EXPLORING QUANTUM PHYSICS THROUGH HANDS-ON PROJECTS

DAVID PRUTCHI AND SHANNI R. PRUTCHI

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In memory of Zeide Simon.
Dedicated to Saba Shlomo, Savta Ruthi, Babbe Rosmari,
Dorith, Hannah, and Abigail.

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INTRODUCTION

> Tell me and I forget. Teach me and I remember. Involve me and I learn.
>
> —Benjamin Franklin

Physics developed steadily after the introduction of Isaac Newton's ideas in the 1600s and had made great progress by the nineteenth century. People really felt the impact of this knowledge when the Industrial Revolution was made possible by the application of everything that scientists had learned about mechanical forces, gravity, electricity, magnetism, heat, light, and sound.

By the late nineteenth century, scientists felt that all of this understanding of physics formed a framework that could describe the world very deeply and thoroughly. Still, there were some nagging inconsistencies between theoretical calculations and experimental data, which were acknowledged by Lord Kelvin (who formulated the First and Second Laws of Thermodynamics) in his 1900 lecture titled "Nineteenth-Century Clouds over the Dynamical Theory of Heat and Light." The two "dark clouds" to which he was alluding were the unsatisfactory explanations that the physics of the time could give for the constancy of the speed of light, as well as for the glow produced by a hot body.

What is now known as "modern physics" was born from the two major physical theories that were developed during the twentieth century to resolve these two "dark clouds": for the former, the Theory of Relativity; for the latter, quantum mechanics.

The shift caused by modern physics was dramatic, because new concepts showed aspects of reality that are completely different from our day-to-day observations. The Theory of Relativity describes how events look very different for two observers who are moving relative to one another. It makes really bizarre predictions about the way clocks tick relative to one another when they move, how objects are measured to be shortened in the direction that they are moving with respect to the observer, and how energy and mass are equivalent (described by the famous equation $E = mc^2$).

Quantum mechanics makes statements that are even weirder than those of relativity. In the odd world of quantum physics—at least as explained through the extreme thought experiments of its original founders—objects can be in two places at the same time, cats can be both simultaneously dead and alive, and everything that looks continuous to us is really pixelated into tiny, discrete chunks.

Exploring Quantum Physics Through Hands-On Projects. By David Prutchi and Shanni R. Prutchi

In spite of its strangeness, a working knowledge of relativity requires no more than basic algebra and geometry. After all, relativity is just a more fundamental, up-to-date, and accurate version of the classical physics founded by Newton. On the other hand, quantum mechanics is much more difficult to understand. Richard Feynman, a physicist who won the Nobel Prize for his work on quantum physics, didn't believe that anyone really understands what the theory tells us. In his words: "I think I can safely say that nobody understands Quantum Mechanics."

Nevertheless, quantum mechanics works so well that it has enabled the development of lasers, transistors, chips, and displays used in the electronic gadgets that are so important to our modern lives. Because of this, quantum physics ought to be an important part of everyone's education. However, the math is so complex, and our most intuitive notions about reality are so shockingly wrong, that understanding of this subject has remained largely confined to a select group of physicists and engineers. Unfortunately, this has also led to many popularizations that grossly misguide readers and give them completely false notions about the concepts and implications of quantum mechanics.

In this book we will try a different approach. The idea is to build an intuitive understanding of the principles behind quantum mechanics through hands-on construction and replication of the original experiments that led to our current view of the quantum world. We have developed the experimental setups in such a way that they can be constructed easily and at low cost. In addition, we have worked and re-worked the math, so that it is accessible to anyone with knowledge of high school algebra, basic trigonometry, and, if possible, a little bit of calculus. We want to point out that in spite of the many simplifications that we make, we strive to present a conceptually correct view of quantum physics to those who are not conversant in its highly specialized jargon and formalism.

Our approach comes from the belief that there is a huge difference between knowing about something and actually understanding it. We believe that if one is to understand anything about quantum mechanics, one must first develop a "gut feeling" about the quantum world, to get past the mystical veil that so tightly wraps its inner workings. We are hands-on tinkerers, so we follow Benjamin Franklin's approach toward education: "Tell me and I forget. Teach me and I remember. Involve me and I learn."

Our hope is that the do-it-yourself approach will demystify quantum physics, and help you navigate away from sensationalistic, speculative, or outright false accounts of this incredibly beautiful field.

Quantum effects tend to vanish as the size of an object increases. For this reason, quantum experiments are practical only for very small objects, such as photons (bits of light), electrons, protons, and other subatomic particles.* In this book, we will show you how to adapt commonly available electronic components, hardware store supplies, and other relatively low-cost items that can be purchased online to reproduce some of the most ground-breaking experiments ever done in physics!

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*The difficulty of studying quantum effects on even slightly larger objects, such as atoms or molecules, is so great that only a few labs around the world are equipped to handle this difficult task.

Throughout the book, we will slowly build up a quantum picture of the world. The first chapter will have you become familiar with the way nineteenth century physicists understood light. Despite the advent of quantum mechanics, nineteenth century optics is still used today to make camera lenses, glasses, telescopes, and microscopes. However, the misbehavior of classical optics under very specific circumstances was one of the two clouds looming on Lord Kelvin's horizon. Understanding the classical view of light is key to appreciating why quantum mechanics would stir such a revolution in physics. In the first chapter, we will perform the experiments that seemed to confirm the correctness of the classical understanding of light's nature, but we'll also look at some of the problems raised by these same experiments.

In the second chapter, we will replicate the experiments that produced the data that could not be reconciled with the theoretical explanations of classical physics. We will study the sweeping explanations proposed by Max Planck and Albert Einstein to resolve this issue.

The third chapter will get us into atomic physics and radioactivity. We will build equipment to perform the experiments that gave us our current view of atoms and that brought chemistry into the modern era.

Next, in chapter 4, we will look at *quantization*—the core principle behind quantum mechanics—and at some of the ways in which it successfully tackles one of Lord Kelvin's "dark clouds."

In the experiments of chapter 5, we will take advantage of technology that was unavailable to the pioneers of quantum mechanics to show that both light and material objects can behave with the characteristics of both waves and particles. This is where quantum physics starts to get really weird, allowing particles to behave as if they are in two places simultaneously!

Chapter 6 will introduce Heisenberg's Uncertainty Principle—the concept that we cannot measure the exact position and momentum of an object at the same time. We will see that this is not due to imprecise measurements. Technology is advanced enough to hypothetically yield correct measurements. Rather, the blurring of these magnitudes is a fundamental property of nature with truly mind-boggling implications about our view of reality.

In chapter 7, we will talk about Dr. Schrödinger and his famous pet. We won't be conducting any experiments with dead or alive (or zombie) cats, but we will build some hands-on demonstrations that show Schrödinger's legendary thought experiment in action.

Last, chapter 8 looks at demonstrations of the existence of *entanglement.* This quantum property is so uncanny that it caused Einstein to mock it by calling it "spooky action at a distance." Entanglement was proven only in the 1980s, but its deep implications are already causing radical changes in the way in which we view our world. We will also look at technologies that are being developed as a consequence of understanding the role of information in quantum mechanics, and will end the book by peeking at how entanglement is quickly making strides into areas that until recently were purely the domain of science fiction, enabling quantum teleportation, unbreakable cryptography, and quantum computing.

PROLOGUE

YOUR QUANTUM PHYSICS LAB

This book assumes that you have some experience in electronic prototype construction. The circuits actually work, and the schematics are completely readable. It will be easy for you to understand them if you know some circuit design. However, the tested, modular circuits, components, and software are easy to use to build practical instrumentation, even if you view them as "black boxes," and do not explore their theoretical basis.

Of course, there are some basic electronic instruments that you will need in order to build, test, and use the equipment that we describe in this book. At the very least, you should equip your lab with the following:

- Soldering pen, pen rest with wet sponge, solder wire, and solder wick. Preferably, you should use a 70-W soldering station in which you can adjust the temperature between 220–480°C.
- Assorted tools, including a sharp diagonal wire cutter, wire stripper, various screwdrivers, hobby knife, needle-nose pliers, etc.
- Two handheld, autoranging, $4\frac{1}{2}$-digit, digital multimeters (DMMs). We suggest that you purchase two identical units. Tektronix and Fluke multimeters are recommended, but any of their $4\frac{1}{2}$-digit look-alikes (sold for around $35) are okay.
- High-voltage probe (>40 kV) compatible with your multimeter.
- Dual-channel, 60-MHz oscilloscope with FFT module. We recommend a second-hand Tektronix TDS210 with FFT module. However, there are many look-alikes that will work equally well. As a lower-cost alternative, you can consider connecting your PC to a USB dual-channel, 60-MHz oscilloscope adapter.
- Adjustable, metered, dual-output, linear, bench power supply. You want a unit capable of delivering two outputs adjustable between 0 and at least 20 VDC at 2 A each. A used Tektronix PS280 would be ideal.

The following are really helpful, but not absolutely necessary:

- High-voltage DC power supply. Ideally, you want to acquire a well-regulated power supply with selectable polarity (that is, you can choose whether the output referenced to ground will be positive or negative) and a range of 0–2,000 V with at least 1-mA current capability. A used HP 6516A would be great.
- Function generator. Doesn't need to be fancy. Something that will produce sine, triangular, and square waves at frequencies of up to at least 1 MHz will do.

- 10-MHz pulse generator. Nothing excessive. We recommend something like a Global Specialties model 4010.
- Spare PC with at least 2-GHz Pentium 4 processor and 2-GB RAM. You should install student editions of Excel and MATLAB to log, plot, and analyze the experimental data that you will obtain.

Since the prime subject in quantum physics is the photon (a particle of light), you will need a few lasers. Fortunately, laser pointers have dropped dramatically in price, placing in our hands wonderful, well-behaved “photon sources” that just a few years ago would have been out of the reach of anyone but the most advanced labs in the world. We recommend that you equip your lab with the following lasers:

- IR diode laser, 980-nm wavelength, 30-mW power.
- Helium-neon (HeNe) laser, 632-nm wavelength (red), 5-mW power.
- Red laser pointer, 670-nm wavelength, 5-mW power.
- Green laser pointer, 532-nm wavelength, 5-mW power.
- Violet laser, 405-nm wavelength, 100-mW power.

Many of the setups require mechanical construction. We have tried to keep this to a minimum by using off-the-shelf parts, but you will need to do some drilling and shaping. Most of the enclosures are made of aluminum, so you should have a handheld drill with a full set of drill bits. You will also need a good hacksaw, tin snips, and a nibbler, as well as an assortment of tools to tap holes, bend metal rods, and assemble parts together.

In addition, you should start a well-organized “junk box” to keep your electronic and optical components. We use plastic stacking shoe boxes that are neatly labeled to keep our parts organized. Useful parts that you may want to collect from old equipment or surplus sales include:

- Capacitors, resistors, inductors, and other passive electronic components.
- Aluminum boxes, power supplies, power adapters, power cords, fuses, rocker switches, panel lights, panel meters, prototyping boards, and other parts to build and enclose instruments.
- High-voltage diodes and capacitors from microwave ovens, old TVs, and CRT monitors.
- Strong magnets from damaged hard drives.
- Old oscilloscope CRT screens, even if the CRTs are dead.
- High-speed op-amps, comparators, and other linear ICs.
- Light-emitting diodes (LEDs) of different colors.
- Laser LEDs and laser modules from CD, DVD, and Blu ray^{TM} players/recorders, and laser pointers.
- Lenses and high-quality mirrors, such as those found in old cameras, binoculars, and projectors.

- High-voltage flyback transformers from old color TVs and CRT monitors.
- Items containing small amounts of radioactive materials such as ionization-type smoke detectors, old-style lantern mantles, and old luminescent watch hands.
- Polarizers from camera lenses, sunglasses, and 3D movie glasses.

Lastly, a word about where to find bargain components and instruments—storefront surplus stores (at least those dealing with electronics and science) are a disappearing breed. Most surplus is traded today on eBay® and other Internet auction sites (e.g., www.ebid.net, www.LabX.com, etc.) The best finds on eBay usually come from estate sales, as well as from people who specialize in buying surplus lots from the government or hi-tech companies that are going out of business. Before bidding on anything, check on the reputation of the seller, and read the item description very thoroughly. From our experience, we can tell you that "unable to test" most often means "broken and not repairable." Especially when buying online, *caveat emptor!*

A few interesting brick-and-mortar surplus stores are still around.* They have a presence on the Internet, but you will find the most interesting pieces by rummaging through their shelves. If you travel around, try to take a detour and visit the following:

- Apex Electronics in the vicinity of Los Angeles, California: You will find racks and racks full of electronics equipment, as well as a yard full of junk (including rocket parts). Plan to spend a full day browsing or leave empty-handed and confused!
- The Black Hole of Los Alamos in Los Alamos, New Mexico: It is similar in character to Apex, but is heavily loaded with atomic research surplus from the Los Alamos National Lab.
- Fair Radio Sales in Lima, Ohio: You will find racks and pallets full of unclassified surplus equipment. It is quite far from the major cities in Ohio, but the drive is worthwhile, since it contains many wonderful one-of-a-kind items that don't make it into their catalog.
- Murphy's Surplus Warehouse near San Diego, California: You will find some of the best surplus military equipment to be found! Definitely a worthwhile place to visit.
- Skycraft Parts & Surplus, very close to Disney in Orlando, Florida: Very cool store. Worthwhile visiting, especially if you have had it with Mickey Mouse and his friends! It is full of otherwise unobtainable stuff, much of it surplus directly from NASA's Kennedy Space Center.
- Surplus Sales of Nebraska in Omaha, Nebraska: This is a place that we haven't visited, but we often purchase very unique equipment from them via their Web site. We can just imagine what unadvertised jewels their warehouse may contain!

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*For readers in Europe, Army Radio Sales in London, United Kingdom, has an excellent selection of useful items. Unfortunately however, they are a mail-only business. You cannot visit their warehouse.

Whether you are a student, hobbyist, or practicing engineer, we hope that this book will help you find how easy it is to understand the principles of quantum physics by building and experimenting with sophisticated setups at a small fraction of the comparable commercial cost.

For additional information, updated software, and more information on the projects detailed in this book please visit our Web site at: www.prutchi.com.

IMPORTANT DISCLAIMER AND WARNINGS

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SAFETY AND GENERAL PRECAUTIONS

Many of the projects presented in this book involve power supplies that pose severe electrical shock hazards. In addition, some of the projects involve sources of laser, microwave, or ionizing radiation that may present hazards to the user, especially to sensitive tissues, such as those of the eyes. It must be stressed to the builder the need to exercise safety precautions involving proper handling, building, and labeling of potentially dangerous equipment. The builder and users of equipment described in this book assume full responsibility for the safe use of such devices.

Warnings Related to the Use of High-Voltage Power Supplies

High-voltage power supplies present a serious risk of personal injury if not used in a safe manner or by unqualified personnel. Needless to say, you need to exercise utmost care when conducting an experiment that uses high voltage. However, you also need to be careful after turning off the power supply, because many power supplies and the devices to which they connect can store energy, so that even with the unit unplugged from the wall a lethal hazard can still exist.

Always remove metal objects such as rings, jewelry, and watches before working with high voltage. Keep one hand in a pocket or closed behind your back and we recommend you wear rubber-soled shoes. Always prove to yourself that there is no voltage present anywhere in the high-voltage equipment on which you are working. Never rely on just one switch to power down a high-voltage supply. Turn the power switch off and disconnect the cord from the wall outlet. Be sure no one will inadvertently reconnect the power while you are working on the device. When working with power supplies of several hundred volts or higher, be especially aware that fully discharged capacitors can "self-charge" through the phenomenon of dielectric absorption.

Lastly, never work with high voltage alone, and never leave a high-voltage experiment unattended!

Warnings Related to the Use of Lasers

Lasers produce a very intense beam of light. Even low-power laser pointers can cause permanent damage if pointed directly at the eye! The coherence and low divergence of laser light means it can be focused by the eye into an extremely small spot on the retina, resulting in localized burning and permanent damage in just an instant. Certain wavelengths of laser light can cause cataracts. Infrared and UV lasers are particularly dangerous, since the body's "blink reflex," which can protect an eye from excessively bright light, works only if the light is visible.

Before turning on a laser, always be sure that it is pointed away from yourself and others. Never look directly into a laser, and never direct a laser at another person. Follow the same rules for direct reflections of laser light from reflective surfaces.

Warnings Related to Exposure to Ultraviolet Light

Ultraviolet light can cause permanent eye damage. Do not look directly at UV radiation, even for brief periods. If it is necessary to view a UV source, do so through UV-filtered glasses or goggles to avoid damage to the eyes. Take appropriate precautions with pets and other living organisms that might suffer injury or damage due to UV exposure.

In addition, please note that light from violet LEDs and lasers may contain substantial amounts of UV light that is absorbed largely in the lens of the eye and may cause cataracts.

Warnings Related to Microwave Exposure

Although the microwaves generated by the Gunnplexers that we will describe in the book are weak, the output is sufficiently concentrated that it could cause eye damage at very close range. Never look into the open end of a Gunnplexer while it operates at a distance under 50 cm.

Warnings Related to the Use of Sources of Ionizing Radiation

The radioactive sources recommended for use in the experiments described in this book are professionally manufactured, sealed sources that are exempt from U.S. Nuclear Regulatory Commission and state licensing. They present no special storage or disposal requirements. The activities of these sources are sufficient to conduct nuclear science experiments using standard Geiger–Müller (GM) counters or scintillation detectors, yet low enough not to present any radiation hazard. Nevertheless, we recommend using lead shields when shipping or storing multiple gamma sources to reduce radiation levels.

Make sure that the radioactive source disks are never breached or damaged. The major hazard with a breached sealed source is that radioactive materials could enter the body by inhalation, skin absorption, or ingestion. Immediately place a damaged source inside a zippered plastic bag and dispose of it according to the manufacturer's instructions.

Everyday items such as smoke detectors, old lantern mantles, and watches with radium-painted dials are radioactive sources that must be treated with respect. Most of these items are no longer manufactured, as exposure to the radioactive material was a health threat to the employees who made them. These everyday items were not designed for instructional or experimental use, and may therefore be hazardous when used for purposes other than originally intended.

Another potential source of radiation in the experiments described in this book comes from the use of vacuum electron tubes powered at over 15,000 V. Detectable levels of X-rays may be produced, depending on the conditions in which these are operated. Caution must be exercised by the experimenter to ensure adequate safety.

Warnings Related to the Use of Vacuum Tubes

Vacuum tubes, especially large ones, present a safety hazard if the tube breaks. Flying glass and electrodes can travel great distances when a tube implodes. This is a particular danger when large tubes, such as CRTs, are used. Treat all glassware under vacuum with respect. Safety glasses should be worn at all times to protect your eyes from flying glass should the glassware break and implode. Before each use, check all vacuum glassware for scratches, cracks, chips, or other mechanical defects that could lead to failure.

Warnings Related to the Use of Rare-Earth Magnets

Some of the projects in this book involve the use of rare-earth magnets (e.g., neodymium and samarium-cobalt magnets), which produce very intense magnetic fields at close distances. The chief hazard with these magnets is that they are strong enough to cause injuries to body parts pinched between two magnets, or a magnet and a metal surface. In addition, magnets allowed to get too near each other can strike each other with enough force to chip and shatter the brittle material, and the flying chips can cause injuries.

Warnings Related to the Use of Chemicals

Some of the experiments described in this book involve the use of hazardous chemicals. Please read the original supplier's MSDS (material safety data sheet), and make sure that you understand how to properly handle each material regarding its toxicity, health effects, first aid, reactivity, storage, disposal, protective equipment, and spill-handling procedures.

Warnings Related to the Authors' Attempts at Humor

Throughout this book, the authors sometimes attempt to use humor to explain certain concepts in a light-hearted manner. However, the authors are not professional comedians, and thus cannot assure the desired effect. Be assured, however, that the authors do not intend to offend any dead, alive, zombie, or otherwise undecided cats.

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ABOUT THE AUTHORS

David Prutchi received his Ph.D. in Engineering from Tel-Aviv University in 1994, and then conducted postdoctoral research at Washington University. His area of expertise is the development of active implantable medical devices, and he is currently the Vice President of Engineering at Impulse Dynamics. He is an adept do-it-yourselfer, dedicated to bringing cutting-edge experimental physics within grasp of fellow science buffs.

Dr. Prutchi has published over 30 papers and holds over 70 patents. He is the lead author of the book *Design and Development of Medical Electronic Instrumentation: A Practical Perspective of the Design, Construction and Test of Medical Devices*, which was published by John Wiley & Sons.

Shanni R. Prutchi is a high-school junior at Jack M. Barrack Hebrew Academy in Bryn-Mawr, Pennsylvania. As an avid science and engineering enthusiast, she conducts research with her father in the areas of radio-astronomy and quantum physics.

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CHAPTER 1

LIGHT AS A WAVE

Before we get into quantum physics, let's understand the classical view of light. As early as 100 C.E., Ptolemy—a Roman citizen of Egypt—studied the properties of light, including reflection, refraction, and color. His work is considered the foundation of the field of optics. Ptolemy was intrigued by the way that light bends as it passes from air into water. Just drop a pencil into a glass of water and see for yourself!

As shown in Figure 1a, the pencil half under the water looks bent: light from the submerged part of the stick changes direction as it reaches the surface, creating the illusion of the bent stick. This effect is known as *refraction*, and the angle at which the light bends depends on a property of a material known as its *refractive index*.

In the 1600s, Dutch mathematician Willebrord Snellius figured out that the degree of refraction depends on the ratio of the two materials' different refractive indices. Most materials have a refractive index greater than 1, which means that as light enters the material from air, the angle of the ray in the material will become closer to perpendicular to the surface than it was before it entered. This is known as Snell's Law, which states that the ratio of the sines of the angles of incidence and refraction (θ_1, θ_2) is equal to the inverse ratio of the indices of refraction (n_1, n_2):

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}$$

Try it out yourself with a small laser pointer! As shown in Figure 1b, partially fill a small aquarium with water. Disperse some milk in the water to make it a bit cloudy, which will make the laser beam visible. Use smoke from a smoldering match or candle to make the laser beam visible in the air above.

Measure the angles between the rays and a line perpendicular to the water surface. The refraction coefficient for water is approximately $n_2 = 1.333$, and for air is more or less $n_2 = 1$. Do your measurements match Snell's Law?

NEWTON'S VIEW: LIGHT CONSISTS OF PARTICLES

In 1704, Sir Isaac Newton proposed that light consists of little particles of mass. In his view, this could explain reflection, because an elastic, frictionless ball bounces off a

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