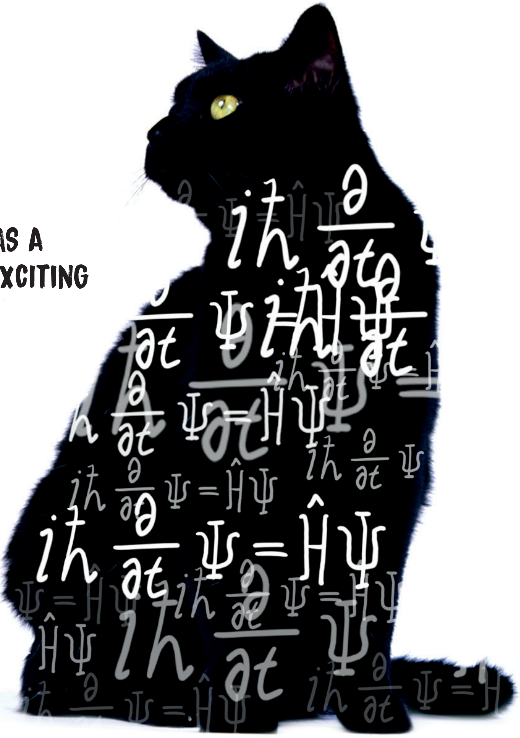
With a new foreword by Dara Ó Briain

‘ABSOLUTELY FASCINATING’
ISAAC ASIMOV

‘AS BEAUTIFUL AS A POEM AND AS EXCITING AS A NOVEL’
A. S. BYATT



IN SEARCH OF SCHRÖDINGER'S CAT

JOHN GRIBBIN

QUANTUM PHYSICS AND REALITY

John Gribbin gained a PhD from the Institute of Astronomy in Cambridge (then under the leadership of Fred Hoyle), before working as a science journalist for *Nature* and later *New Scientist*. He is the 'go to' man for quantum physics and author of many bestselling popular science books, including *Erwin Schrödinger and the Quantum Revolution*, *In Search of Schrödinger's Cat*, *In Search of the Multiverse*, *Science: A History*, *Quantum Computing: From Colossus to Qubits* and *The Universe: A Biography*. He is an Honorary Senior Research Fellow in Astronomy at the University of Sussex.
He blogs at http://johngribbinscience.wordpress.com

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By John Gribbin

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PENGUIN BOOKS

TRANSWORLD PUBLISHERS
Penguin Random House, One Embassy Gardens,
8 Viaduct Gardens, London SW11 7BW
www.penguin.co.uk

Transworld is part of the Penguin Random House group of companies
whose addresses can be found at global.penguinrandomhouse.com

Penguin
Random House
UK

First published in Great Britain in 1984 by Wildwood House,
in arrangement with Corgi Books
Corgi edition published 1985
Black Swan edition published 1991
Black Swan edition reissued 2012
Penguin paperback edition published 2025

A CIP catalogue record for this book
is available from the British Library.

ISBN
9781804993583

Typeset in 11/13pt Janson by Falcon Oast Graphic Art Ltd.
Printed and bound in Great Britain by Clays Ltd, Elcograf S.p.A.

The authorized representative in the EEA is Penguin Random House Ireland,
Morrison Chambers, 32 Nassau Street, Dublin D02 YH68.

‘I don’t like it, and I’m sorry
I ever had anything to do with it.’

ERWIN SCHRÖDINGER
1887–1961

‘Nothing is real.’

JOHN LENNON
1940–1980

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Acknowledgements

My acquaintance with quantum theory goes back more than twenty years to my school days, when I discovered the magical way in which the electron-shell model of the atom explained the periodic table of the elements and virtually all of the chemistry that I had struggled with through many a tedious lesson. Following up this discovery for myself with the aid of library books allegedly ‘too far advanced’ for my modest scholastic level, I immediately discovered the beautiful simplicity of the quantum theory’s explanation of atomic spectra, and experienced for the first time the revelation that the best things in science are both beautiful and simple, a fact that all too many teachers conceal from their students, by accident or design. I felt like the character in C. P. Snow’s *The Search* – which I only read much later – who discovers much the same thing:

> I saw a medley of haphazard facts fall into line and order . . . ‘But it’s true,’ I said to myself. ‘It’s very beautiful. And it’s true.’ (Macmillan edition, 1963, page 27.)

Partly as a result of this insight, I decided to read physics at university. In due course the ambition was fulfilled, and I became an undergraduate at the University of Sussex in Brighton. But there, the simplicity and beauty of the underlying ideas was smothered in a wealth of detail and mathematical recipes for solving specific problems with the aid of the equations of quantum mechanics. Applying these ideas in the world of physics today seemed to bear as much relevance to the underlying truth and beauty as piloting a 747 must bear to hang gliding, and although the power of that initial insight remained as a major influence in my career, for a long time I neglected the quantum world and explored other scientific pleasures.

The fires of that early interest were rekindled by a combination of factors. In the late 1970s and early 1980s, books and articles began to appear attempting, with varying success, to introduce the strange world of quantum to a non-scientific audience. Some of these alleged 'popularizations' were so outrageously far from the truth that I could not imagine any reader discovering the truth and beauty of science by reading them, and I began to feel moved to do the job properly. At the same time, news was coming in of the continuing series of experiments that has now established the reality of some of the strangest features of quantum theory, and that news inspired me to delve back into the libraries and refresh my understanding of those strange ideas. Finally, one Christmas I was asked by the BBC to appear on a radio programme as a kind of scientific counterweight to Malcolm Muggeridge, who had recently announced his conversion to the Catholic faith and was the principal guest at the time of this festival. After the great man had

had his say, emphasizing the mysteries of Christianity, he turned to me and said 'but here's the man who knows all the answers, or claims to know all the answers.' In the limited time at my disposal, I endeavoured to respond in kind, pointing out that science does *not* claim to have all the answers, and that it is religion, not science, that depends essentially on absolute faith and conviction that the truth is known. 'I don't *believe* anything,' I said, and was about to expand on this philosophy when the programme came to an end. All through the festive season, I was greeted by both friends and acquaintances with an echo of those words, and spent hours explaining that my lack of absolute faith in anything did not prevent me from leading a normal life making use of such reasonable working hypotheses as the likelihood that the sun won't disappear overnight.

The process crystallized my thoughts on what science is all about, and involved a lot of discussion of the basic reality – or unreality – of the quantum world, enough to convince me that I really was ready to write the book you now hold. While preparing the book, I tried out many of the more subtle arguments in my regular scientific contributions to a radio show hosted by Tommy Vance and broadcast by the British Forces Broadcasting Service; Tom's probing questions soon uncovered deficiencies in my presentation, and resulted in a better organization of my ideas. The main source of the reference material used in preparing the book was the library of the University of Sussex, which must have one of the best collections of books on quantum theory anywhere, and some more obscure references were tracked down for me by Mandy Caplin, of *New Scientist*, who has a persuasive way with telex messages, while Christine Sutton straightened out

some of my misconceptions about particle physics and field theory. My wife not only provided the essential backup in terms of literary research and organization of the material, but smoothed out many of the rough edges. I am grateful also to Professor Rudolf Peierls for taking the trouble to explain to me in detail some of the subtleties of the 'Clock in the Box' experiment and the 'EPR Paradox'.

So any praise for the good qualities in this book should be laid at the doors of: the 'advanced' chemistry texts, whose titles I now forget, that I found in the Kent County Library at the age of sixteen; the misguided 'popularizers' and publicists for quantum ideas, who convinced me that I could do it better; Malcolm Muggeridge and the BBC; the University of Sussex library; Tommy Vance and BFBS; Mandy Caplin and Christine Sutton; and especially Min. Any complaints concerning the remaining deficiencies in the book should, of course, be addressed to me.

JOHN GRIBBIN
July 1983

Foreword to *In Search of Schrödinger's Cat*

Dara Ó Briain

Before we begin, can I just check? Are you fourteen-years old? I'm sorry. That is a stupid question. Of course you aren't. Fourteen-year-olds don't read forewords. Especially the type of fourteen-year-old who reads books about quantum physics. They, reasonably, want to hurry on to the good stuff. Life moves fast for a fourteen-year-old, and they don't want to spend any of it in the company of a fifty-two-year-old (that's me) reflecting on a book they fondly remember from thirty-eight years earlier.

Because I read this book at fourteen. It is a magical, formative age both for scientists and those of us who toyed with becoming scientists and settled for spending a fraction of our working lives science-adjacent instead. Fourteen is a brilliant age because it is the age when you graduate from books written for your age, which are necessarily upbeat and wondrous and full of exciting facts and answers (Dinosaurs were big! The planets are far away!); and move upwards to the big leagues, books about actual, difficult science, written for every age, often by the scientists themselves; books which are even more wondrous for including not just the exciting stuff we know, but also telling you what we don't know. Books that are compelling for trusting you with the biggest ideas we have and implicitly saying, 'We still have so many questions. Can you be the one to answer them?'

I have tested this theory about the importance of being fourteen. A few years ago I hosted an event to celebrate Science writing at the Royal Society. Among the incredibly august panel were such luminaries as neuroscientist Dame Uta Frith, and astrophysicist Dame Jocelyn Bell Burnell. Every scientist I asked there could recall a book they read at fourteen, a book which fired their youthful imagination, and showed them a wider world waiting for their contribution.

Which brings us back to the book you have in your hand now. I read this in 1986 when I was fourteen, not long after its first paperback release. At the time, I knew nothing of quantum mechanics, other than its standing alongside the far more chronicled relativity as the great achievement of modern physics. This book was my first step into a world of photons and slits, and clouds of electrons, and the marvellous, counter-intuitive world of the very, very small. Step by clear step, John Gribbin maps out the bizarre behavioural quirks and unexpected results that caused a revolution in physics, but also created a theory so solid and predictable that it changed our day-to-day world completely. You might be reading this on a quantum device; I'm certainly writing it on one.

But then there is the twist. It all reads so well, and so clearly, and makes so much sense, that it's easy to miss all the repeated warnings included in the text. For example, right from the start we have the famous Niels Bohr quote about 'Anyone who is not shocked by quantum theory has not understood it'. This should have also been repeated at the end, as a rebuke.

The danger is, Gribbin explains all this so well, by the end of the book you may feel you have mastered it. Then you go to university to study physics and realize, no, I have not mastered quantum mechanics. It turns out that quantum mechanics is actually very difficult to master. Far from the crystal-clear descriptions of light and electrons included here, actual quantum mechanics starts from a series of mathematical assumptions and equations that seem to have no relation to actual physics, or reality. Real quantum mechanics leaves you pining for something as simple as a photon, or an electron.

It is only then that you realize that this book is a masterful act of translation. Actual quantum physics is written in arcane symbols and exponential powers; results emerge from a dense thicket of integrals and field equations, matrices and eigenvalues. This book manages to cut through that, and deliver the nature of reality, contradictory and confusing though it is, in a clear way. It was a pleasure to re-read it and be amazed once more.

But then I came across these words I hadn't seen before. The author says of his own time as an undergraduate: 'The simplicity and beauty of the underlying ideas was smothered in . . . detail and mathematical recipes.' Despite entering university filled with enthusiasm, he was driven away by the arcane nature of the subject. Exactly as happened to me.

The warnings were there, but I never saw them. Because he wrote them in the foreword. I didn't read the foreword. I was fourteen.

So read, and enjoy what is an acknowledged classic of the science explanation canon. This book will be your guide to the greatest of all human intellectual achievements, and you will be led from peak to peak until you correctly begin to doubt the very nature of reality itself. And you can rest assured that you wouldn't know any better, if you sought out the untranslated version. Unless, of course, you're fourteen.

In which case, yes, go read about this amazing field, but let it start you dreaming and questioning and wondering how you can make your contribution. This is where a lifetime in science begins. Because that is how the universe works.

Preface

A hundred years of quantum physics

In 1925, two physicists each working in isolation from their colleagues independently came up with a solution to the greatest mystery of twentieth century science: how to describe the behaviour of subatomic entities in a set of mathematical equations.

To create such a model of quantum mechanics would make it possible to understand and predict the behaviour of the microworld in the same way that Newtonian mechanics makes it possible to describe and predict the behaviour of objects on the human scale – the macroworld. Ever since Max Planck had discovered that the behaviour of light depended on it being composed of discrete chunks, or quanta, twenty-five years earlier, physicists had been struggling to explain what was going on in the microworld. Suddenly, they had two explanations. Both were complete, self-consistent, and explained everything observed in experiments. But to the consternation of the physics community, they were based on diametrically opposed ideas.

Werner Heisenberg, working alone on the island of Heligoland in the North Sea, where he went to recover from a severe bout of hay fever, invented (or discovered) a version of quantum mechanics entirely based on the assumption that quantum entities are particles. Erwin Schrödinger, working alone on a Christmas holiday in the Swiss Alps, invented (or discovered) a version of quantum mechanics entirely based on the assumption that quantum entities are waves. Neither of them knew about the other's work at the time.

A hundred years later, physicists still have two complete, self-consistent and seemingly mutually exclusive descriptions of the microworld. But they also have a more comprehensive understanding of quantum physics, which embraces *both* views, and has paved the way for much of the technology on which our world now runs, including the advent of quantum computing and artificial intelligence. The centenary of the breakthroughs by Heisenberg and Schrödinger seems an ideal time to take stock of where it all began.

Introduction

If all the books and articles written for laymen about relativity theory were laid end to end, they'd probably reach from here to the moon. 'Everybody knows' that Einstein's theory of relativity is the greatest achievement of twentieth-century science, and everybody is wrong. But if all the books and articles written for the layman about quantum theory were laid end to end, they'd just about cover my desk. That doesn't mean that quantum theory is unheard of outside the halls of academe. Indeed, quantum mechanics has become highly popular in some quarters, being invoked to explain phenomena such as telepathy and spoon bending, and providing a fruitful input of ideas for several science fiction stories. Quantum mechanics is identified in popular mythology, so far as it is identified at all, with the occult and ESP, some weird and esoteric branch of science that nobody understands and nobody has any practical use for.

This book was written to counter that attitude toward what is, in fact, the most fundamental and important area of scientific study. The book owes its genesis to several factors that came together in the summer of 1982. First, I had just finished writing a book about relativity, *Spacewarps*, and felt that it would be appropriate to tackle the demystification of the other great branch of twentieth-century science. Second, I was at that time increasingly irritated by the misconceptions trading under the name quantum theory among some non-scientists, Fritjof Capra's excellent *The Tao of Physics* having spawned imitators who understood neither the physics nor the Tao but suspected there was money to be made out of linking western science with eastern philosophy. Finally, in August 1982 the news came from Paris that a team had successfully carried out a crucial test confirming, for those who still doubted, the accuracy of the quantum-mechanical view of the world.

Don't look here for any 'eastern mysticism', spoon bending or ESP. Do look here for the true story of quantum mechanics, a truth far stranger than any fiction. Science is like that – it doesn't need dressing up in the hand-me-downs of someone else's philosophy, because it is full of its own delights, mysteries, and surprises. The question this book addresses is 'What is reality?' The answer(s) may surprise you; you may not believe them. But you will find out how contemporary science views the world.

Prologue

Nothing Is Real

The cat of our title is a mythical beast, but Schrödinger was a real person. Erwin Schrödinger was an Austrian scientist instrumental in the development, in the mid-1920s, of the equations of a branch of science now known as quantum mechanics. Branch of science is hardly the correct expression, however, because quantum mechanics provides the fundamental underpinning of all of modern science. The equations describe the behaviour of very small objects – generally speaking, the size of atoms or smaller – and they provide the *only* understanding of the world of the very small. Without these equations, physicists would be unable to design working nuclear power stations (or bombs), build lasers, or explain how the sun stays hot. Without quantum mechanics, chemistry would still be in the Dark Ages, and there would be no science of molecular biology – no understanding of DNA, no genetic engineering – at all.

Quantum theory presents the greatest achievement of science, far more significant and of far more direct, practical use than relativity theory. And yet, it makes some very strange predictions. The world of quantum mechanics is so strange, indeed, that even Albert Einstein found it incomprehensible, and refused to accept all of the implications of the theory developed by Schrödinger and his colleagues. Einstein, and many other scientists, found it more comfortable to believe that the equations of quantum mechanics simply represent some sort of mathematical trick, which just happens to give a reasonable working guide to the behaviour of atomic and subatomic particles but that conceals some deeper truth that corresponds more closely to our everyday sense of reality. For what quantum mechanics says is that nothing is real and that we cannot say anything about what things are doing when we are not looking at them. Schrödinger's mythical cat was invoked to make the differences between the quantum world and the everyday world clear.

In that world of quantum mechanics, the laws of physics that are familiar from the everyday world no longer work. Instead, events are governed by probabilities. A radioactive atom, for example, might decay, emitting an electron, say; or it might not. It is possible to set up an experiment in such a way that there is a precise fifty-fifty chance that one of the atoms in a lump of radioactive material will decay in a certain time and that a detector will register the decay if it does happen. Schrödinger, as upset as Einstein about the implications of quantum theory, tried to show the absurdity of those implications by imagining such an experiment set up in a closed room, or box, which also contains a live cat and a phial of poison, so arranged that if the radioactive decay does occur then the poison container is broken and the cat dies. In the everyday world, there is a fifty-fifty chance that the cat will be killed, and without looking inside the box we can say, quite happily, that the cat inside is either dead or alive. But now we encounter the strangeness of the quantum world. According to the theory, *neither* of the two possibilities open to the radioactive material, and therefore to the cat, has any reality unless it is observed. The atomic decay has neither happened nor not happened, the cat has neither been killed nor not killed, until we look inside the box to see what has happened. Theorists who accept the pure version of quantum mechanics say that the cat exists in some indeterminate state, neither dead nor alive, until an observer looks into the box to see how things are getting on. Nothing is real unless it is observed.

The idea was anathema to Einstein, among others. 'God does not play dice,' he said, referring to the theory that the world is governed by the accumulation of outcomes of essentially random 'choices' of possibilities at the quantum level. As for the unreality of the state of Schrödinger's cat, he dismissed it, assuming that there must be some underlying 'clockwork' that makes for a genuine fundamental reality of things. He spent many years attempting to devise tests that might reveal this underlying reality at work but died before it became possible actually to carry out such a test. Perhaps it is as well that he did not live to see the outcome of one line of reasoning that he initiated.

In the summer of 1982, at the University of Paris-South, in France, a team headed by Alain Aspect completed a series of experiments designed to detect the underlying reality below the unreal world of the quantum. The underlying reality – the fundamental clockwork – had been given the name 'hidden variables', and the experiment concerned the behaviour of two photons or particles of light flying off in opposite directions from a source. It is described fully in Chapter Ten, but in essence it can be thought of as a test of reality. The two photons from the same source can be observed by two detectors, which measure a property called polarization. According to quantum theory, this property does not exist until it is measured. According to the hidden-variable idea, each photon has a 'real' polarization from the moment it is created. Because the two photons are emitted together, their polarizations are correlated with one another. But the nature of the correlation that is actually measured is different according to the two views of reality.

The results of this crucial experiment are unambiguous. The kind of correlation predicted by hidden-variable theory is not found; the kind of correlation predicted by quantum mechanics is found, and what is more, again as predicted by quantum theory, the measurement that is made on one photon has an instantaneous effect on the nature of the other photon. Some interaction links the two inextricably, even though they are flying apart at the speed of light, and relativity theory tells us that no signal can travel faster than light. The experiments prove that there is no underlying reality to the world. 'Reality', in the everyday sense, is not a good way to think about the behaviour of the fundamental particles that make up the universe; yet at the same time those particles seem to be inseparably connected into some indivisible whole, each aware of what happens to the others.

The search for Schrödinger's cat was the search for quantum reality. From this brief outline, it may seem that the search has proved fruitless, since there is no reality in the everyday sense of the word. But this is not quite the end of the story, and the search for Schrödinger's cat may lead us to a new understanding of reality that transcends, and yet includes, the conventional interpretation of quantum mechanics. The trail is a long one, however, and it begins with a scientist who would probably have been even more horrified than Einstein if he could have seen the answers we now have to the questions he puzzled over. Isaac Newton, studying the nature of light three centuries ago, could have had no conception that he was already on the trail leading to Schrödinger's cat.

Part One

The Quantum

'Anyone who is not shocked by quantum theory has not understood it.'

NIELS BOHR
1885–1962

Chapter One

Light

Isaac Newton invented physics, and all of science depends on physics. Newton certainly built upon the work of others, but it was the publication of his three laws of motion and theory of gravity, more than three hundred years ago, that set science off on the road that has led to space flight, lasers, atomic energy, genetic engineering, an understanding of chemistry, and all the rest. For two hundred years, Newtonian physics (what is now called 'classical' physics) reigned supreme; in the twentieth century revolutionary new insights took physics far beyond Newton, but without those two centuries of scientific growth those new insights might never have been achieved. This book is not a history of science, and it is concerned with the new physics – quantum physics – rather than with those classical ideas. But even in Newton's work three centuries ago there were already signs of the changes that were to come – not from his studies of planetary motions and orbits, or his famous three laws, but from his investigations of the nature of light.

Newton's ideas about light owed a lot to his ideas about the behaviour of solid objects and the orbits of planets. He realized that our everyday experiences of the behaviour of objects may be misleading, and that an object, a particle, free from any outside influences must behave very differently from such a particle on the surface of the earth. Here, our everyday experience tells us that things tend to stay in one place unless they are pushed, and that once you stop pushing them they soon stop moving. So why don't objects like planets, or the moon, stop moving in their orbits? Is something pushing them? Not at all. It is the planets that are in a natural state, free from outside interference, and the objects on the surface of the earth that are being interfered with. If I try to slide a pen across my desk, my push is opposed by the friction of the pen rubbing against the desk, and that is what brings it to a halt when I stop pushing. If there were no friction, the pen would keep moving. This is Newton's first law: every object stays at rest, or moves with constant velocity, unless an outside force acts on it. The second law tells us how much effect an outside force – a push – has on an object. Such a force changes the velocity of the object, and a change in velocity is called acceleration; if you divide the force by the mass of the object the force is acting upon, the result is the acceleration produced on that body by that force. Usually, this second law is expressed slightly differently: force equals mass times acceleration. And Newton's third law tells us something about how the object reacts to being pushed around: for every action there is an equal and opposite reaction. If I hit a tennis ball with my racket, the force with which the racket pushes on the tennis ball is exactly matched by an equal force pushing back on the racket; the pen on my desk top, pulled down by gravity, is pushed against with an exactly equal reaction by the desk top itself; the force of the explosive process that pushes the gases out of the combustion chamber of a rocket produces an equal and opposite reaction force on the rocket itself, which pushes it in the opposite direction.

These laws, together with Newton's law of gravity, explained the orbits of the planets around the sun, and the moon around the earth. When proper account was taken of friction, they explained the behaviour of objects on the surface of the earth as well, and formed the foundation of mechanics. But they also had puzzling philosophical implications. According to Newton's laws, the behaviour of a particle could be exactly predicted on the basis of its interactions with other particles and the forces acting on it. If it were ever possible to know the position and velocity of every particle in the universe, then it would be possible to predict with utter precision the future of every particle, and therefore the future of the universe. Did this mean that the universe ran like clockwork, wound up and set in motion by the Creator, down some utterly predictable path? Newton's classical mechanics provided plenty of support for this deterministic view of the universe, a picture that left little place for human free will or chance. Could it really be that we are all puppets following our own preset tracks through life, with no real choice at all? Most scientists were content to let the philosophers debate that question. But it returned, with full force, at the heart of the new physics of the twentieth century.

Waves or Particles?

With his physics of particles such a success, it is hardly surprising that when Newton tried to explain the behaviour of light he did so in terms of particles. After all, light rays are observed to travel in straight lines, and the way light bounces off a mirror is very much like the way a ball bounces off a hard wall. Newton built the first reflecting telescope, explained white light as a superposition of all the colours of the rainbow, and did much more with optics, but always his theories rested upon the assumption that light consisted of a stream of tiny particles, called corpuscles. Light rays bend as they cross the barrier between a lighter and a denser substance, such as from air to water or glass (which is why a swizzle stick

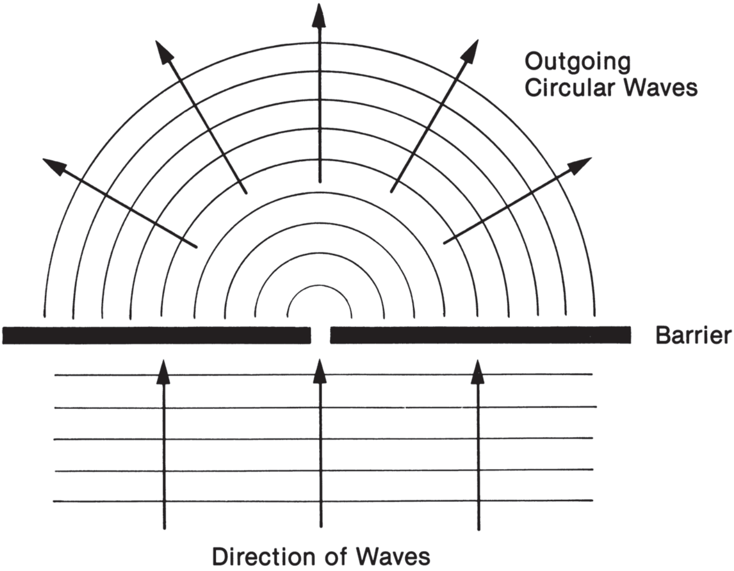

Figure 1.1 Parallel water waves passing through a small hole in a barrier spread out in circles from the hole, leaving no 'shadow'.

in a gin and tonic seems to be bent), and this refraction is neatly explained on the corpuscular theory provided the corpuscles move faster in the more 'optically dense' substance. Even in Newton's day, however, there was an alternative way of explaining all of this.

The Dutch physicist Christiaan Huygens was a contemporary of Newton, although thirteen years older,

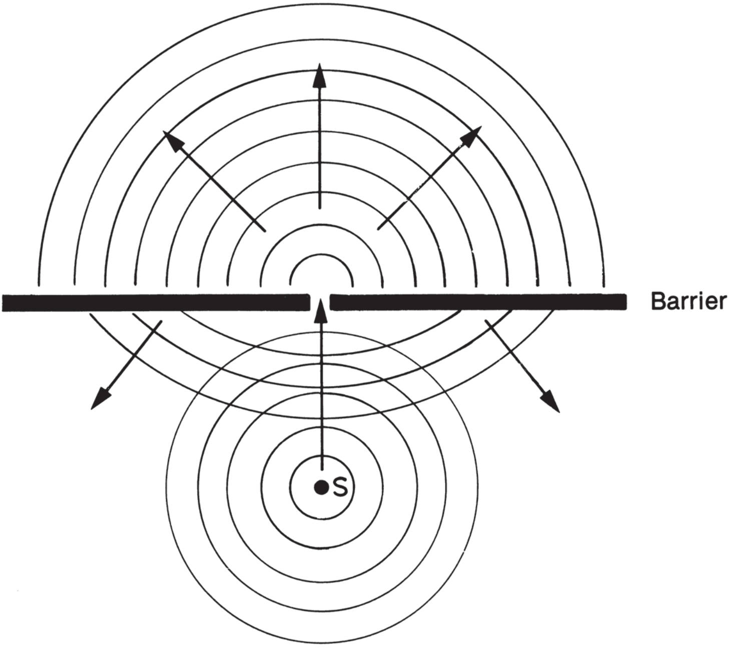

Figure 1.2 Circular ripples, like the ones produced by a stone dropped in a pond, also spread as circular waves centred on the hole when they pass through a narrow opening (and, of course, the waves that hit the barrier are reflected back again).

having been born in 1629. He developed the idea that light is not a stream of particles but a wave, rather like the waves moving across the surface of a sea or lake, but propagating through an invisible substance called the 'luminiferous ether'. Like ripples produced by a pebble dropped into a pond, light waves in the ether were imagined to spread out in all directions from a source of light. The wave theory explained reflection and refraction just as well as the corpuscular theory. Although it said that instead of speeding up the light waves moved more slowly in a more optically dense substance, there was no way of measuring the speed of light in the seventeenth century, so this difference could not resolve the conflict between the two theories. But in one key respect the two ideas did differ observably in their predictions. When light passes a sharp edge, it produces a sharply edged shadow. This is exactly the way streams of particles, travelling in straight lines, ought to behave. A wave tends to bend, or diffract, some of the way into the shadow (think of the ripples on a pond, bending around a rock). Three hundred years ago, this evidence clearly favoured the corpuscular theory, and the wave theory, although not forgotten, was discarded. By the early nineteenth century, however, the status of the two theories had been almost completely reversed.

In the eighteenth century, very few people took the wave theory of light seriously. One of the few who not only took it seriously but wrote in support of it was the Swiss Leonard Euler, the leading mathematician of his time, who made major contributions to the development of geometry, calculus and trigonometry. Modern mathematics and physics are described in arithmetical terms, by equations; the techniques on which that arithmetical description depends were largely developed by Euler, and in the process he introduced shorthand methods of notation that survive to this day – the name ‘pi’ for the ratio of the circumference of a circle to its diameter; the letter *i* to denote the square root of minus one (which we shall meet again, along with pi); and the symbols used by mathematicians to denote the operation called integration. Curiously, though, Euler’s entry in the *Encyclopaedia Britannica* makes no mention of his views on the wave theory of light, views which a contemporary said were not held ‘by a single physicist of prominence’.* About the only prominent contemporary of Euler who did share those views was Benjamin Franklin; but physicists found it easy to ignore them until crucial new experiments were performed by the Englishman Thomas Young just at the beginning of the nineteenth century, and by the Frenchman Augustin Fresnel soon after.

Wave Theory Triumphant

Young used his knowledge of how waves move across the surface of a pond to design an experiment that would test whether or not light propagates in the same way. We all know what a water wave looks like, although it is important to think of a ripple, rather than a large breaker, to make the analogy accurate. The distinctive feature of a wave is that it raises the water level up slightly, then depresses it, as the wave passes; the height of the crest of the wave above the undisturbed water level is its

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*Quote from page 2 of *Quantum Mechanics*, by Ernest Ikenberry; see bibliography.

amplitude, and for a perfect wave this is the same as the amount by which the water level is pushed down as the wave passes. A series of ripples, like the ones from our stone dropped into the pond, follow one another with a regular spacing, called the wavelength, which is measured from one crest to the next. Around the point where our pebble drops into the water, the waves spread out in circles, but the waves on the sea, or ripples produced on a lake by the blowing wind, may run forward as a series of straight lines, parallel waves, one

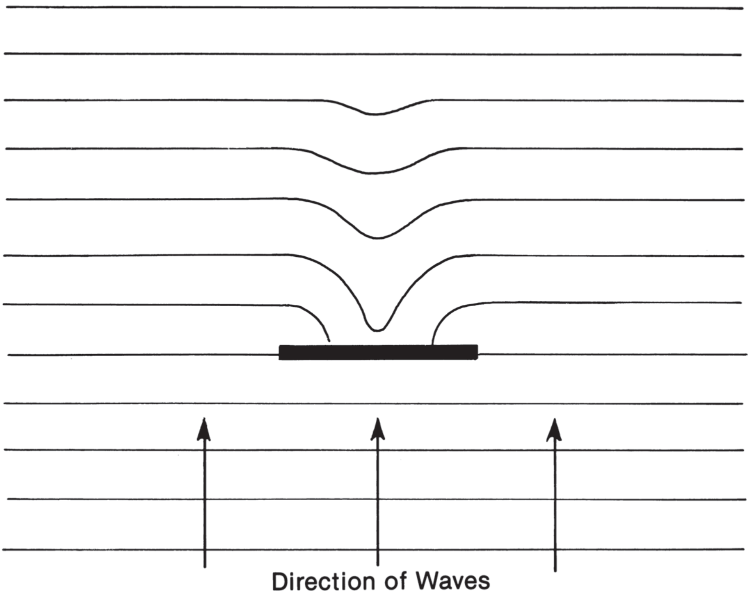

Figure 1.3 The ability of waves to bend around corners also means that they can quickly fill in the shadow behind an obstacle, provided the obstacle is not much bigger than the wavelength of the waves.

behind the other. Either way, the number of wave crests passing by some fixed point – like a rock – in each second tells us the frequency of the wave. The frequency is the number of wavelengths passing each second, so the velocity of the wave, the speed with which each crest advances, is the wavelength multiplied by the frequency.

The crucial experiment starts out with parallel waves, rather like the lines of waves advancing towards a beach before they break. You can imagine these as the waves produced by dropping a very large object into the water a very long way away. The 'ripples' spreading out in

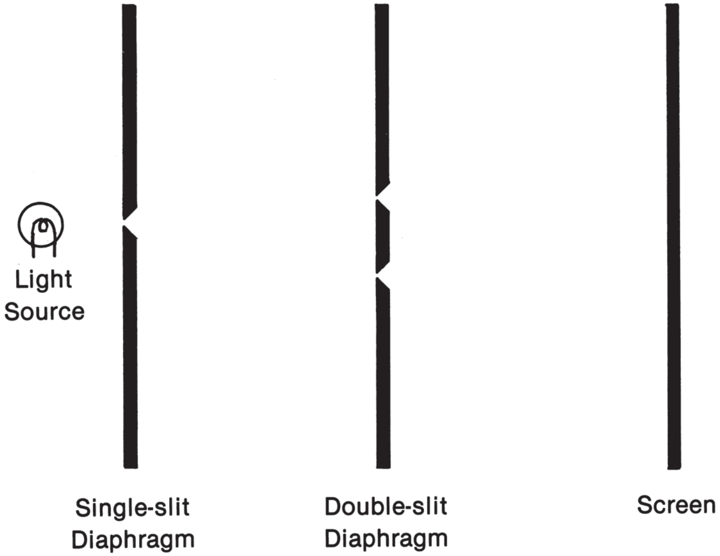

Figure 1.4 The ability of light to diffract around corners and through small holes can be tested using a single slit to make a circular wave and a double slit to produce interference.