CHAPTER ONE

Introduction

In the right light, at the right time, everything is extraordinary.
— Aaron Rose (quoted in *Live in the Light: A Journal of Self-Enlightenment*, Mary Engelbreit)

Of all the remarkable substances of our experience—rain, leaves, baby toes—light is perhaps the most miraculous. Essentially indefinable, it is the ultimate food for our planet's life and allows us to perceive the world in nearly magical detail and diversity. Via warmth, vision, and photosynthesis, and its darker aspects such as radiation damage, light interacts fundamentally with nearly all forms of life. Only certain subterranean species may be free from its influence.

Despite this, light remains relatively unstudied by biologists. In my own field of oceanography, we have instruments known as "CTDs" that measure salinity and temperature as a function of depth. These devices are ubiquitous, and the characterization of a body of water is considered incomplete without the data they provide. However, even though light is known to fundamentally affect the distribution, ecology, and behavior of marine organisms, it is seldom measured, despite the availability of economical light-meter attachments made specifically for this instrument. Oceanography is a field known for the tight connections it provides between biology and physics; in other biological fields light measurement is rare. Even worse, many light measurements are taken incorrectly. It is no fun to tell a colleague that, because they didn't put a two-inch cardboard tube around their detector, the data they collected over the last three years is unsalvageable.

In my opinion, the relative lack of optics in biology is primarily the result of a few factors. First, biologists receive very little training in the subject. What they do get is usually confined to the electromagnetism portion of an introductory physics course that derives Maxwell's equations and Coulomb's Law but gives little practical advice about working with light. While there are some good laboratory courses in optics, they're generally populated by physics majors. Second, no other field uses such an arcane and confusing collection of units. Sorting absorbance from absorption, and irradiance from radiance is hard enough without having to do it using nits, candles, and footlamberts. Third, the equipment needed is generally geared toward physicists, advertised in their journals, and using their units and terminology. This equipment, while smaller and cheaper than it used to be, is still relatively expensive and fussy compared to, for example, a lab balance.

Finally, and perhaps most importantly, there are few good books. Yes, there are excellent books on optical theory and instrumentation, but they assume a graduate degree in physics or engineering. The three exceptions, *Clouds in a Glass of Beer* and *What Light Through Yonder Window Breaks?* by Craig Bohren, and *QED* by Richard Feynman are wonderful books, but give little practical advice. There are a few excellent books on the optics of vision, my favorite being *Animal Eyes* by Michael Land and Dan-Eric Nilsson, but they do not cover other biologically important aspects of light such as scattering, emission, and absorption.

Therefore, the few biologists working with optics either came in with a physics background (and, like myself, had a lot to learn about biology) or were trained by the even smaller number of biologists familiar with the subject. This has led to a bottleneck where there are many more interesting bio-optical problems than there are people able to work on them. One of my favorite activities as a child was to take apart small natural dams in creeks. It is my hope that this book, by providing the basics necessary to measure and use light in biological research, will breach this bottleneck and lead to a flood of new results and insights.

What Is Light?

Optics is about light, so perhaps we should start with what light is. I have no idea. I have thought about light since I was five years old and am no closer to understanding its fundamental nature. I am in good company though. Even Richard Feynman, one of the creators of the theory of how light and matter interact and widely acknowledged as one of the best explainers of physics, said that light cannot be understood. We have mathematical formalisms that let us predict what light will do to a precision of more than twenty signifi-

Figure 1.1: Darth Vader meets Golden Snitch. *Scientific American's* depiction of a photon in the 1970s and 1980s.

cant figures, but no one has come up with a description of light that makes sense. It is unlikely that anyone ever will.

The root of the problem lies in what is called wave-particle duality, which is usually described as "light sometimes behaves like a particle and sometimes behaves like a wave." In particle language, a beam of light is a stream of photons—small massless particles with energy and momentum that travel at high speeds. In wave language, a beam of light is a series of waves of changing electric and magnetic field strength that have phase, amplitude, and wavelength, and—like photons—travel at high speeds. To intuitively describe what light does, you have to jump back and forth between these two interpretations. This isn't easy. It's hard enough to think of something as being both an apple and an orange, let alone both a microscopic ball and a diaphanous wave that extends throughout space. Combining the two images does no good at all. For example, when I was young, the magazine *Scientific American* depicted photons as little spheres with wave-shaped wings, a ridiculous image that has stuck with me for almost forty years (figure 1.1).

People, especially physical scientists, seem to have an innate intolerance of ambiguity, so many physicists have chosen sides. Some, like Lamb (1995) castigate others for using the photon concept. Others, including Feynman (1985), have stated that light is a particle, end of story. Because wave-particle duality is not limited to light, but is a property of all particles, this has become a fundamental argument about how to describe our universe. Read enough about it, and your head will start to itch.

Maybe light honestly is one or the other, but I prefer a practical approach. In my opinion, sometimes the results of experiments with light are more easily predicted or intuited using the mathematics and metaphors appropriate to waves; and sometimes the results are better explained using the mathematics and metaphors appropriate to particles. I prefer to think about the emission and absorption of light in photon language, imagining photons as little hyperactive balls flying out of light sources and being sucked up by matter. I think of polarization and interference in wave language. These two phenomena can be described using particle language, but it's a bit like using political science to teach someone how to fry a chicken. Scattering is a gray area for me, and I jump back and forth between particle and wave language when thinking about it.

This indecision on my part gets complicated when dealing with quantum mechanics, a topic that I'll visit in the last chapter. However, except for some of the more complicated aspects of photochemistry, the truly weird parts of quantum mechanics are not relevant to biology. In fact, some would argue that, because the uncertainty principle, nonlocality, and other aspects of quantum weirdness play no role in the everyday life of humans, there has been no natural selection for a commonsense understanding of them. So, until we meet a species in which quantum weirdness is experienced directly, and that could possibly explain it to us, I think we're left learning to be comfortable with the fact that some aspects of nature are non-intuitive.

However, while the non-intuitive nature of light can be unsatisfying, it doesn't affect our ability to predict events. In other words, as long as you do your measurements and math correctly, you can think of light as little purple buffaloes and it won't matter. After all, we don't really understand the fundamental nature of anything, but manage just fine.

What This Book Is

The remainder of this book is divided into four major sections. The first short section, comprising only the second chapter, attempts to clear up the mess of units that has turned many people away from optics. The next and largest section, running from chapters 3 through 8, describes the various things that light can do, starting with what Craig Bohren calls the birth, life, and death of a photon (emission, scattering, and absorption) and concluding with fluorescence and polarization. The goal of all these chapters is to provide as unified a view of these processes as possible. So, for example, refraction and reflection are treated as special cases of scattering. Biological examples are given to illustrate various points, but the focus is on explaining these fundamental processes.

The third section, found in chapter 9, is a guide to measuring light. This chapter is meant to be practical and detailed. While not a complete manual for producing publishable measurements and models, it should give you the general lay of the land, and most importantly, identify the major pitfalls.

As mentioned above, the book concludes with a brief chapter on quantum mechanics. While by no means comprehensive, it provides a flavor of the fundamental weirdness of light and all matter. The chapter focuses on two central experiments, the interference of light passing through two slits and the effect of measurement on pairs of entangled photons.

This book is short. I did not want to write an encyclopedia, perhaps because I do not enjoy reading them. Because it is short, I wrote it to be read in its entirety. Later chapters often build on material discussed earlier. While the descriptions in this book are brief and (hopefully!) accessible, they have been vetted for accuracy by a number of experts in optics. I'm sure I still screwed up somewhere, but hope it's nothing serious.

What This Book Is Not

What this book is not is vastly larger than what it is. Most importantly, this is not a book about vision or visual ecology. As I mentioned, several excellent authored and edited volumes on human and animal vision exist and can be found in the bibliography. While the book contains some examples drawn from vision research, it is far from comprehensive.

This is also not a book about quantum theory. Again, there are many good books on quantum weirdness, far more in fact than there are on vision. While the last chapter gives a sense of this non-intuitive subject, the bulk of this book deals with classical optics.

This book is also not a comprehensive account of optics or the history of the field. There are massive tomes covering all optical subjects and equally massive and conflicting accounts of the history of the field. It has been said that the person credited with a scientific law is almost certainly not the one who discovered it. Gustav Mie was actually the last person to discover the scattering that bears his name, neither Lambert nor Beer are truly responsible for the Lambert-Beer law of attenuation, and Snell of Snell's Law has had his name spelled wrong for a couple hundred years now (it's actually Snel)

(Bohren and Clothiaux, 2006). I will do my best to give credit where credit is due, but not at the expense of brevity or my central purpose.

Finally, this is not a book for experts. My goal is to briefly and accurately cover what 90 percent of biologists need to know to use optics in their research. As much as possible, complex equations and second-order effects have been omitted. Therefore, if you want to know the difference between Fresnel and Fraunhofer diffraction, what a surface plasmon is, or to delve into the subtleties of nonlinear optics, please consult the excellent texts suggested in the bibliography. I have however, included a number of appendixes that include formulas and constants useful for researchers at any level.

In summary, this book was written to give biologists a brief and clean introduction to this fascinating field. If it does this and encourages you to explore more deeply, via the many excellent and more specialized texts and—more importantly—via your own experience, I'll be satisfied.

Further Reading

My favorite popular books on optics are Craig Bohren's *Clouds in a Glass of Beer* and *What Light Through Yonder Window Breaks?*. These two books, mostly consisting of articles from the journal *Weatherwise*, are down-to-earth explanations of various topics in optics and thermodynamics. Never one to accept conventional wisdom, Bohren is insightful, empirical, and fun to read.

If you're up for the math, Bohren wrote another book with Eugene Clothiaux that I think is the best optics text ever written. Despite the rather specific title *Fundamentals of Atmospheric Radiation*, it covers all the essential aspects of optics. It is also oddly (and accidentally) convergent on the book you are holding, possibly because atmospheric scientists have a similar desire to make optics accessible to a larger world. Unfortunately for biologists, it requires a fair bit of mathematical and physical knowledge to fully appreciate. However, you can still get a lot from reading the summaries and conclusions. It is also one of the few physics texts that is actually funny.

Richard Feynman's *QED*, a highly revised transcript of four public lectures on optics and particle physics, should be read by every scientist. It goes from mirrors to quantum physics in 150 simple pages. Even if you don't ever work with light, the book is worth reading to see how much can be derived from so little.

By far the best book on the optics of eyes is *Animal Eyes* by Mike Land and Dan-Eric Nilsson. It manages to explain the diverse eye architectures of the animal kingdom via a few basic principles.

Finally, if you can afford (and can lift!) it, the *Handbook of Optics*, published by the Optical Society of America and edited by Michael Bass is an amazing resource. The 1995 second edition comes in two volumes, its eighty-three comprehensive chapters covering just about everything you would ever want to know, from basic geometric optics to thin-film coatings to optical oceanography to making holograms. There is even a sixty-three-page chapter on making things black. The third edition just came out in 2009 and comprises five volumes and weighs twenty pounds. I can't imagine what else they found to add.