge of all kinds. Knowledge of nature, or natural philosophy, became known as physics. At one time physics included all that was known of the human body and its ailments, and persons specializing in these subjects are still known as physiologists and physicians. As other areas of knowledge within natural science have developed (biology, chemistry, geology, astronomy, and so forth), physicists have concentrated more on the principles that underly all of nature, leaving the applications of those principles to biologists, chemists, engineers, and others. Similarly, chemists strive to understand how and why chemical reactions occur and the principles by which these reactions can be used to synthesize new materials or to analyze existing materials. The problems of producing such materials are the domain of the chemical engineer.

Aristotle, a student of the philosopher Plato and a teacher of Alexander the Great, lived in the fourth century B.C., when science as we know it did not yet exist; but Aristotle attempted to deal with the broad domain of science, producing masterful discussions that served as textbooks for nearly 2000 years. Perhaps in part because of Aristotle and his works, there was very little progress in understanding nature during that long period of time. A major difficulty was that Aristotle explained too much. By explaining everything, he left little room for those who followed to contribute new insights in one area or another. It was a formidable challenge to attack so comprehensive a view of nature and replace it with a more complete, or more accurate, interpretation.

At the same time, Aristotle's views were generally incorrect, for a very important reason. He could explain very convincingly *why* an object falls toward the earth, but he could not explain *how* an object falls toward the earth. That is, Aristotle neglected to make quantitative measurements as part of his observations. If he had done so, he would almost certainly have discovered that many of his explanations did not agree with nature. By contrast, nearly 20 centuries later, Galileo set aside the question of *why* objects fall toward the earth and, instead, carefully measured *how* objects fall. Modern science, especially physics, is founded on the work of Galileo rather than Aristotle. Galileo contributed far less explanation of nature than Aristotle had done, but because Galileo concentrated on careful observation of nature, including careful measurements, what he contributed was correct. Galileo's work formed a basis on which Newton and others could construct an understanding that would be further refined but that is not in danger of being later overthrown by new findings.

Obtaining information about nature often requires great art, or skill. It certainly requires originality and creativity in finding the right questions to ask and in constructing models and theories that can summarize, in a statement or an equation, the results of many experiments. Some experiments today involve almost unbelievable accuracy, equivalent to measuring the distance to the moon to within the width of a single letter on this page or detecting the weight of a nickel added to 500,000 automobiles. Other experiments and theories involve extended mathematical calculations. But much of physical science still requires primarily an ability to observe accurately, including measurements with simple devices such as rulers and clocks, where necessary. These observations must be combined with some simple calculations involving addition, subtraction, multiplication, and division.

The primary aim of this course is not to provide you with information, although it contains a great deal of useful and interesting information about the world around you and how it behaves. Information can be all too quickly forgotten. The more important purpose of a first course in physical science is to help you learn how to learn, by helping you learn to observe more carefully and, often, more quantitatively, and by helping you learn how to analyze those observations.

We start with the assumption that you have already learned to add, subtract, multiply, and divide but that you may not be skilled in applying those techniques to solve equations and may be unaccustomed to carrying out calculations in your head. These skills are so necessary to efficient functioning in the modern world that we will not apologize for expecting you to become more skillful. We will try to make it easy by starting with practice on the simplest problems until you are ready for some of the problems you remember seeing (and perhaps even working) in high school algebra.

3. THE ART OF OBSERVING

Often we neglect to observe things that we see all the time. Do you know, for example, how many steps there are in any stairway in your home? Or do you know where in the sky you should expect to see the moon at 10:00 tonight or what shape it will have?

The foundation of understanding is observation followed by measurement. Neither is as easy as it sounds. Skilled observers will see far more than the average person and make far fewer mistakes of observation and recollection. Even as trivial a task as measuring the length of a line cannot be performed by most people without practice.

Observation provides the broad picture of what is happening. Measurement provides the test of potential explanations of those events. You may have observed that the sun rose this morning at nearly the same time as yesterday morning and at about the same place; a measurement of the time at which the sun rose would probably show that the time was actually slightly earlier or later than yesterday. The model that you construct for the motions of the earth, moon, and sun depends on whether the time of sunrise changes or does not change. It also depends on what you observe and measure for the time at which the moon rises or sets.

No one can remember everything important that he or she observes. It is necessary to write down many of your observations, so that you can refer back to them, until you have sufficient understanding to predict accurately what the measurements should be. For some observations, of course, that understanding will come very quickly, and the recorded notes simply provide a check on your model. Other observations may involve phenomena that are more complex, for which you will not have developed adequate models. Sorting out the simple effects from the complex is also an important part of learning.

A very important part of any measurement is knowing how accurate the measurement must be. If someone asks your age, an answer to within a year is usually sufficient (e.g., age at last birthday). If someone asks your height, it is unlikely that either of you will take into consideration the heels on your shoes or when your hair was last cut. But a carpenter who measured the pieces of your kitchen cabinet only to the nearest inch would probably never be paid for the cabinet. And a difference of a thousandth of an inch could be enough to keep some parts of your automobile from working at all.

One rough but convenient way to designate accuracy is to specify how much time will be spent in a measurement. If it is not enough time to obtain a precision gauge or to check the gauge against reference standards, the accuracy will be less than the best possible. Measurements of time can easily be made with a typical watch or clock to the nearest 5 minutes of "absolute" time without checking, but by synchronizing the watch with standard time the accuracy can be improved to a few seconds. Time differences could be measured to within a few seconds with the same watch, without checking the calibration. Accuracy depends not only on the equipment but also on how it is used.

The following questions can be answered by direct observation or measurement without special equipment. Some are easy, requiring a single observation; others may require a planned series of observations and measurements. In either case, it is important to write down your observations and measured values. Where measurements are required, you may assume that no measurement should require longer than about 5 minutes and most will be within 1 minute. That will provide a guide to how accurately you can and should make your measurements.

Perhaps you can answer all of the questions right now. More likely, you can answer only some of them now, but you should be able to provide answers to all of them, by observation, before we discuss them in the chapters that follow. Do not wait to start; some of these observations must be made at special times.

We will start with some easy questions and work up to some whose answers you probably do not know yet. Even if you know an answer, however, confirm it with an observation. The practice will help with your other observations, and sometimes you will discover there are features you had previously overlooked.

A. OBSERVATIONS OF THE SUN Be careful not to look directly at the sun, except when it is very low on the horizon.

1. Where does the sun rise?
2. Does it rise at the same place each morning?
3. Does it rise at the same time each morning?
4. How long is the sun up? Is it always the same number of hours?
5. When, if ever, is the sun directly above your head? (How can you demonstrate that it is or is not directly above, especially without looking directly into the sun?)
6. Does the sun always follow the same path through the sky?
7. Does the sun look exactly round? If you have a simple magnifier lens, you can look at the image on a sheet of paper. When the sun is on the horizon you may be able to look directly at it without discomfort or danger.

B. OBSERVATIONS OF THE MOON It is especially important to keep notes on your observations of the moon, including dates, times, and directions, because you are more likely to miss observations of the moon, either because of obscuring clouds or simply because you are inside. Records will help you piece together a broader picture of how the moon appears at different times.

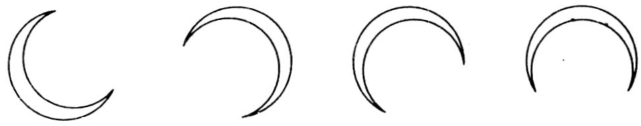

Figure 1.1.

1. Where does the moon rise?
2. Does it rise at the same time every day (or night)?
3. Is the moon ever totally nonvisible at night when the sky is not cloudy (that is, when you can see stars across the entire sky)?
4. Can you ever see the moon during the daytime?
5. Does the moon change its shape during the night?
6. Which of the shapes (including orientations, or "directions") shown in Fig. 1 can you see (not, of course, at the same time)?
7. Are you more likely to see any one of these in the morning than in the evening? If so, where in the sky?
8. Are you more likely to see any one of these in the evening than in the morning? If so, where in the sky?
9. If you were on a camping trip in the woods and woke up in the dark to discover that your watch had stopped but the moon was hanging near the horizon looking like Fig. 1.2,

a. Could you estimate the time from the moon?

b. Could you tell which direction is north by looking at the moon?

Figure 1.2.