CHAPTER 1

Introduction

1.1 OVERVIEW

Ours is an increasingly technological world. We take for granted the rapid pace of scientific progress and its consequences for our daily lives, exemplified by *Moore's law*, which says that computer speeds double about every 18 months [[1]]. This remarkable fact is familiar to many of us because most educated people in the western world use computers, to some extent, so that the speed increase with each successive computer purchase is evident. Less well known is the equally remarkable speed at which modern medicine advances. The situation is different, partly because medical progress of a patient is often not quantifiable and partly because most people are not aware of incremental developments in the medical field. For those individuals who are interested in understanding this progress, like this book's readers, it is fortunate that the underlying *principles of modern medicine change much more slowly than the applications themselves*. Since these principles and their connection to modern applications are the focus of this book, we are optimistic about its value lasting longer than the lifetime of most computers.

The reader of this text will become capable of understanding the fundamental basis of many of the most important medical tools used today. While space considerations alone constrain the extent to which we can provide detailed descriptions of these devices and the principles underlying them, there are several other reasons for this limitation. One is that two of the three authors (Cole and Strikman) are theoretical physicists, who are not researchers in this field. The third (Spartalian) is an experimental physicist familiar with the underlying scientific principles, but he, too, is not a researcher in the field of medical physics.

Another reason for the book's focus on general principles is related to the pace of technical advance; tomorrow's technology will not be that of today, so the details of the most recent developments are not crucially important for most readers to understand—except in those few instances when the progress is based on the application of *new* or *different* principles. Finally, we think that it is important for "students" (including the authors!) to appreciate how these developments have occurred; this means that some discussion of the history of these various developments is provided. For exam-

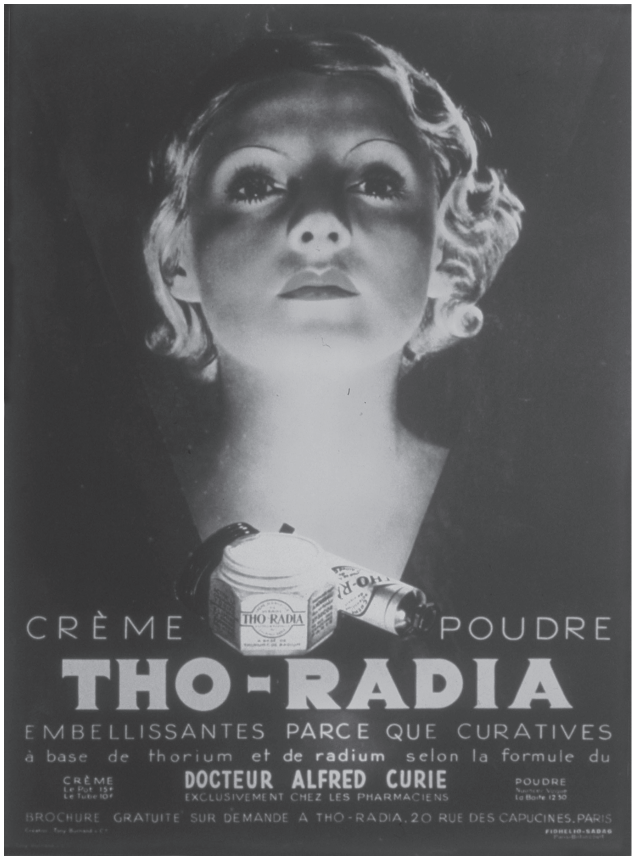

Figure 1.1. Advertisement for Tho-Radia cream and powder from 1934. It describes this product as beautifying because it is healing, made "according to the formula of" Dr. Alfred Curie, no relation to Pierre or Marie Curie. Figure provided by the Marie Curie Museum, Paris, where the advertisement's description labels this product as "very costly, but with such a small dose of radiation as to be harmless."

ple, by learning that some of the most famous pioneers of nuclear physics (e.g., three Nobel Prize winners: Pierre and Marie Curie and their daughter, Irène Joliot-Curie) suffered from radiation damage, one is reminded of the importance of laboratory precautions. By learning that António Egas Moniz won the 1949 Nobel Prize for the invention of frontal lobotomy, a now discredited technique, we are reminded of the ephemeral nature of some scientific "discoveries." Figure 1.1 provides another kind of learning experience, taken from an era when the perceived benefits of radiation received more attention than concern about its potential harm. The advertisement, shown in full color in plate 1, attributes to the radioactive skin product the glow emanating from the woman's face, exuding beauty and health. The subtitle "Embellissantes parce que curatives" translates as [these products are] "beautifying because (they are) healing."

Monographs and numerous scientific publications describe each of the tools of modern medicine. We will refer only to some of the most useful of these in the appropriate sections of this book. A reader interested in a complete, detailed survey of either the principles or their applications will have to search beyond this book. One place to find some relevant articles is the Web site accompanying this book, http:modernphysicsinmedicine.com. At that site is a bibliography of books and papers selected from the literature of medical physics, emphasizing articles at the level intended for readers of this book. Also found there are some of the classic articles important to the history of this field as well as a current version of the lectures accompanying this course.

The term *modern physics* appears in this book's title. Its meaning, which is conventional in physics, includes the numerous revisions of our scientific understanding that began with the discovery of X-rays by Wilhelm Roentgen in 1895 and that of radioactivity by Henri Becquerel in 1896. The flood of subsequent discoveries includes that of the particle nature of matter (atoms and the zoo of subatomic particles) as well as the laws of relativity and quantum mechanics. Many of these revolutionary findings are critically important for the subsequent progress in medical technology. In describing these relationships, we will do our best to explain the basic principles underlying them.

"Think like a physicist" is an expression often quoted in our community and an attribute that we hope to foster in our readers and students. This expression refers to a thinking person's ability to use whatever information is known to *estimate* a quantity of some interest. Such a strategy has immense practical value, even in the age of the Internet, when many alleged "answers" are readily obtained. A famous example of this approach is attributed to the Italian-American physicist, Enrico Fermi, who tried to imbue in his students an appreciation of this approach to both physics and thinking, in general. His classic question to his students was more or less this:

How many piano tuners work in the city of Chicago?

Obviously, this question has very little to do with physics, but it can be answered approximately with Fermi's approach to estimating quantities. For the sake of this book, we propose that you (the reader) address a more relevant question about medicine:

How many obstetricians are there in the United States?

Before reading the following "solution," try thinking about the problem patiently and then answering it as best *you* can. As you will see here, the Fermi way of thinking yielded different "solutions" for the three authors of this book, who addressed it independently. We will call our answers N_1, N_2, and N_3.

Here is one author's method of answering the question. His calculation (yielding N_1) assumes "steady state," meaning no net population growth. It also oversimplifies many other variables. Assume that there are 300 million residents of the United States. Of these, about half are female and, of those, perhaps a fourth are of childbearing age. This means that there are about 40 million women in the cohort who are capable, in principle, of bearing children. Let us suppose that each of these women has two children during her 20-year, childbearing interval. Hence, there are $2/20 = 0.1$ children per year borne by each woman. This results in a total of $0.1 \times 40 = 4$ million births per year. Now, let us suppose (and this is a completely uneducated guess!) that the average obstetrician delivers 3 babies per day for each of 300 working days of the year, or a total of 900 babies per year. By dividing this number into the total number of births, one concludes that there are about $N_1 = 4 \times 10^6/900 \sim 4000$ obstetricians in the United States. Note the rounding present at each step of the calculation, in recognition of the uncertainty present in each variable.

This "solution" to the problem can be written as a formula:

$$N_1 = \frac{(\text{population}) \times (\text{childbearing fraction}) \times (\text{children per year per eligible woman})}{(\text{delivery rate})},$$

$$N_1 = \frac{(300 \times 10^6) \times (\frac{1}{8}) \times \frac{1}{10}}{900} \approx 4000.$$

This very approximate formula is based on several crude estimates as well as rounding and hand-waving assumptions. We could provide uncertainties of each quantity, resulting in an estimate of the overall uncertainty in the calculation. Suppose, for example, that each of the four factors appearing in the preceding equation has an uncertainty of ±15%. Then, the final answer has an uncertainty of 4 × 15% = 60%. Thus, the actual answer could reasonably be expected to lie within the interval 1600 to 6400. That is quite an extended range of values, but perhaps even this uncertainty is an understimate.

The answer N_2 found by a second author of this book is much higher than these values: $N_2 = 40{,}000$ obstetricians, based on a set of alternative assumptions, equally naïve and equally valid. Start with a population of 4 million babies born in a year, estimated as before, which is equivalent to a birth rate of 13 babies per 1000 residents, that is, (4 million babies per year)/(300 million residents).

Assumptions of author 2:

(a) The mothers of each of these babies see an obstetrician for prenatal care.
(b) All pregnancies last 36 weeks.
(c) Including delivery, a mother is seen by her obstetrician 10 times altogether.
(d) An obstetrician sees 20 prospective mothers in a week and works 48 weeks per year.

From the last assumption, the number of visits per year to one obstetrician is 20 × 48 = 960 visits. The number of obstetricians is then given as follows:

$$N_2 = \frac{\text{total no. of maternal visits per year}}{\text{no. of visits per obstetrician per year}}$$

$$N_2 = \frac{4 \times 10^6 \times 10}{960} \approx 40{,}000$$

This answer is a factor of 10 higher than the previous estimate, N_1, even lying outside of the range of uncertainty mentioned before. The second calculation (made independently of the first) evidently relies on alternative assumptions. It is not obvious where either estimate made one or more fundamental errors. However, a careful examination will reveal that the different approaches correspond to a number of visits in the first case that is lower by a factor of 10 than in the second.

What about N_3, the third author's estimate? Without going into detail, we report that author 3's answer was $N_3 = 4000$ obstetricians, consistent with the first estimate. Does the agreement between authors 1 and 3 suggest that their answer is correct? No! Even unanimous agreement would ensure nothing; after all, most people thought the earth's surface was flat just a few centuries ago. In point of fact, according to the American College of Obstetricians and Gynecologists, there are more than 30,000 board-registered obstetricians or gynecologists in the United State at present. Hence the low estimate made by authors 1 and 3 is much less reliable than that made by author 2.

What is the lesson here for medicine and science in general? First, to reiterate, even if everyone obtains similar answers, such a consensus does not guarantee that the consensus answer is close to correct! We may all have made one or more unwarranted approximations. This happens often in science when new discoveries are made that contradict existing assumptions, however confidently these are held. The need to revise knowledge in the light of new evidence is especially important in the field of medicine; this is one aspect that makes the field so fascinating. However, remembering that human lives may be at stake, uncertainties have serious consequences. We must all be aware, at all times, of the provisional nature of human knowledge.

1.2 THE MEANING OF THE TERM *MODERN PHYSICS*

The understanding of physics achieved during the nineteenth century entailed numerous discoveries that gave the scientific community a well-justified sense of accomplishment. One of the most remarkable of these discoveries was the realization that *work* and *heat transfer* are closely related properties, the reason being that both involve the fundamental concept of energy. This realization led to a fundamental conclusion, embodied in the first law of thermodynamics:

Energy is conserved at the macroscopic scale just as it is at the microscopic scale.

Arguably of equal consequence is an apparently unrelated discovery involving a connection between two other physical properties:

Electricity and magnetism are "*unified*."

The term *unified* means that one must take into account simultaneously the presence of both electric and magnetic fields rather than considering either one in isolation. A change in one field necessarily induces a change in the other field. While manifestly of importance as a basic principle, this realization is also important for practical applications, such as electric power generation in a *turbine* and voltage change in a *transformer*. The climax of this discovery is often identified as the mathematical summary embodied in Maxwell's equations. The solution of these equations showed for the first time that light is a manifestation of the *electromagnetic field*. With these equations, one could show that a fluctuating current (as in an antenna) gives rise to an electromagnetic field that propagates outward from the source. This prediction was later confirmed in experiments of Hertz, who showed how radio waves can be created at a source and then propagate through space. Thanks to this discovery, previously inconceivable devices like telephones and cell phones (as well as electronic networking) became possible.

The confidence derived from these and many other discoveries was deserved—but surprises were yet to come. Many of these occurred within a few years of 1900, so many that the period was recognized as revolutionary. What emerged from this turbulent period is what we now call modern physics, a set of principles and resulting phenomena that could not have been anticipated by even the most imaginative thinkers of the day. These properties are discussed in chapter 3, where contrast is made to the "laws" that the discoveries replaced.

1.3 MORTALITY

Having referred earlier to "medical progress," we believe that it is worthwhile to describe its consequences before embarking on a detailed account of medicine's many developments, which constitutes the remainder of this book. There are many ways to address this progress question. The scope of this issue is much broader than can be presented here except in a cursory way. We attempt to do so nevertheless. Figure 1.2 compares mortality data in the United States for two specific years, 1941 and 2008 (chosen in part because the relevant statistics are available). The *mortality rate*, denoted by $\lambda(a)$ here, is defined as the *probability* that a person of age a will die in the coming year. The first point we note is the one most relevant to the present purpose, showing the progress of modern medicine: the mortality rate has decreased by a factor of about 2.5 over the 67-year interval between these two studies. For example, the figure reveals that an 80-year-old person had a 12% probability of dying (in the coming year) in 1941, while in 2008 this probability had fallen to just 5%. The rate λ is much smaller (about a factor 100 smaller), of course, for a 20-year-old person than for an 80-year-old person. Specifically, the rate $\lambda(20)$ fell from about 0.14% to 0.07% during the same 67-year interval. Particularly interesting, in our view, is that the decrease in mortality is so dramatic for young children, those younger than the minimum in the function $\lambda(a)$, which occurs at around $a = 10$ years. We believe that these longitudinal differences are attributable in large part to improved medical care,* although other variables, like better nutrition, shorter workday, reduced manual employment, greater awareness of the relation between lifestyle and health and improved sanitation, are also factors contributing to the reduction in mortality rate.

The abundance of statistical data permits quite-focused studies of individual kinds of disease. For example, the overall mortality rate in the United States declined by 45% between 1963 and 2010. This decrease has different contributions from the various individual diseases. For example, over this 47-year period, the death rate due to cardiovascular disease declined by 71%, while that due to noncardiovascular diseases decreased by just 5%. The difference between these percentages is usually attributed to two factors: a decrease in smoking (about 50% reduction during this period) plus the greatly improved diagnosis and treatment of heart disease, especially the use of medications to control cholesterol and high blood pressure (even though

* More specifically, a large part of this decrease in mortality is due to successes in treating and preventing heart disease and cancer, both of which came in the wake of advances in diagnostics and better treatment.

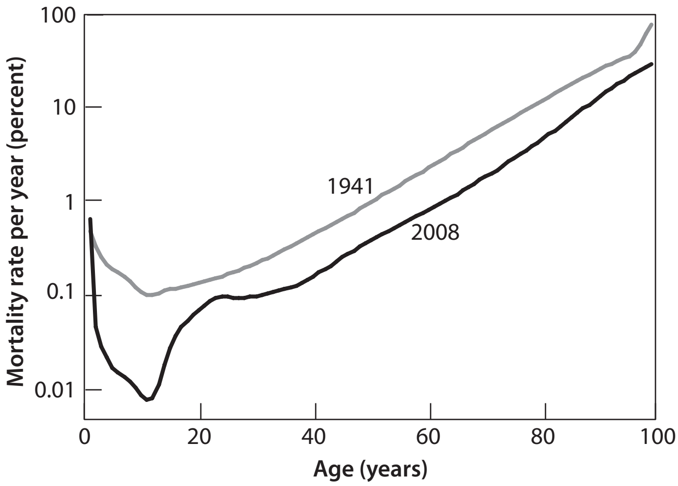

Figure 1.2. Mortality rate $\lambda(a)$ as a function of age for the United States in the years 1941 (light line) and 2008 (dark line), as indicated. Data from sources cited in the footnotes [2]. Note the logarithmic scale on the ordinate.

the risk factor of obesity is increasing rapidly*). During this same interval, incidentally, the mortality rate due to asthma and chronic obstructive pulmonary disease (COPD, which includes bronchitis and emphysema) actually *increased* by 156%! Since smoking is one primary cause of COPD, one is tempted to attribute the difference between the large increase in COPD and the large decrease in cardiac disease to one other factor: increasing air pollution, which is the second major cause of COPD. Such comparisons belong in the realm of epidemiology, which is outside of the primary domain of this book.

In appendix B we discuss the subject of mortality from a somewhat different perspective. One reason for doing so is to illustrate how simple mathematical models can capture the key ideas in a problem and yield accurate predictions of fairly complicated behavior. Such an approach, like Fermi's way of estimating physical quantities, is valuable for analyzing problems of medical physics.

1.4 HOW TO USE THIS BOOK

This book discusses topics varying considerably in their conceptual or mathematical complexity. Among these topics are many for which we aspire to convey just a *qualitative* understanding of the subject matter. For example, the next chapter is concerned with the physics involved in some traditional medical instruments, like the stethoscope. Technical details are not discussed because they are unnecessary and not very helpful, the basic reason being that the *physics* of the stethoscope has remained essentially that of the year 1900, which marks the advent of the modern era. This, however, does not imply that the device itself has not evolved; it is now much more sensitive than when first developed.

* During this interval, the obese fraction of the adult population in the United States has increased from about 13% to 35%, according to the National Institutes of Health. http://win.niddk.nih.gov/publications/PDFs/stat904z.pdf

In contrast to the second chapter, much of the book is concerned with techniques that require some understanding of the principles of modern physics. In some of these cases, we feel that a quantitative discussion is important. Then we present the mathematical apparatus that we regard as necessary for a quantitative understanding of the technique. Since not all readers may want or need that level of sophistication, such a presentation may be skimmed without sacrificing the qualitative side of the subject.

At the end of each chapter, we have appended a number of exercises. These are intended to consolidate one's understanding of the material by bringing together topics that are discussed in the text with knowledge already acquired in an introductory-level physics course. For some of these exercises, it is expected that one may either know or know how to find certain numerical values on the Internet. The required mathematical sophistication is at the level of a second course in calculus.

Having brought up mathematics, it is appropriate to discuss a subject not greatly appreciated: different systems of units, an unavoidable complication. While for the most part we feel obliged to use the modern SI system, there are many cases where other units are more practical and/or conventional (like electron volts in atomic and nuclear physics). In such cases, we usually present calculations in both sets of units. Appendix A presents tables of conversion between these systems, as well as values of the important constants used in this book.

EXERCISES

1.1 Let's practice thinking like a physicist, in the spirit of Enrico Fermi. We will consider three problems:

(a) You have Avogadro's number, $N_0 = 6 \times 10^{23}$, of grains of rice. For how long will you able to feed everyone on the earth, assuming that people eat only rice and that the population remains constant?
(b) Demographers have estimated upper limits to future population growth; now it is your turn. How many people can be packed on the land surface of the earth, assuming that each person is about one arm's length from his or her neighbors?
(c) Ben Franklin estimated the size of an oil molecule in the eighteenth century by pouring a teaspoonful of oil on a pond of area ½ acre. The result of his experiment was that the surface became "as smooth as a looking glass." What molecular size can be deduced from this finding?

1.2 Suppose that Jorge, an elderly man, contracts a disease with a *constant* mortality rate $\lambda = 0.2$ per year. What is the probability that Jorge will live at least 5 years after he first gets the disease? What is the probability that Jorge will live another 5 years but will not make it to the sixth year?

1.3 Figure 1.2 shows two nearly straight lines on a semilogarithmic plot. Each curve can be approximated by the equation $\ln[\lambda(a)] = m(a - a_0) + \ln b$, where m and b are constants, a is the age, and a_0 is some "initial age" below which the mortality rate is negligibly small and above which the curves are approximately linear. Consider the 1941 data.

(a) Assuming that $a_0 = 40$ years, estimate the slope m and intercept a_0.
(b) Estimate the median lifetime (the "life expectancy") such that one-half of the cohort born in 1941 is deceased. *Hint*: Use appendix B.

1.4 Note that the two curves in figure 1.2 differ essentially by a lateral shift by 12 years (beyond age 40). Making few (if any) additional approximations use this observation to argue that the life expectancy of the 2008 cohort exceeds that of the 1941 cohort by 12 years.

1.5 As reported in the CDC/NCHS National Vital Statistics Report, Vol. 61, no. 4, May 8, 2013, the overall mortality rate of black Americans has long been approximately 25% higher than that of white Americans. The data in appendix B show that approximately 50% of the 2008 cohort is predicted to die before age 82. What percentage of black Americans is predicted to die before that age?