PRAISE FOR

How to Teach Quantum Physics to Your Dog

"Don't let Orzel's laid-back nature or clever sense of humor fool you—he is explaining some pretty serious stuff. A levelheaded and confident guide, he takes Emmy (and the reader) through everything from wave-particle duality and superpositions to quantum tunneling and the so-called 'many worlds' interpretation ('many worlds, many treats')."

—NewScientist.com

"It's hard to imagine a better way for the mathematically and scientifically challenged, in particular, to grasp basic quantum physics."

—*Booklist*

"This charming little book is a lighthearted and amusing way for lay-people to learn about one of the strangest and most important aspects of modern science. It is also a great resource for practicing 'quantum mechanics' who want new ideas on how to more effectively explain their work to the public."

—William D. Phillips, 1997 Nobel Laureate in Physics

"Professor Orzel has a gift for funny dialogue and straightforward explanation. In addition to the entertaining conversations with Emmy, there are fascinating explanations of how the theories behind quantum mechanics were developed and how a few have been tested."

—DogSpelledForward.com

"Dogs make the perfect sounding board for physics talk. . . . [Orzel's] cheerful discussion [is] a real treat."

—*Publishers Weekly*

"I've long believed that everyone should be familiar with the wonders of quantum mechanics. I had no idea that 'everyone' would include dogs! Chad Orzel's book is a fast-moving and fun introduction to some of the deepest mysteries of modern physics. And Emmy is a star."

—Sean Carroll, author of *From Eternity to Here*

"Chad Orzel teases out the mysterious and seemingly incomprehensible side of advanced physics and makes it comprehensible via one-sided monologues to even the most distractible: dogs, humans, and in my case even disdainful felines or somewhat puzzled infants."

—Tobias S. Buckell, author of *HALO: The Cole Protocol*

"An absolutely delightful book on many axes: first, its subject matter, quantum physics, is arguably the most mind-bending scientific subject we have; second, the device of the book . . . finally, third, it is extremely well-written, combining a scientist's rigor and accuracy with a natural raconteur's storytelling skill."

—boingboing.net

"Orzel's whimsical take on quantum physics is a delight, and Emmy is the perfect Everyman, posing the questions we'd all like to ask about the intricacies of this most esoteric of subjects."

—Jennifer Ouellette, author of *The Physics of the Buffyverse*

"Quantum physics is perhaps the most interesting and slipperiest scientific subject; who knew that Socratic discussion with an adorable dog was the key to unraveling it?"

—Cory Doctorow, author of *Little Brother* and coeditor of Boing Boing

"My dog Kodi tells me that Chad Orzel explains physics with far more clarity and humor than I ever did, and that now she's just keeping me around for my opposable thumbs. Thanks a lot, Chad."

—John Scalzi, author of *Old Man's War* and
The Rough Guide to the Universe

HOW TO TEACH QUANTUM PHYSICS TO YOUR DOG

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To Kate,
whose laugh
started the whole thing

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HOW TO TEACH QUANTUM PHYSICS TO YOUR DOG

INTRODUCTION

Why Talk to Your Dog about Physics? An Introduction to Quantum Physics

The Mohawk-Hudson Humane Society has set up a little path through the woods near their facility outside Troy, so you can take a walk with a dog you're thinking of adopting. There's a bench on the side of the path in a small clearing, and I sit down to look at the dog I've taken out.

She sits down next to the bench, and pokes my hand with her nose, so I scratch behind her ears. My wife and I have looked at a bunch of dogs together, but Kate had to work, so I've been dispatched to pick out a dog by myself. This one seems like a good fit.

She's a year-old mixed-breed dog, German shepherd and something else. She's got the classic shepherd black and tan coloring, but she's small for a shepherd, and has floppy ears. The tag on her kennel door gave her name as "Princess," but that doesn't seem appropriate.

"What do you think, girl?" I ask. "What should we call you?"

"Call me Emmy!" she says.

"Why's that?"

"Because it's my name, silly."

Being called "silly" by a dog is a little surprising, but I guess she has a point. "Okay, I can't argue with that. So, do you want to come live with us?"

"Well, that depends," she says. "What's the critter situation like?"

"Beg pardon?"

"I like to chase things. Will there be critters for me to chase?"

"Well, yeah. We've got a good-sized yard, and there are lots of birds and squirrels, and the occasional rabbit."

"Ooooh! I like bunnies!" She wags her tail happily. "How about walks? Will I get walks?"

"Of course."

"And treats? I like treats."

"You'll get treats if you're a good dog."

She looks faintly offended. "I am a *very* good dog. You *will* give me treats. What do you do for a living?"

"What? Who's evaluating who, here?"

"I need to know if you deserve a dog as good as me." The name "Princess" may have been more apt than I thought. "What do you do for a living?"

"Well, my wife, Kate, is a lawyer, and I'm a professor of physics at Union College, over in Schenectady. I teach and do research in atomic physics and quantum optics."

"Quantum what?"

"Quantum optics. Broadly defined, it's the study of the interaction between light and atoms in situations where you have to describe one or both of them using quantum physics."

"That sounds complicated."

"It is, but it's fascinating stuff. Quantum physics has all sorts of weird and wonderful properties. Particles behave like waves, and waves behave like particles. Particle properties are indeterminate until you measure them. Empty space is full of 'virtual particles' popping in and out of existence. It's really cool."

"Hmmm." She looks thoughtful, then says, "One last test."

"What's that?"

"Rub my belly." She flops over on her back, and I reach down to rub her belly. After a minute of that, she stands up, shakes herself off, and says "Okay, you're pretty good. Let's go home."

We head back to the kennel to fill out the adoption paperwork. As we're walking, she says, "Quantum physics, huh? I'll have to learn something about that."

"Well, I'd be happy to explain it to you sometime."

Like most dog owners, I spend a lot of time talking to my dog. Most of our conversations are fairly typical—don't eat that, don't climb on the furniture, let's go for a walk. Some of our conversations, though, are about quantum physics.

Why do I talk to my dog about quantum physics? Well, it's what I do for a living: I'm a college physics professor. As a result, I spend a lot of time thinking about quantum physics.

What is quantum physics? Quantum physics is one part of "modern physics," meaning physics based on laws discovered after about 1900. Laws and principles of physics that were developed before about 1900 are considered "classical" physics.

Classical physics is the physics of everyday objects—tennis balls and squeaky toys, stoves and ice cubes, magnets and electrical wiring. Classical laws of motion govern the motion of anything large enough to see with the naked eye. Classical thermodynamics explains the physics of heating and cooling objects, and the operation of engines and refrigerators. Classical electromagnetism explains the behavior of lightbulbs, radios, and magnets.

Modern physics describes the stranger world that we see when we go beyond the everyday. This world was first revealed in experiments done in the late 1800s and early 1900s, which cannot be explained with classical laws of physics. New fields with different rules needed to be developed.

Modern physics is divided into two parts, each representing a radical departure from classical rules. One part, **relativity**, deals with objects that move very fast, or are in the presence of strong gravitational forces. Albert Einstein introduced relativity in 1905, and it's a fascinating subject in its own right, but beyond the scope of this book.

The other part of modern physics is what I talk to my dog about. **Quantum physics** or **quantum mechanics*** is the name given to the part of modern physics dealing with light and things that are very small—molecules, single atoms, subatomic particles. Max Planck coined the word "quantum" in 1900, and Einstein won the Nobel Prize for presenting the first quantum theory of light.† The full theory of quantum mechanics was developed over the next thirty years or so.

The people who made the theory, from early pioneers like Planck and Niels Bohr, who made the first quantum model of the hydrogen atom, to later visionaries like Richard Feynman and Julian Schwinger, who each independently worked out what we now call "quantum electrodynamics" (QED), are rightly regarded as titans of physics. Some elements of quantum theory have even escaped the realm of physics and captured the popular imagination, like Werner Heisenberg's uncertainty principle, Erwin Schrödinger's cat paradox, and the parallel universes of Hugh Everett's many-worlds interpretation.

Modern life would be impossible without quantum mechanics. Without an understanding of the quantum nature of the electron, it would be impossible to make the semiconductor chips that run our computers. Without an understanding of the quantum nature of light and atoms, it would be impossible to make the lasers we use to send messages over fiber-optic communication lines.

Quantum theory's effect on science goes beyond the merely

*The terms "quantum physics," "quantum theory," and "quantum mechanics" are more or less interchangeable.

†Inventing relativity didn't exactly hurt, but the official reason for Einstein's Nobel was his quantum theory of the photoelectric effect (page 22).

practical—it forces physicists to grapple with issues of philosophy. Quantum physics places limits on what we can know about the universe and the properties of objects in it. Quantum mechanics even changes our understanding of what it means to make a measurement. It requires a complete rethinking of the nature of reality at the most fundamental level.

Quantum mechanics describes an utterly bizarre world, where nothing is certain and objects don't have definite properties until you measure them. It's a world where distant objects are connected in strange ways, where there are entire universes with different histories right next to our own, and where "virtual particles" pop in and out of existence in otherwise empty space.

Quantum physics may sound like the stuff of fantasy fiction, but it's science. The world described in quantum theory is our world, at a microscopic scale.* The strange effects predicted by quantum physics are real, with real consequences and applications. Quantum theory has been tested to an incredible level of precision, making it the most accurately tested theory in the history of scientific theories. Even its strangest predictions have been verified experimentally (as we'll see in chapters 7, 8, and 9).

So, quantum physics is neat stuff. But what does it have to do with dogs?

Dogs come to quantum physics in a better position than most humans. They approach the world with fewer preconceptions than humans, and always expect the unexpected. A dog can walk down the same street every day for a year, and it will be a new experience every day. Every rock, every bush, every tree will be sniffed as if it had never been sniffed before.

If dog treats appeared out of empty space in the middle of

*"Microscopic" for a physicist means anything too small to be seen with the naked eye. This covers a range from bacteria to atoms to electrons. It's a wide range of sizes, but physicists think it would be confusing to have more than one word for small things.

a kitchen, a human would freak out, but a dog would take it in stride. Indeed, for most dogs, the spontaneous generation of treats would be vindication—they always expect treats to appear at any moment, for no obvious reason.

Quantum mechanics seems baffling and troubling to humans because it confounds our commonsense expectations about how the world works. Dogs are a much more receptive audience. The everyday world is a strange and marvelous place to a dog, and the predictions of quantum theory are no stranger or more marvelous than, say, the operation of a doorknob.*

Discussing quantum physics with my dog is useful because it helps me see how to discuss quantum mechanics with humans. Part of learning quantum mechanics is learning to think like a dog. If you can look at the world the way a dog does, as an endless source of surprise and wonder, then quantum mechanics will seem a lot more approachable.

This book reproduces a series of conversations with my dog about quantum physics. Each conversation is followed by a detailed discussion of the physics involved, aimed at interested human readers. The topics range from ideas many people have heard of, like particle-wave duality (chapter 1) and the uncertainty principle (chapter 2), to the more advanced ideas of virtual particles and QED (chapter 9). These explanations include discussion of both the weird predictions of the theory (both practical and philosophical), and the experiments that demonstrate these predictions. They're selected for what dogs find most interesting and also illustrate the parts that humans find surprising.

"I don't know. I think it needs . . . more."

"More what?"

*Which unquestionably follows classical rules, but does, alas, require opposable thumbs to operate.

"More me. You don't talk about the fact that I'm an exceptionally smart dog."

"Well, okay—"

"And exceptionally cute, too."

"Sure, but—"

"And don't forget good. I'm way better than those other dogs."

"What other dogs?"

"Dogs who aren't me."

"Look, this is really a book about physics, not a book about you."

"Well, it ought to be more about me, that's all I'm saying."

"It's not, and you'll just have to live with that."

"Okay, fine. You need my help with the physics stuff, though."

"What do you mean?"

"Well, sometimes you leave some stuff out, and don't answer all of my questions. You shouldn't do that."

"Like what? Give me an example."

"Ummm . . . I can't think of one now. If you read it to me, though, I'll point them out, and help fix them."

"Okay, that sounds fair. Here's what we'll do. We'll go over the book together, and if there are places where you think I've left stuff out, we can talk about them, and I'll put your comments in the book."

"Talk about them like we're doing now?"

"Yeah, like we're doing now."

"And you'll put the conversation in the book?"

"Yes, I will."

"In that case, we should talk about how I'm the very best, and I'm cute, and I should get more treats, and—"

"Okay, that's about enough of that."

"For now."

CHAPTER 1

Which Way? Both Ways: Particle-Wave Duality

We're out for a walk, when the dog spots a squirrel up ahead and takes off in pursuit. The squirrel flees into a yard and dodges around a small ornamental maple. Emmy doesn't alter her course in the slightest, and just before she slams into the tree, I pull her up short.

"What'd you do that for?" she asks, indignantly.

"What do you mean? You were about to run into a tree, and I stopped you."

"No I wasn't." She looks off after the squirrel, now safely up a bigger tree on the other side of the yard. "Because of quantum."

We start walking again. "Okay, you're going to have to explain that," I say.

"Well, I have this plan," she says. "You know how when I chase the bunnies in the backyard, when I run to the right of the pond, they go left, and get away?"

"Yes."

"And when I run to the left of the pond, they go right, and get away?"

"Yes."

"Well, I've thought of a new way to run, so they can't escape."

"What, through the middle of the pond?" It's only about eight inches deep and a couple of feet across.

"No, silly. I'm going to go both ways. I'll trap the bunnies between me."

"Uh-huh. That's an . . . interesting theory."

"It's not a theory, it's quantum physics. Material particles have wave nature and can diffract around objects. If you send a beam of electrons at a barrier, they'll go around it to the left and to the right, at the same time." She's really getting into this, and she doesn't even notice the cat sunning itself in the yard across the street. "So, I'll just make use of my wave nature, and go around both sides of the pond."

"And where does running headfirst into a tree come in?"

"Oh, well." She looks a little sheepish. "I thought I would try it out on something smaller first. I got a good running start, and I was just about to go around when you stopped me."

"Ah. Like I said, an interesting theory. It won't work, you know."

"You're not going to try to claim I don't have wave nature, are you? Because I do. It's in your physics books."

"No, no, you've got wave nature, all right. You've also got Buddha nature—"

"I'm an enlightened dog!"

"—which will do you about as much good. You see, a tree is big, and your wavelength is small. At walking speed, a twenty-kilogram dog like you has a wavelength of about 10^{-35} meters. You need your wavelength to be comparable to the size of the tree—maybe ten centimeters—in order to diffract around it, and you're thirty-four orders of magnitude off."

"I'll just change my wavelength by changing my momentum. I can run very fast."

"Nice try, but the wavelength gets *shorter* as you go faster. To get your wavelength up to the millimeter or so you'd need to diffract around a tree, you'd have to be moving at 10^{-30} meters per second, and that's impossibly slow. It would take a billion years to cross the nucleus of an atom at that speed, which is way too slow to catch a bunny."

"So, you're saying I need a new plan?"

"You need a new plan."

Her tail droops, and we walk in silence for a few seconds. "Hey," she says, "can you help me with my new plan?"

"I can try."

"How do I use my Buddha nature to go around both sides of the pond at the same time?"

I really can't think of anything to say to that, but a flash of gray fur saves me. "Look! A squirrel!" I say.

"Oooooh!" And we're off in pursuit.

Quantum physics has many strange and fascinating aspects, but the discovery that launched the theory was **particle-wave duality**, or the fact that both light and matter have particle-like and wavelike properties at the same time. A beam of light, which is generally thought of as a wave, turns out to behave like a stream of particles in some experiments. At the same time, a beam of electrons, which is generally thought of as a stream of particles, turns out to behave like a wave in some experiments. Particle and wave properties seem to be contradictory, and yet everything in the universe somehow manages to be both a particle and a wave.

The discovery in the early 1900s that light behaves like a particle is the launching point for all of quantum mechanics. In this chapter, we'll describe the history of how physicists discovered this strange duality. In order to appreciate just what a strange development this is, though, we need to talk about the particles and waves that we see in everyday life.

PARTICLES AND WAVES AROUND YOU: CLASSICAL PHYSICS

Everybody is familiar with the behavior of material particles. Pretty much all the objects you see around you—bones, balls, squeaky toys—behave like particles in the classical sense, with their motion determined by classical physics. They have different shapes, but you can predict their essential motion by imagining each as a small, featureless ball with some mass—a particle—and applying Newton's laws of motion.* A tennis ball and a long bone tumbling end over end look very different in flight, but if they're thrown in the same direction with the same speed, they'll land in the same place, and you can predict that place using classical physics.

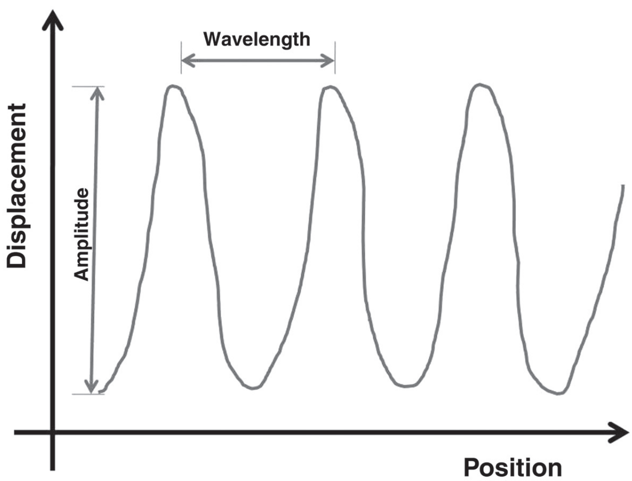
A particle-like object has a definite position (you know right where it is), a definite velocity (you know how fast it's moving, and in what direction), and a definite mass (you know how big it is). You can multiply the mass and velocity together, to find the **momentum**. A great big Labrador retriever has more momentum than a little French poodle when they're both moving at the same speed, and a fast-moving border collie has more momentum than a waddling basset hound of the same mass. Momentum determines what will happen when two particles collide. When a moving object hits a stationary one, the moving object will slow down, losing momentum, while the stationary object will speed up, gaining momentum.

The other notable feature of particles is something that seems almost too obvious to mention: particles can be counted. When you have some collection of objects, you can look at them and determine exactly how many of them you have—one bone, two squeaky toys, three squirrels under a tree in the backyard.

*Sir Isaac Newton, of the falling apple story, set forth three laws of motion that govern the behavior of moving objects. The first law is the principle of inertia, that objects at rest tend to remain at rest, and objects in motion tend to remain in motion unless acted on by an external force. The second law quantifies the first, and is usually written as the equation $F = ma$, force equals mass times acceleration. The third law says that for every action there is an equal and opposite reaction—a force of equal strength in the opposite direction. These three laws describe the motion of macroscopic objects at everyday speeds, and form the core of classical physics.

Waves, on the other hand, are slipperier. A wave is a moving disturbance in something, like the patterns of crests and troughs formed by water splashing in a backyard pond. Waves are spread out over some region of space by their nature, forming a pattern that changes and moves over time. No physical objects move anywhere—the water stays in the pond—but the pattern of the disturbance changes, and we see that as the motion of a wave.

If you want to understand a wave, there are two ways of looking at it that provide useful information. One is to imagine taking a snapshot of the whole wave, and looking at the pattern of the disturbance in space. For a single simple wave, you see a pattern of regular peaks and valleys, like this:



As you move along the pattern, you see the medium moving up and down by an amount called the "amplitude" of the wave. If you measure the distance between two neighboring crests of the wave (or two troughs), you've measured the "wavelength," which is one of the numbers used to describe a wave.

The other thing you can do is to look at one little piece of the wave pattern, and watch it for a long time—imagine watching a duck bobbing up and down on a lake, say. If you watch carefully, you'll see that the disturbance gets bigger and smaller in a very regular way—sometimes the duck is higher up, sometimes lower down—and makes a pattern in time very much like the pattern in space. You can measure how often the wave repeats itself in a given amount of time—how many times the duck reaches its maximum height in a minute, say—and that gives you the "frequency" of the wave, which is another critical number used to describe the wave. Wavelength and frequency are related to each other—longer wavelengths mean lower frequency, and vice versa.

You can already see how waves are different from particles: they don't have a position. The wavelength and the frequency describe the pattern as a whole, but there's no single place you can point to and identify as *the* position of the wave. The wave itself is a disturbance spread over space, and not a physical thing with a definite position and velocity. You can assign a velocity to the wave pattern, by looking at how long it takes one crest of the wave to move from one position to another, but again, this is a property of the pattern as a whole.

You also can't count waves the way you can count particles—you can say how many crests and troughs there are in one particular area, but those are all part of a single wave pattern. Waves are continuous where particles are discrete—you can say that you have one, two, or three particles, but you either have waves, or you don't. Individual waves may have larger or smaller amplitudes, but they don't come in chunks like particles do. Waves don't even add together in the same way that particles do—sometimes, when you put two waves together, you end up with a bigger wave, and sometimes you end up with no wave at all.

Imagine that you have two different sources of waves in the same area—two rocks thrown into still water at the same time, for example. What you get when you add the two waves together depends on how they line up. If you add the two waves together such that the crests of one wave fall on top of the crests of the other, and the troughs of one wave fall in the troughs of the other (such waves are called "in phase"), you'll get a larger wave than either of the two you started with. On the other hand, if you add two waves together such that the crests of one wave fall in the troughs of the other and vice versa ("out of phase"), the two will cancel out, and you'll end up with no wave at all.

This phenomenon is called *interference,* and it's perhaps the most dramatic difference between waves and particles.

"I don't know . . . that's pretty weird. Do you have any other examples of interference? Something more . . . doggy?"

"No, I really don't. That's the point—waves are dramatically different than particles. Nothing that dogs deal with on a regular basis is all that wavelike."

"How about, 'Interference is like when you put a squirrel in the backyard, and then you put a dog in the backyard, and a minute later, there's no more squirrel in the backyard.' "

"That's not interference, that's prey pursuit. Interference is more like putting a squirrel in the backyard, then putting a second squirrel in the backyard one second later, and finding that you have no squirrels at all. But if you wait *two* seconds before putting in the second squirrel, you find four squirrels."

"Okay, that's just weird."

"That's my point."

"Oh. Well, good job, then. Anyway, why are we talking about this?"

"Well, you need to know a few things about waves in order to understand quantum physics."

"Yeah, but this just sounds like math. I don't like math. When are we going to talk about physics?"

"We are talking about physics. The whole point of physics is to use math to describe the universe."

"I don't want to describe the universe, I want to catch squirrels."