To the student

The man who cannot wonder is but a pair of spectacles behind which there is no eye.
— *Thomas Carlyle, 1795–1881*

This is a book about the physical nature of light, and how it was transformed in the 20th century. This is also a book about the many uses living organisms have found for light, and the strategies they have evolved, especially the formation of visual images representing the world and their transmission to the brain. Finally, this is a book about extensions of light-based imaging, technologies invented from earliest times right up to the present, each of which brought revolutionary improvements in our understanding of the microworld.

That's a lot of territory, but I believe that every student, both in the life sciences and physical sciences, needs to know the basics of this field. For one thing, experiments keep demonstrating that Life makes specific use of the weird, yet manageable, quantum character of light: To understand your own vision, photosynthesis, or a host of other topics, you need to appreciate this aspect of Nature. Moreover, the recent explosion of superresolution and other advanced imaging techniques is also mostly inaccessible without that viewpoint.

The good news, which came as a surprise to me, is that *many important topics are no harder to understand from the modern viewpoint* than they are from the older one rooted in the classical, 19th-century model of light ("Maxwell's equations"). In fact, because so many biophysical topics seem to rely on quantum behavior, and so few on details of the classical model, the main part of this book will never introduce the heavy mathematical apparatus of Maxwell's equations at all. It's important for some rather specialized topics (for example, birefringence), but this book regards classical electrodynamics as a *more advanced topic* that you should learn *later*—it's an approximation that, when applicable, makes some detailed calculations more tractable. In this way, we will avoid the inevitable, uncomfortable moment when we must say, "Actually, everyone agrees that this (classical) model is wrong."

If you have already been indoctrinated in the older view, don't worry. Please keep an open mind to what the experiments described in the next chapters are telling us about light, and how the framework developed here can make sense of those experiments. With your background, you'll be able to delve into Chapter 13 and see the connection to what you've learned before.

Features of this book

- Most chapters end with an appendix labeled "Track 2." Some of these give extra details for advanced students, including literature citations. There are also Track 2 footnotes and problems, marked with the symbol $\boxed{T_2}$.
- Appendix A summarizes graphical and mathematical notation, then lists key symbols that are used consistently throughout the book. Appendix B discusses

some useful tools for solving problems. Appendix C gathers some numerical constants for reference. Appendix D gives a refresher on complex numbers.

- The notations "Equation x.y" and "Idea x.y" both refer to the same numbered series.
- When a distant figure gets cited, often its reference includes a small version of the image in the margin. You can look at this icon and decide whether you want to flip back to see the full figure and its caption.

Skills and habits

> You cannot become a ship's captain, nor any kind of craftsman, from reading a book.
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> — *Galen of Pergamum, second century CE*

Science is not just a heap of facts for you to repeat on demand. It is a collection of *skills and habits* that over time have proven successful at creating *new knowledge.* To be creative in that sense, you must begin by gaining fluency with the building blocks of scientific ideas. And reading this book, or any book, is only one part of a conscious strategy to gain that fluency. When this book poses a question, or when you hit a stumbling block, don't immediately look to see who has already answered that question on the Web. What will make you grow as a scientist is to attempt that problem yourself with the tools at your disposal. Later, when you attack problems that nobody has answered yet, this discipline will pay off.

Again: science is about doing things that *nobody has ever done before.* This book will tell you stories of how it has happened in the past, and offer you many opportunities to develop the skills you'll need when it's your turn. In fact, some are literally flagged with the tag "Your Turn." You'll find others as you read; take the time to derive each formula in the text, hit obstacles, and overcome them. You may need help from your instructor or a classmate for that. Use them.

One major skill emphasized in this book is writing short computer programs. Today essentially all science is done with the help of computers, so the sooner you acquire this skill the better. Several excellent software platforms now exist to help you do the everyday tasks that arise in the lab, and also when learning any subject. Some of these are free and open-source, for example Python, R, or Octave. You also can find a wealth of free help online, but be warned: You'll need a lot of daily experience before this unnatural activity begins to feel natural. Some available resources are written with the specific goal of helping you learn what you need in order to manipulate and visualize both experimental data and theoretical models, for example, the two short guides Nelson & Dodson, 2015, and Kinder & Nelson, 2015.

About you

Parts I and II of this book are a one-semester course intended for anyone who has completed a year of university-level physics and calculus. (I have found, however, that even students with much more background than that find many topics and ideas here that did not come up in their earlier courses.) In addition, you may want to read some or all of the "Track-2" sections at the end of each chapter. The chapters in Part III cover advanced topics; here you will need background from other courses on quantum mechanics or electromagnetism.

Very few biological or chemical prerequisites are assumed, though from time to time you may need to use an external resource to fill in some of the background to the story.

Mostly, this book assumes a great deal of curiosity on your part about how the world works, including things you see around you every day. In fact, it's useful to visualize science as a form of espionage: We have some distant, complex adversary (perhaps cancer, or blindness). We belong to a far-flung network of people who are trying to find useful things. Some have obviously relevant missions. That's called applied research.

But other agents are out there trying to understand the world by looking for things that *don't fit.* That's called pure research. It could be something that other people have seen without realizing that it doesn't fit. It could be pointing to an important nugget of intelligence, as we will see in a number of case studies. We must integrate, think laterally, maybe discard preconceptions. Sometimes there is a high-tech gadget that we can invent to get the key datum, perhaps originally designed for a very different purpose.

Like real spycraft, the work is often mundane, and sometimes lonely. Often it ends up not directly benefiting anyone. But sometimes there's a valuable insight, maybe not useful for the purpose we had in mind, but someone else can see the connection to something important. Sometimes lives get saved. Let's get started.