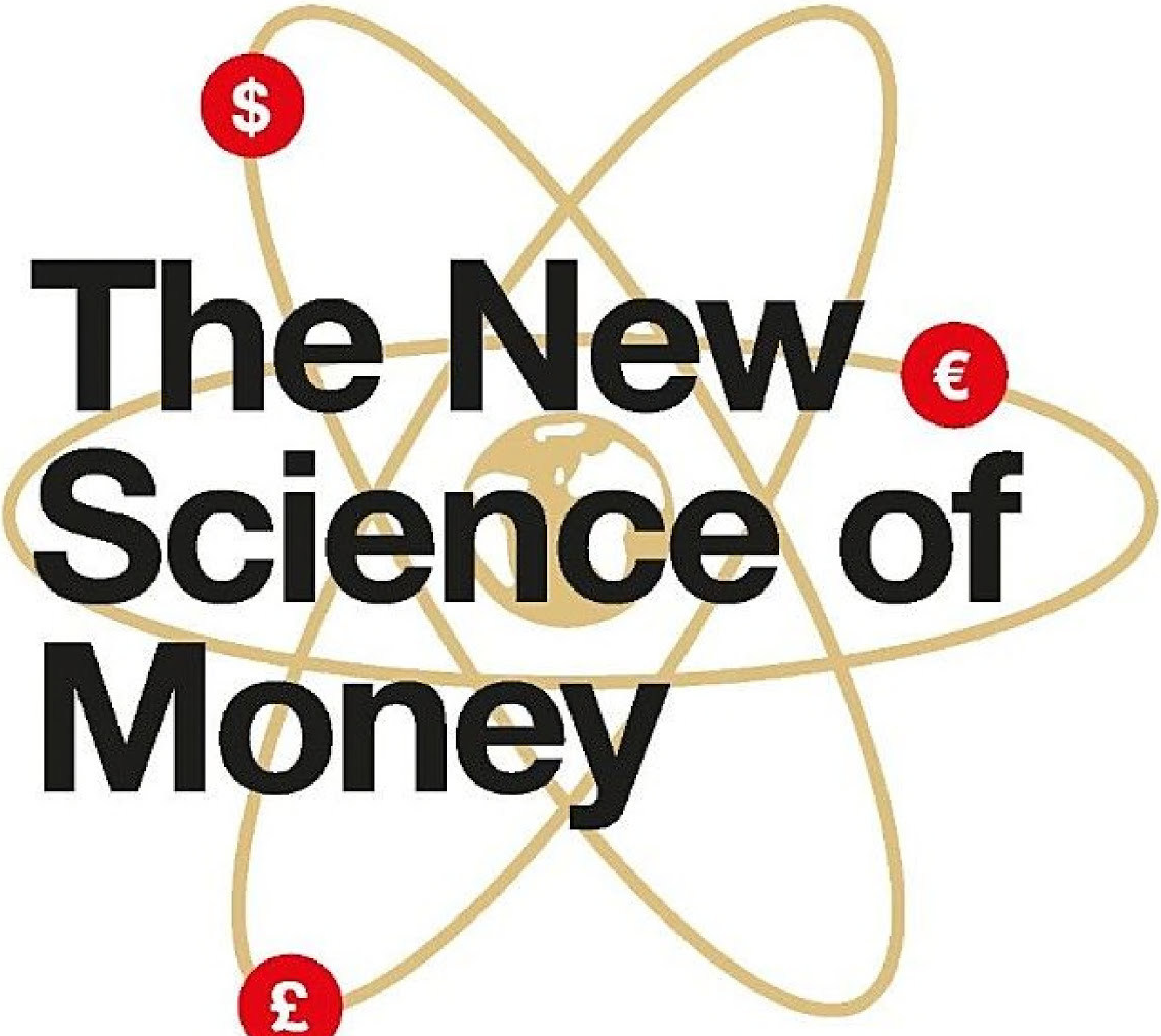
Quantum Economics



The New Science of Money

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'A must-read for anyone wanting to understand the weird, and getting weirder, world of modern finance.' Margaret Wertheim

Contents

Introduction

You never change things by fighting the existing reality. To change something, build a new model that makes the existing model obsolete.
R. Buckminster Fuller

If there be nothing new, but that which is Hath been before, how are our brains beguil'd, Which, labouring for invention, bear amiss The second burthen of a former child!
Shakespeare, Sonnet 59

What is economics?

How about this for an exciting definition: economics is the study of transactions involving money.

Obvious, right? Economists talk about money all the time. Everything gets expressed in terms of dollars or euros, yen or yuan. The health of a nation is reduced to how much they produce, as measured by Gross Domestic Product; a person's value to society is expressed by how much they earn. Economics is about money, everyone knows that.

And yet – if you look at an economics textbook, it turns out that the field is defined a little differently. Most follow the English economist Lionel Robbins, who wrote in 1932 that 'Economics is a science which studies human behaviour as a relationship between ends and scarce means which have alternative uses.'[1] Gregory Mankiw's widely-used *Principles of Economics* for example states that 'Economics is the study of how society manages its scarce resources.'[2] Or as it is sometimes paraphrased, economics is the science of scarcity. No mention of money at all.

And if you read a little further in those same textbooks, you will find that economists do not talk about money all the time – in fact they steer clear of it. Money is used as a metric, but – apart perhaps from chapters to do with basic monetary plumbing – is not considered an important subject in itself. The textbooks are like physics books that use time throughout in equations but never pause to talk about what time is. And both money and the role of the financial sector are usually completely missing from economic models, or paid lip service to.

Economists, it seems, think about money less than most people do: as the former Bank of England Governor Mervyn King observed, 'Most economists hold conversations in which the word "money" hardly appears at all.'[3]

Believe it or not, defining economics in terms of money transactions is a rather radical statement. For one thing, it leads to the related question: what is money?

In this case, the accepted answer is to quote Paul Samuelson's 'bible' textbook

Economics and say that money is '*anything that serves as a commonly accepted medium of exchange*' (his emphasis).[4] This certainly seems to be a good description of how we use money in the economy. But again, it doesn't give us a sense of how money attains this special status as a medium of exchange; and it implies that money's only importance is to act as a passive intermediary for trade. The economy can therefore be viewed as a giant barter system, in which money is nothing more than a veil, a distraction from what really counts. The exciting and sometimes disturbing properties of money, which have fascinated and intrigued its users over millennia, have been largely written out of the story.

This book argues that the textbook definitions – and the economics establishment in general – have it the wrong way round. It makes the case for a new kind of economics, which puts money – and the question *how much* – at its centre. The time has come to talk about money – and the implications of this simple adjustment promise to be as significant in economics as the quantum revolution was in physics.

Talking about a revolution

People have of course been calling for a revolution in economics for a rather long time – and especially since the financial crisis of 2007–08. In 2008 the physicist and hedge fund manager Jean-Philippe Bouchaud wrote a paper in the journal *Nature* with the title 'Economics needs a scientific revolution'.[5] In 2014 Ha-Joon Chang and Jonathan Aldred of Cambridge University called for a 'revolution in the way we teach economics'.[6] A number of student groups around the world agreed, releasing their own manifestos demanding a more pluralistic approach from their professors. In 2017 the UK's Economic and Social Research Council let it be known that it was setting up a network of experts from different disciplines including 'psychology, anthropology, sociology, neuroscience, economic history, political science, biology and physics', whose task it would be to 'revolutionise' the field of economics.[7] And there have been countless books on the topic, including my own *Economyths* which called in its final chapter for just such an intervention by non-economists, when it first came out in 2010.[8]

The reasons for this spirit of revolutionary zeal are clear enough. For the past 150 years mainstream (aka neoclassical) economics has clung to a number of assumptions that are completely at odds with reality – for example, the cute idea that the economy is a self-stabilising machine that maximises utility (i.e. usefulness; the wheels fell off that one a while ago). It fails even in terms of its own scarcity-based definition: with social inequality and environmental degradation at a peak, mainstream economics doesn't seem up to the task of addressing questions such as how to fairly allocate resources or deal with natural limits.

While there have been many calls for a revolution, though, the exact nature of that revolution is less clear. Critics agree that the foundations of economics are rotten, but there are different views on what should be built in its place.

Most think that the field needs more diversity and should be more pluralistic (though as revolutionary demands go this one seems a bit diffuse). Most also agree that the emphasis on economic growth for its own sake needs to be reconciled both with environmental constraints and with fair distribution. Many have pointed out that economic models should incorporate techniques from other areas such as complexity theory, and properly account for the role of the financial sector. And the idea of rational economic man – which forms the core of traditional models – should be replaced with something a little more realistic.

But what if the problems with economics run even deeper? What if the traditional approach has hit a wall, and the field needs to be completely reinvented? What if the problem comes down to our entire way of thinking and talking about the economy?

This book argues that we need to start over from the beginning, by considering the most basic feature of the economy, which is transactions involving money. Rather than treat money as a mere metric, or as an inert medium of exchange, we will show that money has special, contradictory, indeed magical properties which feed into the economy as a whole. We can no more ignore these properties than weather forecasters can ignore the properties of water when making their predictions. Rather than treat people as rational, computer-like agents, with a few tweaks for behavioural effects, as in traditional economics, we will take their complex, multi-faceted behaviour at face value. And instead of seeing the economy as a machine that optimises utility, we will show that it is better described as a complex, connected system with emergent features that reflect the contradictions at its core.

All of this will come from analysing the meaning of the simple phrase: *how much*. Or in Latin, *quantum*.

A quantum of money

The word 'quantum' of course has a lot of history. It was applied by physicists over a century ago to describe another kind of transaction – the exchange of energy between subatomic particles. And it eventually overturned our most basic assumptions about the universe by showing that, instead of a deterministic machine, it was something more complex, entangled, and alive.

Classical or Newtonian physics, of the sort that was accepted orthodoxy in the first years of the twentieth century, was based on the idea that matter was made up of individual atoms that interacted only by bouncing into one another. The motion of these particles could be understood and predicted using deterministic laws. Quantum physics changed all this by showing that quantities such as position and momentum were fundamentally indeterminate, and could only be approximately measured through a process which affected the thing being measured, and which furthermore seemed to some theorists to depend on the choices made by the persons carrying out the measurements. And the states of particles were entangled, so a measurement on one could instantaneously inform an experimenter about the state of another. As physicist David Bohm observed, 'It is now clear that no mechanical explanation is available, not for the fundamental particles which constitute all matter, inanimate and animate, nor for the cosmos as a whole.'[9]

One might think that quantum principles and techniques apply only to the subatomic realm, and are of no relevance to our everyday lives – and indeed this was long commonly believed. But in recent years, a number of social scientists working in everything from psychology to business have put ideas from quantum mechanics to new uses in their own fields. The area where quantum mechanics has perhaps its most direct application is in the rather technical area of mathematical finance. As we will see later, many of the key results of that field, such as the equations used by traders to calculate the price of an option (contracts to buy or sell securities at a future date), can be expressed using the mathematics of quantum mechanics. The aim of these researchers is not to prove that finance is quantum in a direct physical sense or somehow reduces to quantum mechanics, but that it has properties which are best modelled using a quantum-inspired methodology. This offers some computational advantages over the usual statistical approach, but also changes the way we think about the financial system, from being a mechanistic system with added randomness, to a world of overlapping alternative possibilities, in which uncertainty is intrinsic to the system rather than an extra added feature.

The emerging fields of quantum cognition and quantum social science, meanwhile, take broader inspiration from quantum mechanics to think about how human beings make decisions and interact with one another.[10] While most applications to date have been in psychology or sociology, these findings are also very relevant to the economy. In particular, researchers have shown that many of the behavioural quirks long noted by behavioural economists – such as our tendency to act in a less than rational way when interacting with money – may elude classical logic, but can quite easily be expressed using a version of quantum logic, which allows for effects such as context and interference between incompatible concepts (the cause of cognitive dissonance). As physicist Diederik Aerts notes, 'People often follow a different way of thinking than the one dictated by classical logic. The mathematics of quantum theory turns out to describe this quite well.'[11]

Instead of behaving like independent Newtonian particles, as assumed in mainstream neoclassical economics, we are actually closely entangled and engaged in a sort of collective quantum dance. As the feminist theorist (and trained physicist) Karen Barad puts it, 'Existence is not an individual affair. Individuals do not preexist their interactions; rather, individuals emerge through and as part of their entangled intra-relating.'[12] We'll get on to what that means in later chapters – some of which draw heavily on the findings of these scholars and scientists – but the upshot is that rather than being quite as weird and counterintuitive as we have been taught, many aspects of quantum behaviour are actually rather like everyday life (which can also be weird). We have more in common with the subatomic realm than we thought.

Nowhere is this more true than in our dealings with money and our own approach to the commonly-asked financial question *how much*. This is shown by another theory presented here – dubbed the quantum theory of money and value – which provides the central thread of the book and states that money has a dualistic quantum nature of its own. Money is a way of combining the properties of a number with the properties of an owned thing. The fact that numbers and things are as different as waves and particles in quantum mechanics is what gives money its unique properties. The use of money in transactions is a way of attaching a number (the price) to the fuzzy and indeterminate notion of value. It therefore acts like the measurement process in quantum physics, which assigns a number to the similarly indeterminate properties of a particle.

The act of money creation also finds a direct analogue in the creation of subatomic particles out of the void, as we will discover. One implication is that the information encoded in money is a kind of quantum entanglement device, because its creation always has two sides, debt and credit. And its use also entangles people with each other and with the system as a whole, as anyone with a loan will know. All this will be explored in more detail as we delve into the world of the quantum.

This view of money – which I have previously described for an academic audience in talks, papers and a book – was originally inspired as much by the dualities of ancient Greek philosophy, and the need to explain the emergence of modern cybercurrencies such as bitcoin, as by quantum physics.[13] But when combined with quantum finance and quantum social science, each of which were developed independently in different settings and for different ends, the result is what I am calling quantum economics – which is to neoclassical economics what quantum physics was to classical physics.

Don't mention the quantum

I should address a few concerns here. One is that, since the time quantum mechanics was first invented, it has been treated as a highly esoteric area that can only be understood by experts. Commonly attributed quotes from famous physicists state that quantum mechanics is 'fundamentally incomprehensible' (Niels Bohr); 'If you think you understand quantum mechanics, you don't understand quantum mechanics' (Richard Feynman); 'You don't understand quantum mechanics, you just get used to it' (John von Neumann). Einstein said it reminded him of 'the system of delusions of an exceedingly intelligent paranoiac, concocted of incoherent elements of thoughts'.[14] If even such luminaries can't grasp the meaning of 'quantum', then what chance does anyone else have?

Perhaps as a result, the word has also long been seen as a marker for pretension, pseudery, or worse. 'Where misunderstanding dwells', wrote physicist Sean Carroll in 2016, 'misuse will not be far behind. No theory in the history of science has been more misused and abused by cranks and charlatans – and misunderstood by people struggling in good faith with difficult ideas – than quantum mechanics.'[15] Physicist Murray Gell-Mann devoted an entire chapter of his 1994 book *The Quark and the Jaguar* to 'Quantum Mechanics and Flapdoodle'.[16] Economist Paul Samuelson wrote back in 1970: 'There is really nothing more pathetic than to have an economist or a retired engineer try to force analogies between the concepts of physics and the concepts of economics ... and when an economist makes reference to a Heisenberg Principle of [quantum] indeterminacy in the social world, at best this must be regarded as a figure of speech or a play on words, rather than a valid application of the relations of quantum mechanics.'[17] (Though this didn't stop him from later writing a paper on 'A quantum theory model of economics' which as Philip Mirowski points out, 'has nothing whatsoever to do with quantum mechanics'.[18])

Speaking as a former project engineer I agree that translating concepts and equations in a literal way from quantum mechanics to economics smacks of physics envy. In my previous books, such as *Economyths* and *The Money Formula* (with Paul Wilmott), I have done as much as most people to argue against the idea that economics can be simply transposed from physics. However, metaphor is intrinsic to our thought processes, and neoclassical economics has long been replete with metaphors from Victorian mechanics – one of its founders, Vilfredo Pareto, for example said that 'pure economics is a sort of mechanics or akin to mechanics' – so perhaps it is time to expand our mental toolbox.[19] As we'll see, it isn't just quantum mechanics which has been 'misused and abused' – bogus claims for the efficacy of mechanistic economics have probably damaged more lives than things like 'quantum healing' – and while it is understandable that physicists are protective of their quantum turf, overly-reactive policing of it is one reason social scientists are stuck in an oddly mechanistic view of the world.

Also, while I did study quantum mechanics and use it in my work (my early career was spent designing superconducting magnets which rely on quantum processes for their function), my intention is not to further mathematicise economics – quite the opposite. Although a number of books and papers cited throughout do take a heavily mathematical approach, the core ideas of the theory proposed here are very simple, and do not require equations or sophisticated jargon. If, as I believe, the money system has quantum properties of its own, then one could imagine a historical scenario where things developed in a different order, and quantum physicists were using economics analogies to explain their crazy ideas (though it is hard to think of physicists being accused of economics envy, or of borrowing from the high prestige of social science).

Some of the remoteness of quantum mechanics has also worn down as the field is increasingly adopted by technologists and featured in the media. For example, the logic circuits of quantum computers – whose design is turning into something of a cottage industry in many countries – rely explicitly on quantum principles to make calculations far faster than a classical computer. And if the price of a financial derivative, such as an option to buy a stock at a future date, can be calculated more rapidly and efficiently using a quantum model running on a quantum computer, then a degree in quantum financial engineering may turn out to be a rather lucrative qualification – a 'quant' (short for quantitative finance) degree with bells on.

Quantum processes begin to seem even less remote when we consider the hypothesis advanced by a number of scientists such as the physicist Roger Penrose that the mind itself is a quantum computer.[20] While this hypothesis remains controversial, it is consistent with the impression, at least from some interpretations of quantum mechanics, that consciousness seems to be inextricably linked with quantum processes (not to mention the fact that we live in a quantum universe). It is also buttressed by recent findings in quantum biology, which show how quantum effects are exploited in everything from photosynthesis in plants, to navigation by birds.[21] If this is the case, then things like quantum cognition begin to seem less like metaphor, as it is usually treated, than physical fact.

I will also argue that, just as understanding quantum physics helps to understand economics, it also works the other way: understanding how money works in the economy makes quantum physics seem a lot more accessible. Consider for example the notion that a particle's position is described by a probabilistic 'wave function' which only 'collapses' to a unique value when measured by an observer. That sounds impossibly abstract, until you realise that the price of something like a house is also fundamentally indeterminate, until it 'collapses' to a single value when it is sold to a buyer.

The notion of entanglement between particles, where the status of one particle is instantaneously correlated with measurements on its entangled twin, also seems less bizarre when financial contracts such as loans enforce a similar link between creditor and debtor. And the idea that quantum particles move in discrete jumps, rather than continuously, sounds less mysterious and counterintuitive when you compare it to buying something with a credit card at a store, where the money goes out in a single jump rather than draining out in a steady flow like water. When these properties were observed in the behaviour of subatomic particles, they led to the development of quantum mechanics as we now know it – but exactly the same argument can be applied to say that we need a quantum theory of money. Perhaps the main difference is that in quantum mechanics, the underlying explanation for phenomena such as wave function collapse or entanglement is unknown, and the topic of much controversy; while in the economy, these are just what we are used to.

It is sometimes said that, in order to free ourselves from the mechanistic worldview imposed on us by society, we need to familiarise ourselves with the mysteries of quantum physics, which offer a radically different picture.[22] But we don't need a PhD in quantum physics or access to a particle accelerator to accomplish this. We just need to look more closely at money. When we compare quantum physics with our everyday notion of how objects exist and move around it makes no sense; but when we compare it with monetary transactions it all seems rather reasonable. Money therefore has much to tell us about the quantum world. (And perhaps money really does make the world go round.)

The approach here is therefore not so much to use quantum physics as an analogy for social processes, or to assert a direct physical link between the two, but instead to start with the idea that money is a quantum phenomenon in its own right, with its own versions of a measurement process, entanglement, and so on, of which we all have direct experience.[23] Nor of course is it to say that the economy obeys immutable laws. A mortgage entangles the debtor and creditor in a formal sense, but a default might be a negotiated process rather than a sudden event. A money object has an exact value within a certain monetary space, but depends on things like locally-enforced laws or norms. One way to interpret this is to say that the money system is our best attempt to engineer a physics-like quantum system; but another, as we will see later, is to say that money is embedded in a larger, more complex social quantum system with competing forms of entanglement. However, the quantum approach was initially adopted in physics, not for abstruse philosophical reasons, but for pragmatic ones, since it was needed in order to mathematically describe physical reality; and from a similarly pragmatic viewpoint I will argue that the more pressing question is not one of how to interpret quantum ideas (a question which is still debated in physics), but of how they can be put to use in economics – and why it took so long for their relevance to be recognised.

While discussing these concepts with both economists and physicists I soon found that, while many were supportive or at least tolerant, a rather common initial reaction was a visceral resistance to my use of words such as 'entanglement' to describe the monetary system that went beyond normal scepticism. One economist insisted I was just introducing new words for things like contracts, as I would know if I had ever taken an economics course, while physicists (who sometimes confuse their equations with the underlying reality) tended to see these as technical terms unique to their own domain, subject to control and quarantine. But John Maynard Keynes for one spoke about 'economic entanglement' in 1933 (see page 305), before Schrödinger introduced the physics version in a 1935 paper.[24] As physicists Gabriela Barreto Lemos and Kathryn Schaffer noted in a 2018 essay for the School of the Art Institute of Chicago, 'scholars in the arts, humanities, and many interdisciplinary fields now write about the "observer effect" and "entanglement" – technical physics concepts – in work that has a distinctly social or political (that is, not primarily physics-based) emphasis'.* My own use of such terms is intended to carefully relate the money system to the broader findings of quantum social science, not to mention their other meanings in the English language.† And I felt the objections seemed to be more about an instinctual response to some perceived transgression of boundaries on my part than about anything of substance. Words are themselves an entangling device, in physics or in economics, and in binding minds and ideas together they can also define limits and remove flexibility. So while the path of least resistance may have been to stick with neutral language and avoid such conflicts, why ignore the obvious connections? If physicists once felt fit to adopt a particular set of mathematical tools, why shouldn't social scientists do the same now? More deeply, is there something about quantum behaviour that repels some part of us? As we will see later, there is much to be learned by following these threads, even or especially when they lead to topics that are considered off-limits or even taboo in economics.

Finally, one may reasonably object that economics should not be just about money and finance; it should also be about quality of life, social justice, power, the environment, and so on, none of which lend themselves easily to a monetary description. If quantum economics doesn't address these issues, then how is it any better than the existing neoclassical approach, which at least claims to be about happiness? Yet I will argue that recognising the importance of money affects how we see all of these things, and that limiting the domain of economics can paradoxically make it more useful and relevant. And while finance employs relatively few people directly, my own motivation for getting involved in economics grew out of a response to the 2007–08 financial crisis which affected the lives of many people, and not just bankers.

The idea of *how much* – of quantifying value, of putting numbers on the world – goes to the very heart of what economics should be about, which is monetary transactions. Following this thread will reveal new ways of approaching our gravest economic issues including inequality, financial stability, and the environmental crisis, while giving fresh insights into the sources of economic vibrancy and energy. Instead of predicting an economy that is efficient, fair, and stable, quantum economics suggests one that is creative but tends towards inequity and instability – rather like the world we live in.

Quantum knitting

The aim of this book is to look at a very simple question – what we mean in economics by the expression *how much*. Following the spirit, but not the letter, of quantum physics, we start with the small and knit our way out to form a cohesive whole. The goal of the book is not to present a new vision of society or expand human consciousness – as desirable as those may be – but to make economics smaller but more grounded and realistic. The book is divided into two parts. The first part, Quantum Money, begins by tracing the history of quantum physics from its discovery at the start of the twentieth century, and explaining some of its key principles. We then relate these findings to the dualistic properties of money, a substance which is as important to the economy as water is to life. We show how money is produced in the modern economy; and reveal how the banking system exploits the magical properties of money to produce wealth, especially for the bankers.

In the second part, The Quantum Economy, we expand the picture to include the economy as a whole. We first delve into the field of quantitative finance. As we'll see, the equations behind these derivatives grew out of the project to build a nuclear bomb – economists who resist the idea of importing ideas from quantum physics might be surprised to learn that it already happened, if in a rather distorted way – and this connection to quantum mechanics has been rediscovered in recent years by experts working in the area of quantum finance. Similarly, the mathematics of game theory, which underlies much of mainstream economic theory, assumes rational behaviour; but rather than acting as individual atoms when making financial decisions, we behave more like members of an entangled complex system, and operate according to a kind of quantum logic which resonates in interesting ways with the quantum properties of money. We will see that many key aspects of the economy emerge as the product of our quantum money system. The book concludes by drawing these ideas into recommendations for the reform of economics.

Along the way we will explore topics including:

Money. During the gold standard, money was thought to be a real thing, while today it is more commonly seen as a number representing virtual government-backed debt, except for cybercurrencies which don't quite fit with either picture. We will show that money is both real and virtual, in the same way that light is both particle and wave.

Value. Classical economists such as Adam Smith believed that money was measuring labour, neoclassical economists that it measures utility. According to quantum economics, money is measuring – money, which is a form of information.

Pricing. In conventional theory, prices are thought to be determined by imaginary supply and demand curves, which – as we'll see – have no empirical backing. Quantum economics shows that price is an uncertain property which is in a sense *created* through transactions – just as a particle's position or momentum is inherently indeterminate until measured. This has implications for areas such as quantitative finance, but also for the dynamics of things like the price of your house or the value of your pension.

Debt. Mainstream economics treats debt as something that comes out in the wash – what one person owes, another is owed, so they cancel out. According to quantum economics, though, debt is a force that entangles people, institutions, and the financial system as a whole in ways that are difficult to understand and potentially destructive. This is a concern, given that global debt is now estimated at over $200 trillion.[25]

Risk. Mainstream theory assumes that markets are stable, efficient, and self-correcting. Quantum economics shows that none of these assumptions stand up, which means that the risk models currently taught in universities and business schools, and relied upon by businesses and financial institutions, are not fit for purpose (as many guessed after the last crisis). We need to update our approach to handling risk.

Decision-making. Mainstream models assume that consumers make rational decisions, with the occasional adjustment to account for behavioural factors such as 'bounded rationality' (i.e. the fact that we make decisions under informational and cognitive limitations).[26] Quantum economics admits no such bound, and treats things like emotion and entanglement as integral to the decision-making process.

Finance. Mainstream models downplay or ignore the role of the financial sector, which is one reason financial crises always come as a surprise. Quantum economics puts money in its rightful place at the centre of economics, and offers new tools for understanding the financial system. Only by acknowledging the dynamic and unstable nature of the system can we find ways to better control it. Nowhere is this more true than with the quadrillion dollars'-worth of complex derivatives which hang over the economy.

Inequality. Mainstream economics was inspired by classical thermodynamics and concentrates on optimising average wealth (like the average temperature) instead of its distribution. But the dynamics of money tend towards disequilibrium and asymmetry. This helps to explain why a group of people who could fit into the first-class cabin of a jet now control as much wealth as half the world's population.[27]

Happiness. Mainstream economics assumes that people act to optimise their own utility, which leads to maximum societal happiness. Quantum economics draws on the field of quantum game theory to show that the truth is more complicated, in part because people are entangled – and asks whether economics is the best tool for thinking about happiness in the first place.

Environment. As quantum cognition shows, context is important when we take decisions. The inbuilt biases of neoclassical economics have meant that for too long, we have been ignoring the wider environmental context, with very visible effects. Quantum economics points the way to an economics which can, not account for, but *make space* for fuzzy, uncertain quantities such as the health of ecosystems; while also addressing one of the main contributors to environmental damage, which is our money system.

Ethics. Just as money has been excluded from mainstream economics, so has ethics. One reason is that, as with classical physics, the economy has been treated as an essentially mechanistic system where things like will, volition, and personal responsibility seem to have no role. Another is the fact that, ironically, economics itself has been influenced by money. Quantum economics is the ethical alternative.

Modelling. Orthodox models of the economy used by everyone from economists to central banks to policy-makers are based on a Newtonian, mechanistic view of human interactions and emphasise qualities such as stability, rationality, and efficiency. Quantum economics starts from a different set of assumptions, and leads to models that exploit techniques developed for the study of complex, living systems. A word of warning: this area is new, so while I will concentrate on tested methods, not all of the ideas and techniques described here have been demonstrated yet in an economics context. I will make it clear when that is the case.[‡]

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Quantum economics will therefore provide a consistent and much-needed alternative to the mainstream approach: one which is rooted in recent developments in areas such as social science, information theory, and complexity; which radically challenges our most basic assumptions about how the economy works; and which leads to concrete recommendations for the reform of economics. We begin by showing what happened over a century ago, when a physicist working for a lighting company asked *how much* – and came up with a rather surprising answer.

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† As the political scientist – and leader in the area of quantum social science – Alexander Wendt notes: 'money is not only a perfect illustration, but arguably (along with language) one of the most fundamental "quantum" institutions in all of society.' Personal communication, 2017.

‡ Readers interested in mathematical details are referred to: 'Introduction to the mathematics of quantum economics', available at davidorrell.com/quantumeconomicsmath.pdf

PART 1

Quantum Money

CHAPTER 1

THE QUANTUM WORLD

The great revelation of the quantum theory was that features of discreteness were discovered in the Book of Nature, in a context in which anything other than continuity seemed to be absurd according to the views held until then.
Erwin Schrödinger, *What is Life?* (1944)

Natura non facit saltum (Nature makes no sudden leaps) Epitaph of Alfred Marshall's 1890 *Principles of Economics.*
It remained there until the final edition of 1920

Money, according to the media theorist Marshall McLuhan, is a communication medium that conveys the idea of value. To understand the properties of this remarkable medium, we begin by looking at a different kind of exchange – that of energy between particles. This chapter traces the quantum revolution in physics which began in the early twentieth century, and shows how its findings changed the way we think about things like matter, space, time, causality, and even the economy. As we'll see, economic transactions have more in common with the quantum world than one might think.

How much? This was the question pondered by the German physicist Max Planck in the late nineteenth century. *How much energy is carried by a light beam?*

Planck's employer was the Imperial Institute of Physics and Technology, near Berlin, and his work was sponsored by a local electrical company. Their interest was in getting the most light out of a bulb with the least energy. A first step was to figure out a formula for how much light is produced when you heat something up.

Anyone who has placed a poker in a fire knows that as the metal heats it begins to glow red, then yellow, and then – at very high temperatures – a bluish white. When you turn on a lightbulb the thin filament inside does the same thing, except that it skips quickly to the white.

Scientists at the time knew that light was a wave, and that both the colour and the energy were determined by the frequency (or the closeness of the wave crests).* When something is heated, it emits light at a range of frequencies which depend on the temperature. An object at room temperature emits light in the low-frequency, low-energy infrared range, which is visible only through night-vision goggles. At extremely high temperatures, most of the light is in the invisible, high-frequency, high-energy ultraviolet range, but the object appears to our eyes as white – which is a mix of all frequencies.

The problem was with conventional theory, which predicted that a heated object would *always* emit light at all frequencies. Since high-frequency waves carry a lot of energy, an implication was that the energy would be channelled into arbitrarily short wavelengths of unlimited power. The question *how much* was therefore giving a puzzling answer: infinitely much. Instead of warming us, a log fire would vaporise us.

Few people at the time were calling for a revolution in physics. When Planck was contemplating a career in physics, a professor advised him against it, saying that 'in this field, almost everything is already discovered, and all that remains is to fill a few holes'.[1] In 1894 the American physicist and future Nobel laureate Albert Michelson had announced that 'it seems probable that most of the grand underlying principles have been firmly established and that further advances are to be sought chiefly in the rigorous application of these principles to all the phenomena which come under our notice'.[2] And Planck was not setting out to disrupt the field when he found a way in 1901 to model the radiation distribution with a neat formula. He just needed to use a little trick, which was to assume that the energy of light could only be transmitted in discrete units. The energy of one of these units was equal to its frequency multiplied by a new and very small number, denoted *h*. To name these little parcels of energy, Planck chose the word *quanta*.

The only problem with this assumption was that it violated the time-honoured principle that *Natura non facit saltum*: nature makes no sudden leaps. Or as Aristotle put it in *Metaphysics*, 'the observed facts show that nature is not a series of episodes, like a bad tragedy'. But as Planck later wrote, he considered it 'a purely formal assumption … actually I did not think much about it'.[3]

Thus was launched what became known as the quantum revolution. It took a while for the waves of this revolution to lap onto the shores (let alone the textbooks) of academic economics, but as we'll see, it promises to have the same effect on that field as it did on physics.

A century after Planck, the Nobel laureate economist Robert Lucas, famous for his theory of 'rational expectations', echoed Planck's teacher when he told his audience in 2003: 'My thesis in this lecture is that macroeconomics in this original sense has succeeded: Its central problem of depression prevention has been solved, for all practical purposes, and has in fact been solved for many decades.'[4] All that remained, it turned out, was to fill a few holes – like the ones left by the great financial crisis that started just a few years later, when the economy took a sudden leap off a cliff. But we're getting ahead of ourselves.

The colour of their money

While Planck's quanta may have been intended as just a pragmatic technical fix, they soon proved useful in solving another problem, which had to do with the photoelectric effect. This refers to the tendency of some materials to emit electrons when light is shone on them. Physicists found for example that, if they placed two metal plates close together in an evacuated jar, connected the plates to the opposite poles of a battery, and shone a light on the negatively charged plate, then the light dislodged electrons which raced across to the other, positively charged plate, in the form of a sudden spark.

According again to the classical theory, the energy of the emitted electrons should depend only on the intensity (i.e. brightness) of the light source. Shine a bright light, get a bigger spark. But in practice, it turned out that what really mattered was the colour, or frequency: high-frequency blue light created a bigger spark than low-frequency red light. And each material had a cut-off frequency, below which no amount of light would work. In a 1905 paper – one of a stream of results including his famous formula $E=mc^2$ which would define the new physics – Albert Einstein showed that the photoelectric effect could be explained by use of Planck's quanta.

According to Einstein's theory, electrons were emitted when individual quanta of light struck individual atoms. Think of the metal plate as a marketplace of atoms, each selling electrons at a particular price, measured in energy; and think of the quanta of light as being the spending power of individual shoppers. Shining red light onto the plate is like sending a lot of low-budget shoppers into the market. No matter how many there are, if none of them have sufficient cash then no electrons are released – they can look but they cannot buy. High-frequency blue light, on the other hand, is an army of high-spenders. So what counts is not just the number of shoppers (the brightness) but how much each shopper can spend (the colour).

Einstein of course did not use this metaphor, and he gave his paper the careful title 'On an heuristic[†] viewpoint concerning the production and transformation of light'. But it was clear that unlike Planck, he saw these light quanta – which later became known as photons – not as mathematical abstractions, but as real things. As he wrote, 'Energy, during the propagation of a ray of light, is not continuously distributed over steadily increasing spaces, but it consists of a finite number of energy quanta localized at points in space, moving without dividing and capable of being absorbed or generated only as entities.'[5]

This sounds mysterious when applied to light, but again is similar to the way that we make financial transactions. When you receive your pay packet, there isn't a little needle which shows the money draining into your account. Instead it goes as a single discrete lump. The same when you use your credit card at a store, or when a bank creates new funds by issuing a loan. And it is impossible to make payments smaller than a certain amount, such as a cent.

Most physicists responded to these new ideas in the same way most mainstream economists react to disruptive ideas today, which was to ignore them totally and hope they went away. But the question *how much* soon proved useful in solving another problem, which this time went right to the heart of what we mean by things – the atom.

Atomic auction

In the early twentieth century it was understood, at least according to the classical model, that there were two basic kinds of phenomena: waves and particles. Light, for example, was a wave, an electromagnetic perturbation in the ether, which played the role of a background medium through which the wave moved (this substance was later dropped, as discussed below). Objects, on the other hand, were made of atoms, and these in turn were composed of negatively charged electrons circling a small, but heavy, positively-charged nucleus like planets around the Sun. The energy of an electron depended on the radius of its path. The simplest atom, hydrogen, had only one electron, but larger atoms had multiple electrons at different energy levels.

The solar system model, as it was known, did explain a number of features of atoms, for example experimental results which showed that they mostly consisted of empty space. Fire small charged particles at a thin foil, and most pass through as if there were nothing there, while only a few bounce back. Again, though, there were a couple of problems. One was that the model didn't spell out why atoms of a particular substance, say hydrogen, are identical with one another. What made electrons of different atoms always whizz round at the same radius? An even more serious issue was that, according to classical theory, a circulating electron should immediately radiate away all its energy and crash into the nucleus, like Mars colliding with the Sun.

In 1912 the Danish physicist Niels Bohr proposed a novel solution. If the energy of light was limited to discrete units, as Planck said, then so perhaps was the energy of the electron.[6] This would mean that electrons could not have a continuous range of energies, but would be limited to multiples of some lowest base amount. And the reason an electron couldn't radiate away all its energy was because it could only give it away in lumps, and it couldn't go to zero. Electrons could gain energy, for example from a passing photon, and move to a higher level; or they could lose energy, by emitting a photon, and go down a level; but the change in energy would again always be a multiple of the base amount. The process was like an auction in which the auctioneer sets a certain base price, and only accepts bids that are multiples of some amount. The price can never go below the minimum, and can only go up in discrete steps.

Evidence that Bohr was on the right track was provided by the fact that his model could help to explain another puzzle. It was known that atoms of different elements emit and absorb light at certain distinct, characteristic frequencies or spectra (this is the basis of spectroscopy, used to determine the chemical makeup of a material). This property was again inconsistent with classical physics, which predicted a continuous spectrum; but starting with the simplest case of hydrogen, Bohr showed that it matched his model rather well. The favoured frequencies just reflected the possible transitions from one energy level to another, as electrons absorbed or released photons.

In Bohr's model, the analogue solar system picture was therefore replaced with a digital one in which electrons could live only in certain layers arranged in concentric rings around the nucleus. The inner layer could hold at most two electrons. The next layer out could hold a maximum of eight. If the atoms of a particular element had a full outer layer, then that element was chemically stable. Helium, for example, has only two electrons, both in the inner layer. Neon has ten electrons, with two in the inner layer, and eight in the next layer, so again it is a full house. Sodium, however, has eleven electrons, with the extra one in the third layer, and is so reactive that it can explode in contact with water. Chlorine, a poisonous gas, has seventeen electrons – organised as 2-8-7 – so is one short in the third layer. The combination of the two is stable because sodium shares its extra electron with chlorine. This is a useful feature, since otherwise sodium chloride – aka table salt – would presumably be both explosive and poisonous, which would limit its attraction as a seasoning (the taste of salt is an example of an emergent property, which, as discussed later, implies that it is not the same as the sum of its parts).

Odd versus even

Quanta, it seemed, could explain much about the basic structure of matter, but Bohr's model still had a few problems. One was that it had little to say about the experimental observation that a material's spectral lines were split when it was placed in a magnetic field. To accommodate such effects, three more quantum numbers eventually had to be added; two which described the orbit's exact shape and orientation, and another number called the spin which was like a quantum version of a particle's rotation around its own centre. For photons, as discussed below, their spin is related to the polarisation of light.

The model seemed to be getting rather cumbersome, but in 1925 the young physicist Wolfgang Pauli realised that it could be used to explain why the electrons in an atom didn't all drop down to the ground state.[7] The reason was that the quantum numbers acted as an address, and no two electrons could live in the same place. The helium atom, for example, has two electrons in the same inner ring, but they differ in spin.

It was later found that Pauli's 'exclusion principle' applied only to the particles known as fermions, which include the basic constituents of the atom such as the electron and proton, and that have an odd multiple of the basic unit of spin.[‡] Bosons, which are responsible for force transmissions and include photons, have an even-multiple spin. These are less stand-offish and can share the same space.[§] (In her 1990 book *The Quantum Self*, Danah Zohar describes bosons evocatively as 'particles of relationship' and fermions as 'anti-social'.[8])

A more basic question, though, was what it meant for matter and energy to be divided into quanta at all. After all, scientists knew that light was a wave. Thomas Young had demonstrated this fact back in 1801, in his famous double-slit experiment.[9] He shone a beam of light from a point source through two thin slits, and looked at the pattern projected onto a screen behind them. Instead of finding two distinct bright spots, which one would expect for streams of particles, he instead found that each light beam was diffracting as it passed through the slit, and then merging to form an interference pattern of alternating bright and dark bands, just like the ones formed in water when the crests and troughs of one wave add or subtract from the crests and troughs of another. In 1861 James Clerk Maxwell derived the equations which proved that this wave was nothing other than an oscillating electromagnetic field. But here were Einstein and the others saying that it consisted of photons – particles.

An answer of sorts was supplied in 1909 by Geoffrey Taylor, who tried the same experiment as Young, but this time using a very faint light source, so faint that individual photons were emitted one at a time.[10] What he found was perplexing – because even when the photons passed through the slits individually, the interference pattern was still reproduced. It was as if each photon was somehow interfering with itself. The wave crests now corresponded to places where there was a high probability of seeing a photon, while the troughs had a low probability.

As Einstein told a German newspaper in 1924: 'There are therefore now two theories of light, both indispensable, and – as one must admit today in spite of twenty years of tremendous effort on the part of theoretical physicists – without any logical connection.' [11] The reason, as we'll see, was that matter wasn't based on classical logic – it was based on quantum logic.

The indeterminacy principle

The question *how much* had led to the idea that light waves were actually particles. But if that were true, then surely – if only for the sake of symmetry – particles could be waves as well? This was the idea suggested in his 1924 PhD thesis by a student at the Sorbonne called Louis de Broglie.[12]

Physicists had abandoned the idea of an ether, for both experimental reasons (the speed of light, denoted *c*, was the same in every direction, which made no sense if the planet was spinning through some invisible medium) and theoretical reasons (Einstein's relativity, which set this constant c as a universal speed limit), and they now thought of waves as some kind of free-standing entity. De Broglie combined Einstein's theory with Planck's quanta, plugged the results into the equation for a wave, and reasoned that the wavelength associated with a particle should be Planck's constant *h* divided by the momentum.

Experimental results soon proved De Broglie right: electron beams do indeed diffract like waves when they encounter matter (this is the principle behind modern electron microscopes). And the orbit of an electron circulating around an atomic core could be viewed as a standing wave, with an integer number of peaks corresponding to the quantum number of the energy level. The main difference between photons and other particles such as electrons is that electrons have mass, while photons don't.

Physicists were adept at computing the behaviour of waves, such as those of a vibrating string, and within months Austrian physicist Erwin Schrödinger had come up with a detailed equation that could be used to model electron waves. He also showed, at least for simple cases such as the hydrogen atom, that the possible quantum states of an electron correspond to the harmonics of its mathematical wave function, just as musical notes correspond to the sound waves produced by a tuned instrument. These quantum states therefore 'occur in the same natural way as the integers specifying the number of nodes in a vibrating string'.[13]

It was less clear how to interpret what the wave equation – which was just an abstract mathematical formulation – actually *meant*. De Broglie had viewed it as representing a kind of pilot wave that guided the position of the electron. Schrödinger's colleague Max Born suggested instead that the wave was supplying probabilistic information, so the chance of finding an electron in a particular place depended on the amplitude (distance between peak and valley) of the wave squared.[14] Because the wave function is expressed in so-called complex numbers, whose square can be negative, this allows for negative probabilities. When waves interfere, as in the double-slit experiment, it is because one wave is subtracting from the other. As Paul Dirac noted, 'Negative energies and probabilities should not be considered as nonsense. They are well-defined concepts mathematically, like a negative of money.'[15]

This seemed a reasonable interpretation, except that waves and particles have very different properties. For example, a property of waves is that they tend to be leaky. Think about sound waves: you might be able to reduce most of the noise from your neighbour by putting insulation in the wall or wearing earplugs, but reducing it to zero is impossible. Similarly, the wave associated with a particle can leak through boundaries, and since this wave describes a probability of finding the particle at a particular location, it means that the particle can potentially appear on the other side. In fact, this is the principle of alpha decay, in which a radioactive substance such as uranium emits an alpha particle, which is a helium atom stripped of its electrons. According to classical physics, alpha decay shouldn't happen because the alpha particle could never escape the attractive force of the nucleus, which imposes an apparently insurmountable boundary. But in quantum physics, this only means there is a very small chance that the particle will escape, which is not the same thing at all (see atom bombs).

The diffuse nature of the wave equation meant that the true state of a particle could never be completely nailed down. The German physicist Werner Heisenberg argued that it therefore made no sense to speculate about what was going on inside the atom.[16] The true state of a particle was unknowable, and all we had were observations, which were subject to inherent uncertainty because of the wave equation. He quantified this with his uncertainty principle, which stated that the more accurately a particle's position was measured, the more uncertain was its momentum, and vice versa.

One way to think about this uncertainty is to note that, in quantum mechanics, the chance of finding a particle in a certain location is specified by the wave function; and it turns out the more you know about the location – i.e. the narrower the wave – the less you know about how fast the particle is moving. In general there is always a trade-off between position and momentum (defined as mass times velocity), so you can never know both perfectly. The same type of uncertainty relationship applies to other pairs of quantities, such as energy and time, where the latter refers to a characteristic time such as a particle's lifetime. This is why a so-called virtual particle can appear out of nowhere, exist a brief time, then disappear back into the void without violating conservation of energy.

As an example of the uncertainty principle, suppose that we wish to measure the position and momentum of an electron. One method, as Heisenberg noted, would be to shine light on it and use a microscope to look at the reflected light. To accurately measure the position we need to use the shortest possible wavelength of light, since otherwise the image will be fuzzed out. This equates to using photons with short wavelengths (or equivalently high frequencies). But such photons have high energy, so will deliver a kick to the electron and change its momentum: 'thus, the more precisely the position is determined, the less precisely the momentum is known, and conversely.'[17]

It is important to note, though, that the problem is not just a practical one of measurement. In quantum physics (or at least the standard interpretation – see below), the wave function means that quantities such as position and momentum have no real independent meaning until the moment they are measured, so are fundamentally indeterminate rather than just impossible to precisely measure. (As is often noted, a better name might be the indeterminacy principle.) Measurement is therefore not a neutral, passive process, but an active process which affects what is being measured. For example, it has been shown in the laboratory that the results of different measurements depend on the order in which they are made.[18] As we will see later, the same effects apply in human psychology.

To be, or not to be

The idea that matter had attributes of both waves and particles made sense from a purely mathematical standpoint, which as far as Heisenberg was concerned was all that mattered. Bohr argued, however, that it had a deeper meaning. According to his principle of complementarity, the mutually incompatible wave and particle descriptions each gave one aspect of a single, unified reality. Instead of wave or particle, it was wave *and* particle.

This collided head-on with the most basic principles of logic. In *Metaphysics*, Aristotle had written that 'it is impossible for anyone to believe the same thing to be and not to be, as some think Heraclitus says'.[19] (The dissident Heraclitus was ahead of his time.) As Heisenberg noted, 'it was found that if we wanted to adapt the language to the quantum theoretical mathematical scheme, we would have to change even our Aristotelian logic. That is so disagreeable that nobody wants to do it; it is better to use the words in their limited senses, and when we must go into the details, we just withdraw into the mathematical scheme.'[20] Less controversial was Bohr's principle of correspondence, which stated that at scales large enough that the effects of Planck's constant h could be neglected, quantum mechanics should converge to classical mechanics – although quantum effects can sometimes be scaled up, as discussed below.

The philosophical debate over the meaning of the wave equation has never been settled, but in 1927 a kind of compromise was presented to the luminaries of physics at a conference in Solvay, Belgium. The Copenhagen interpretation, as it later became known, asserted that until it is observed, a particle's state is given by its wave function, and is uncertain; but when a measurement takes place, the wave function somehow reduces or 'collapses' so that the attribute measured has a specific value.

The Copenhagen interpretation therefore retained some of the deterministic flavour of classical mechanics, with a couple of important differences. One was that the determinism now applied to probabilistic wave functions. Instead of particles obeying mechanistic laws, said Born, 'probability itself propagates according to the law of causality'.[21] The other was that uncertainty was inherent rather than statistical. For example, if a jar is filled with 50 red beads and 50 blue beads, and we choose one at random, then from statistics we know that there is a 50 per cent chance that it will be red. In quantum physics, there is a bead in a jar, which is in a superposition of two states. When we pull it out, it might be red, but it could just as well have been blue. Instead of having a fixed colour, the bead has a potential colour that is resolved only upon measurement.

This sounds mysterious and magical, but – to again use a financial example – when you put your house up for sale, you might have a rough idea how much it will fetch, but you don't know for sure, because your house has neither a fixed price tag nor a guaranteed buyer. A hundred people might show up for the open house, resulting in a bidding war and a magnificent winning offer. Or you might get zero offers and have to lower the price. Your house does not have a fixed price, any more than a quantum particle has fixed attributes such as position. Only when someone actually buys it does the uncertainty collapse.

Mind control

Not everyone was convinced by the Copenhagen interpretation. Einstein in particular couldn't accept the idea that random behaviour – or worse yet, some kind of agency – could be built into the fabric of the cosmos. 'I find the idea quite intolerable', he wrote in 1924, 'that an electron exposed to radiation should choose of its own free will, not only its moment to jump off, but also its direction. In that case, I would rather be a cobbler, or even an employee in a gaming house, than a physicist.'[22] He believed instead that such behaviour was actually the result of undetected processes, or hidden variables.

The process of wave function collapse was also unspecified. In 1935, Schrödinger came up with a famous thought experiment to illustrate the theory's flaws. This involved a cat locked up in a steel chamber along with a small amount of radioactive substance, which had a 50-50 chance of emitting a radioactive particle within one hour. A Geiger counter is set up so that, if radiation is detected, a 'small flask of hydrocyanic acid' is released, killing the cat.[23] The fate of the cat was therefore linked to the wave function of the radioactive particle, which in turn collapsed only when observed. Taken literally, the Copenhagen interpretation therefore seemed to imply that the cat would be both alive and dead at the same time, until the moment someone opened the door and observed what had happened.

Perhaps the most disturbing feature of quantum mechanics, at least for physicists such as Einstein, was that it seemed to hold out a role for mind. As the mathematician John von Neumann argued in 1932, the special ingredient in a measurement process was not the measuring device itself, which was just part of the physical system, but the presence of a conscious observer.[24] Schrödinger also wrote in 1935 that the process relies on 'the living subject actually taking cognizance of the result of the measurement'. But just as classical logic drew a firm line between being and not being, so it drew a line between mind and body, subjective and objective. The idea that just observing something could affect its behaviour was about as repugnant as believing that a magician can make a table levitate using his mind alone. Something was fishy – and Einstein was determined to figure out the trick. The same year as Schrödinger's thought experiment, he and two collaborators finally hit on an (animal-free) thought experiment which could disprove the Copenhagen interpretation, and reveal the hidden variables that were operating behind the scenes.

The so-called Einstein-Podolsky-Rosen (EPR) paradox arises when two quantum systems are related in such a way that information on one yields information on the other, in a manner which appeared to contradict the idea that quantum properties are fundamentally indeterminate.[25] For example, suppose we know that a particle decays into two particles, A and B, which by conservation of angular momentum – a law which here implies the spins will add to zero – must have opposite spin. The two particles are then entangled, as if bound by an invisible contract, because information about the state of one yields information about the other. More generally, as Schrödinger noted, whenever two systems interact, their wave functions 'do not come into interaction but rather they immediately cease to exist and a single one, for the combined system takes their place'.[26] If we measure A's spin, then we automatically know B's spin – it will be the opposite. So in other words we have successfully carried out a measurement on B without disturbing it in any way. This contradicts the idea that such properties are intrinsically uncertain quantities that are known only after the collapse of some mysterious wave function. It also implies that the notion of individuality breaks down, since A and B are effectively part of a single system.

The only way out of this would be to assume that A and B can communicate in some way – but for that to work within the formalism of quantum theory, the information would have to be transmitted instantaneously, even if the particles were light years apart. This would violate Einstein's theory of relativity, which showed that nothing – including signals between particles – could travel faster than the speed of light, an idea he famously mocked as 'spooky action at a distance'. Einstein therefore concluded that quantum theory was incomplete, and something else had to be going on. The theory was correct in the sense that it made many accurate predictions, but it was best seen as a statistical approximation to a fuller theory which would explain all of its apparent randomness with a more logical explanation.

Getting entangled

The EPR paradox remained a mental puzzle until in 1964 the Irish physicist John Bell worked out a way to actually test it. The first step is to get a pair of particles that are suitably entangled. This can be done quite easily in the laboratory by shining an ultraviolet laser through a particular sort of crystal;

some of the ultraviolet photons get split into two entangled infrared photons of half the energy, and with opposite polarisations.

As shown by Maxwell, a light wave consists of electric and magnetic fields oscillating at right angles to one another. The polarisation refers to the orientation of these fields relative to the direction of travel of the wave. In unpolarised light, the light is a mix of all different orientations. When light is reflected, for example from the surface of a lake, it naturally becomes polarised. Polaroid sunglasses work by using polarisation filters to preferentially filter out this reflected light.

Just like light waves, individual photons also have a particular polarisation, which is associated with their spin. The difference is that, if you test whether the photon is horizontally polarised, for example by passing it through a filter which only allows horizontally polarised light to pass, you don't get some partial answer like 12 per cent horizontal for that photon – you just get a yes or a no. It is Aristotelian logic in action. Before being measured, the photon's state is a superposition of vertical and horizontal polarisation, but if it passes through the filter, it's like it was horizontal all along (see figure opposite).

Because photons A and B are entangled, if photon A gives a yes when tested for horizontal polarisation, then so will photon B, since it is horizontal too (but opposite). But now suppose you measure photon A's horizontal polarity, but photon B's polarity along another direction. If the two directions are at right angles to one another, e.g. horizontal and vertical, then the results will be uncorrelated – knowing the polarisation along one tells you nothing about polarisation along the other. But for intermediate angles the situation is more complicated. John Bell showed that, if quantum mechanics is correct – in which case the particle polarisations are indeterminate up until the time they are measured – then the correlation is as much as 50 per cent higher than if the particles are following some kind of deterministic plan.[27]

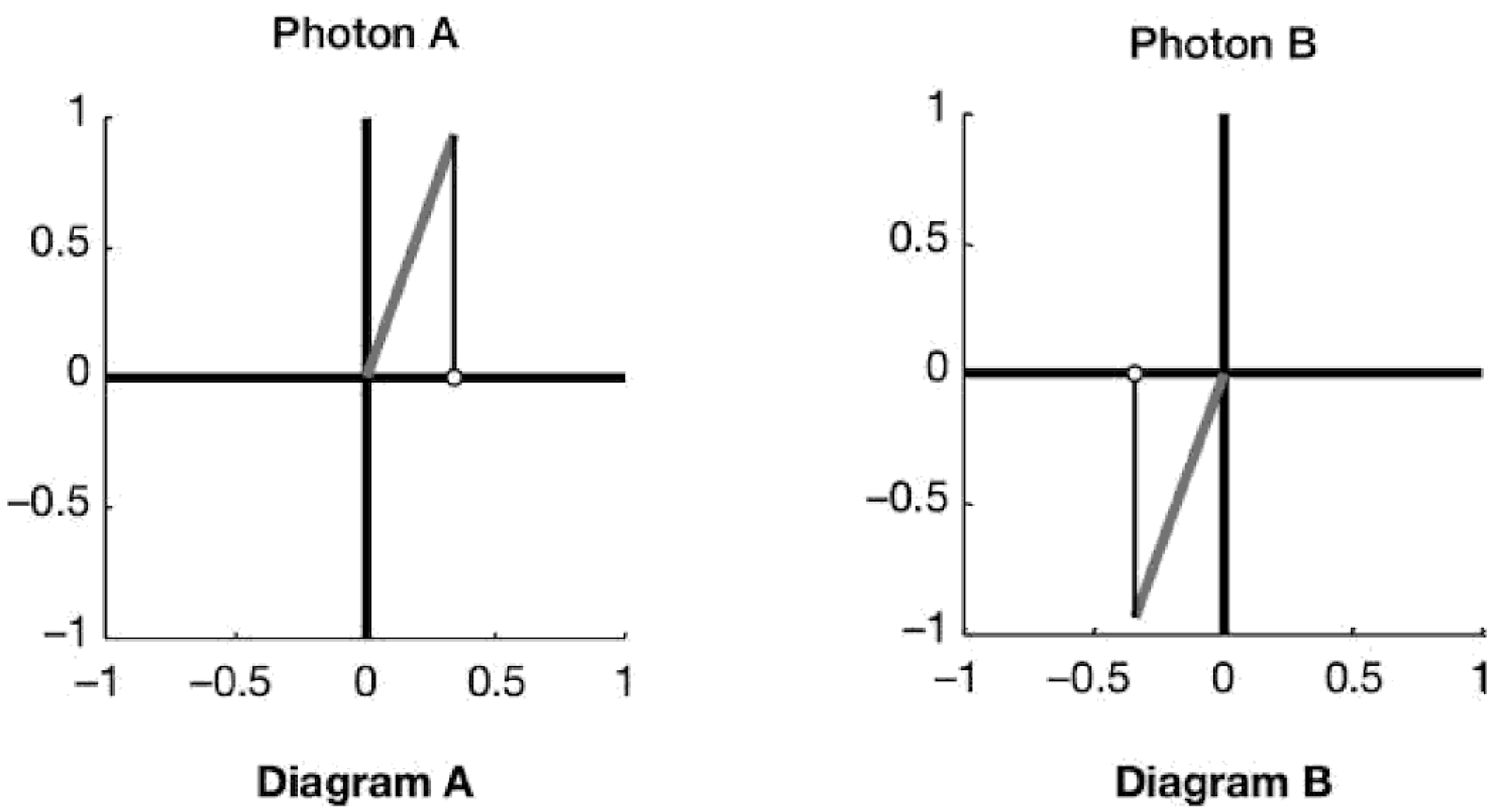

Figure 1. The grey line in diagram A describes the indeterminate spin state of a polarised photon, one of an entangled pair A and B, before measurement. The probability of the polarisation being measured as horizontal is given by the square of the projection onto the horizontal axis, indicated by the circle symbol. In this case the length of the projection is 0.35, which squares to about 0.12, corresponding to a probability of 12 per cent. Similarly the chance of the polarisation being measured as vertical is given by the square of the projection onto the vertical axis, which works out as 0.88 or 88 per cent (note the probabilities must add to 1 because the photon must be in one state or the other). The quantum state of photon B is shown in diagram B; the measured spin will always be in the same axis, but opposite in direction to that of photon A.

Bell's paper therefore supplied a way to test a deep philosophical puzzle about the nature of reality. Most physicists were too busy applying quantum mechanics to take notice, and the paper at first received little attention. But eventually interest picked up, and in the 1970s and 1980s a series of increasingly refined experiments managed to put Bell's ideas to the test – and established that the predictions of quantum mechanics did indeed hold. Even if the quantum state of one entangled particle is completely random, and only determined upon measurement, it is still linked to the quantum state of its partner; and a measurement on one entangled particle effectively acts as a measurement on the other. This would be the case even if the particles were located at opposite ends of the universe (experimentalists haven't managed to do this, but they can send entangled particles to satellites in space).[28] Since particles have had plenty of time since the birth of the universe to become entangled with one another, the implication is that space – or at least the concept of spatial separation – isn't quite as much of a barrier as we think it is.

Entanglement is not limited only to single particles. In 2001 a similar experiment was performed for individual atoms, and in 2017 scientists demonstrated quantum entanglement of crystals comprising up to a billion atoms. 'What this work shows us', noted physicist Vladan Vuletić, 'is that there are certain types of quantum mechanical states that are actually quite robust.'[29] Indeed quantum entanglement is one of the key features exploited by quantum computers (discussed in Chapter 6), quantum cryptology (using entangled particles as keys to a code), and quantum teleportation (sending information via entangled particles), which promise to revolutionise areas from finance to defence. It has even been suggested that similar experimental techniques could be applied to the quantum entanglement of the smallest living organisms, such as viruses.[30] Not quite Schrödinger's cat, but getting there.

In a 1985 article for *Physics Today*, physicist David Mermin wrote that 'The EPR experiment is as close to magic as any physical phenomenon I know of'.[31] However, while it may challenge our understanding of physical reality, the concept of entanglement will be quite familiar to anyone who has signed a contract or taken out a loan. Indeed, as we will see later, the process by which private banks create money by issuing a mortgage is rather similar to an entanglement experiment. Instead of photons with opposite polarity, the bank creates a negative credit for the customer, which is balanced in the bank's books by the positive credit of the underlying property. From that moment on, the customer and the bank are entangled, and an event on one side affects the other. As in quantum physics, these entanglements are not felt as mechanistic influences or forces, but as informational changes in state. For example, if the customer decides to default on a mortgage because they lost their job, and they return the keys to the bank, then that changes the state of the loan instantaneously, even if the bank doesn't find out until they open their mail. At least as far as the loan is concerned, the two parties can no longer be considered separate entities.

Back to the future

An even more graphic demonstration of quantum magic can be arranged by performing what is known as the quantum erasure experiment. As *Scientific American* showed in a 2007 article, a modern version can be done at home using readily available equipment such as a pen laser and polarising filters.[32] Instead of passing the light from a point source through two slits, you just point the laser at a screen about two metres away, and place a vertical wire directly in its path. The photons stream either side of the wire, diffract, and interfere with themselves to create an interference pattern on the screen, of the sort Young found in 1801.

Now, suppose that we want to analyse what is going on and find out which side each photon is taking. One way to do this is to attach oppositely-oriented polarisers on either side of the wire, so that for example only vertically polarised photons pass on the left, and horizontally polarised photons pass on the right. These filters effectively label each photon, and make it possible to distinguish which photon takes which path. What effect does this labelling have on the interference pattern?

Since the filters have no effect on the photons other than to stop them or not, we might expect that the interference pattern should remain unchanged. In fact, though, the effect is to make it disappear. The reason is that by measuring the photon's polarisation – or actually just making it possible in principle to measure – we have in effect collapsed its wave function and made it behave like a particle. And while the wave function can explore all possible paths, and so interfere with itself, the particle has to choose.

Note that what counts here is not whether we actually check the polarity of each photon and go through the exercise of determining which side it came from. The point is that the information has been made available by the labelling. To see this, we can repeat the experiment but this time scramble the labels so the information is lost. (One way to do this is to place a third polariser between the wire and the screen which is oriented *diagonally*. Both the left-hand and the right-hand photons then have a 50 per cent chance of getting through, and we can no longer tell which they are, so their labels have been erased.) The interference pattern then magically reappears.

To recap: photons form an interference pattern, but labelled photons don't. If we do something to scramble the labels and make them useless, then the interference pattern reappears. So the thing that controls the interference effect is the information in the labelling. Richard Feynman famously said that the double-slit experiment 'has in it the heart of quantum mechanics. In reality, it contains the *only* mystery.'[33] This therefore hints at a deep relation between quantum theory and information, which we return to in Chapter 8.

Another variation known as the delayed-choice quantum erasure experiment can also be carried out in the laboratory on pairs of entangled photons, by using the same apparatus but this time moving the detection equipment so that a measurement on one photon is registered only *after* the first photon has completed its path. Remarkably this doesn't change the result, implying that the behaviour of a particle is affected by what happens to its twin in the future – as if the system is entangled, not just in space, but also in time.

Not so strange

As Karen Barad notes, 'Quantum mechanics poses some of the most thoroughgoing challenges to our common-sense worldview'. [34] Quantum entities such as photons sometimes present as virtual waves, sometimes as real objects. Particles don't move continuously, like normal objects, but in sudden jumps. Quantities such as position or momentum are fundamentally indeterminate until measured. Particles can be entangled so that a change in one instantly affects the other. They can magically appear out of nowhere, and then disappear back into the void.

Obviously, this has nothing to do with the way things behave in the real world that we live in. A bottle of wine on the table doesn't suddenly disappear and rematerialise in the kitchen. The feeling that quantum mechanics was somehow alien to common sense was also cemented by physicists themselves. Textbooks such as Paul Dirac's *Principles of Quantum Mechanics* focused on 'unadorned presentation, the logical construction of the subject from first principles and the complete absence of historical perspective, philosophical niceties and illustrative calculations'.[35] The Copenhagen interpretation, with its emphasis on abstract mathematics, seemed particularly baffling; while other interpretations, according to the physicist John Clauser, were 'virtually prohibited by the existence of various religious stigmas and social pressures, that taken together, amounted to an evangelical crusade against such thinking'.[36] One result, as mentioned in the Introduction, is that the insights of quantum physics have been lost behind an intimidating wall of mathematics. A similar trend towards mathematisation was seen in economics.

At the same time, though, the quantum universe does not seem quite so bizarre or alienating when viewed from an economic perspective. As noted earlier, the emission of energy in terms of discrete quanta, as in the photoelectric effect, is similar to the transfer of money in discrete amounts. Money can present as real objects, like coins, or as a kind of virtual transmission, as when we tap a credit card at a store. It doesn't flow continuously, but is transmitted in sudden jumps. The quantised structure of an auction resembles the discrete energy levels of an atom; and while stock market investors haven't figured out a way to look into the future, they can buy futures contracts which depend on events that have yet to happen.

The quantity known as price is fundamentally uncertain, and is determined only during the measurement procedure, when things are exchanged for money. Like elementary particles, money objects can be created out of the void, for example when banks create money by issuing loans, but can also be annihilated and removed from the system. And while it is hard to think how one could perform something like a Bell's test on a loan agreement, this doesn't mean the entanglement is any less real.[37] Like a wave function, the loan contract is a virtual thing which in a sense exists outside the physical constraints of time and space.

One might object that effects such as the uncertainty principle or interference do not apply to money objects themselves. We know a ten-dollar bill is worth exactly ten dollars, and it doesn't interfere or cancel out if we put it next to a five-dollar bill in our wallet. But if we view a money object as an exact store of energy, then zero uncertainty in the energy translates, according to the uncertainty principle, to an indefinite lifetime – which just means that a ten-dollar bill is worth ten dollars for ever (even if that amount won't always buy you the same thing). Such fixed and stable quantities do exist in quantum physics, for example the charge of an electron. And while their fixed nature means that money objects can't interfere with one another, they can certainly produce interference effects in the human mind, as we'll see in Chapter 7 (though the mind can also do that by itself – see box below).

Quantum behaviour therefore isn't quite as alien as we have been led to believe – in fact we deal with it every time we go shopping or cash a cheque. The point is not just that quantum mechanics can be viewed as a metaphor for understanding money (though all models are metaphors, including quantum mechanics), but that the economy is a quantum system *in its own right*, with its own very real versions of measurement, indeterminacy and entanglement. (We therefore have to wrestle these words away a little from their subatomic context, while respecting their meaning – if it helps, set aside what you read in this chapter, and imagine that we are describing the money system from scratch. Or say that we will model the money system as if it followed quantum rules, and see where it takes us.) An advantage is that these concepts lack the obscure and confusing nature of their counterparts in physics. We don't need a Schrödinger wave equation to know that value is uncertain, or an obscure process of wave function collapse to understand transactions. Since metaphors are usually used to explain complex phenomena by comparing with something concrete and familiar, it actually makes more sense to use money as a metaphor for quantum physics than the other way round. After all, we may be able to calculate a particle's wave function, at least for certain cases, but we can actually *feel* a sense of value. According to one interpretation (there are many) of quantum physics, known as quantum Bayesianism (or QBism), the wave function represents an agent's subjective degree of belief, and its collapse represents the agent updating their beliefs in response to information, which seems to match the economic context quite well.[38]

The correspondence principle

Of course, even if money has quantum properties, does this mean that we have to change the way we do economics? After all, as Barad notes, 'It would be wrong to simply assume that people are the analogues of atoms and that societies are mere epiphenomena that can be explained in terms of collective behavior of massive ensembles of individual entities (like little atoms each), or that sociology is reducible to biology, which is reducible to chemistry, which in turn is reducible to physics. Quantum physics undercuts reductionism as a worldview or universal explanatory framework.'[39]

Indeed, it is often said that quantum physics is the foundation of all the sciences, just because it deals with the building blocks of matter; but when it comes to large-scale properties of materials it is impossible to derive much of anything directly from quantum mechanics. Instead it is more accurate to say that these properties *emerge* from quantum mechanics (which perhaps emerges from something else). They are therefore an example of what complexity scientists call emergent properties, which cannot be reduced to some lower level of explanation.[40] But on the other hand quantum-like behaviour does appear at the macroscopic scale. An example is sound waves passing through a metal bar. If these are weak enough, the sound becomes quantised into discrete pulses just as light does. The waves are equivalent to an 'emergent particle' known as a phonon, which has a well-defined momentum.[41] So the fact that a system cannot be reduced to quantum physics does not mean that it cannot have quantum properties of its own, or inherit those properties from lower levels. In the same way, the quantum properties of money are not limited to small transactions but are felt around the world.

Such macro-level quantum properties are also regularly exploited in engineered systems. It has been estimated that some 30 per cent of the United States' gross domestic product can be traced to technologies such as microchips, GPS, and so on which are explicitly based on properties that arise from quantum effects.[42] Quantum mechanics is also used directly in many areas of engineering, such as nanotechnology, drug design, and of course nuclear weapons. In economics, the closest thing to an engineered system (though as we'll see, it's not that close) is financial markets, which perhaps explains why 'financial engineering' was one of the first areas to explore quantum ideas.

Bohr's principle of correspondence, which is sometimes used to suggest that quantum effects at the micro level are no longer relevant at the macro level, or to everyday life, therefore doesn't always apply. Also, the fact that we cannot reduce a system to its quantum foundations, does not mean that we can reduce them to mechanistic foundations instead, as is commonly attempted in economics. The complex macro properties of water, for example, are ultimately the result of quantum processes at the molecular level. The same is true of living beings, which exploit such emergent properties in their own ways. As we will see in later chapters, this is why the most appropriate models for economics tend to be based on mathematical techniques such as complexity and network theory that have proved useful for the study of complex organic systems in general.

Quantum economics therefore reflects principles which have shaped other areas of science in recent decades, and is consistent with our understanding of the quantum universe. It could even provide a path for helping to understand the behaviour of subatomic particles. The fact that matter gives us weird answers when we try to put numbers on quantities such as position or momentum reflects the same kind of fundamental incompatibility or tension between number and the real world that we see when we try to put a number on the fuzzy quality of value. And even if the economy is not the same as the subatomic world, we certainly seem to have designed it to be as close as possible. This will become clearer in the next few chapters, where we study the properties of the mysterious, shapeshifting, polarising, and dynamic quantum entity known as money.

Fruit and veg

Quantum interference doesn't just apply to subatomic particles, it also seems a good description of the way that we order our thoughts. This was illustrated in a study led by the physicist Diederik Aerts.43[43]

Aerts worked from a data set where experimental subjects were presented with a list of 24 fruits and vegetables, and asked to estimate the typicality of each being chosen as a good example of 'Fruits', 'Vegetables', and 'Fruits or Vegetables'. The complete list was: Almond, Acorn, Peanut, Olive, Coconut, Raisin, Elderberry, Apple, Mustard, Wheat, Root Ginger, Chili Pepper, Garlic, Mushroom, Watercress, Lentils, Green Pepper, Yam, Tomato, Pumpkin, Broccoli, Rice, Parsley, Black Pepper. Some of these fit neatly into one category or another, but several, such as mushroom, mustard or black pepper, don't. The results were then tabulated to calculate the probability of each being chosen.

If we think of the concept 'good example of a fruit from this list' as being represented by the conceptual equivalent of a wave function, then the probabilities of each choice correspond to the probability that the wave function will collapse to that state.

Consider for example the vexed question of whether a tomato is a fruit or a vegetable. To a botanist, a fruit is something that develops from a flower's fertilised ovary, while a vegetable is some other part of the plant. However, the word fruit is from the Latin *fructus*, meaning enjoyment, while vegetable is from *vegetabilis*, which just means growing; and many people associate the former with something that is typically eaten raw, like an apple, and the latter with something that you cook.

This all came to a head in New York in 1883 when tomato importers were slapped with a 10 per cent tax on 'foreign vegetables' even though, as they pointed out, it was a fruit. The case went all the way to the Supreme Court who ruled in 1886 that, even though tomatoes were *logically* a fruit, in the 'common language of the people' they were a vegetable because they 'are usually served at dinner in, with, or after the soup, fish, or meat, which constitute the principal part of the repast, and not, like fruits, generally as dessert'.[44]

In Aerts' study, 8.8 per cent thought a tomato was a good example of a fruit, 6.7 per cent said it was a good example of a vegetable, and 6.9 per cent thought it was a good example of a fruit or vegetable. So a slight majority disagrees with the Supreme Court ruling, no doubt because the 'common language of the people' has evolved since then. But the logic still doesn't quite add up.

According to classical logic, if the weighting of one selection is A, and the weighting of another is B, then the relative weighting of it being one or the other should be the average of A and B. For the tomato, this gives a probability of 7.8 per cent for fruit or vegetable, but the observed probability from the survey was only 6.9 per cent. The discrepancy is much larger for some other choices. For example, mushroom was rated 1.4 per cent for fruit, and 5.5 per cent for vegetable (it is actually a fungus, so neither). The average of these is 3.4 per cent, but the survey gave 6.0 per cent for fruit or vegetable – almost as high as tomato.

According to Aerts, this can be explained by assuming that the concepts of fruit and vegetable – which always have a probabilistic, uncertain element – interfere in our minds, so that asking each in turn is different from asking both at the same time. The situation is like a double-slit experiment, where one slit is labelled fruit and the other vegetable. The probability of a particle passing through the fruit slit with the other closed corresponds to the chance of being picked as a good example of a fruit, and likewise for vegetables; while the probability of fruit or vegetable is like having both slits open, which causes interference. Similarly, the statistics of word association experiments show that pairs of related words behave like entangled particles, and obey the linguistic version of Bell's inequalities.[45]

But really, tomatoes are a fruit. And don't let's get started on pronunciation.

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* The frequency of a wave, in the usual unit of hertz, is the number of waves that pass a point in one second.

† Here 'heuristic' refers to a kind of mental shortcut.

‡ The term 'spin' is a little misleading since in quantum mechanics it doesn't make sense to think of a particle as a solid object, so it isn't clear what would be spinning. The basic

unit of spin is defined as ½, so fermions can have spins of ½, $^{3}/_{2}$, and so on, while bosons have integer spins.

§ Fermions were named after Enrico Fermi, bosons after the Indian physicist Satyendra Nath Bose.

CHAPTER 2

How much

All things are measured by money.
Aristotle, *Nicomachean Ethics*[*]

The growing differentiation of our representations has the result that the problem of 'how much' is, to a certain extent, psychologically separated from the question of 'what' – no matter how strange this may sound from the logical point of view.
Georg Simmel, *The Philosophy of Money* (1900)[1]

According to quantum physics, everything in the universe has complementary wave/particle attributes. The same can be said of one of our most powerful technologies: money. Money objects such as coins, notes, or even bitcoins have dualistic properties which rival those of photons or electrons. This chapter takes the reader through a brief early history of money, and shows how its twin aspects have shaped everything from Western philosophy to the way we make decisions.

How much? For many of us, our first experience of hands-on economics is buying a candy or a treat with a parent. In your hands are a few metal coins with numbers on them. In the display case there is the desired object – say, a chocolate-chip cookie. *How much is that*, you ask tentatively, gazing up at the sales person (or if you're in Italy, you might say 'Quanto?', which makes the link with quantum a little clearer). They tell you a number – say $2. Then you show them your coins – the colour of your money. Your parent might help you count them out. The numbers on the coins, you understand, must add to a sum which is greater than or equal to the cost of the item, in order for it to be released. The sales person puts the coins into the till, and gives you the cookie in a paper bag, along with any change. The transaction is complete.

The act of purchasing things soon becomes so automatic that we no longer think about it. Instead of counting out coins, we usually just swipe or tap a card. Purchases are made online – cookies are as likely to be the sort that vendors place on your computer as the sort you put in your mouth. The exchange of money has become increasingly virtual and invisible. We often don't think any more about it than we do about breathing.

Which of course is not to say that we don't think about money at all – indeed, surveys have shown that it is one of the greatest sources of stress.[2] Money has probably never been more important than it is today. And when we make a payment, there is still a sense that we are handing over something real – a kind of object – especially when we are short of the stuff. But the ebb and flow of money is largely taken for granted, as is the effect it has on our minds and our behaviour.

Even if you later enrol in an economics class, or go to business school, money is treated as little more than an inert medium of exchange, an intermediary for barter. But this obscures the fact that something else was going on when you bought that cookie as a child. In effect, you were making a measurement. You were discovering what the cookie was worth, in numerical units. You were putting a number on it. You were finding an answer to the question, *how much*.

In this case, of course, the answer was already provided, so it was a rather trivial exercise. The cookie had a firm price. The number was probably on a sign or a label nearby. The sales person didn't just pull a figure out of their head. But that is only because the procedure had been organised in a particular way. Later on, your parents might teach you to haggle or bargain at places like a yard sale, where the price is negotiable or you can get a discount if you buy more than one thing. And when it comes time to buy a house, the list price is often just a starting suggestion.

But even when the price is stated in advance, you are still performing a measurement when you purchase the cookie, because you are confirming the amount. Suppose for example that the sales person says they are all out of the preferred chocolate-chip flavour. Then the price is merely hypothetical. Perhaps they will have more in stock tomorrow, but for all you know the price may have changed by then because of large demand. Later on, you will have this experience when booking a hotel room or an airline flight online – only one available at this price, says the website, but by the time you have typed in your credit card details the price has already changed. If you are in a country suffering from hyperinflation, like Venezuela at the time of writing, price lists are constantly updated. If for some reason the entire financial system crashed, say because of a nuclear war, the price of that cookie would be pretty much undefined. And in general, the only way you truly know the price of something is at the exact moment you make the transaction.

So buying something with money is equivalent to putting a number on it. Which when you think about it, is a rather curious thing in itself. How can we put a number on something like a cookie? After all, numbers and things have rather different properties. It makes sense to think of two things, in the sense of counting, but it is less obvious how a cookie can be 2.

The transaction is rather like the measurement process in physics, where we measure – put a number on – the position of a particle, or record how far it moves in a certain time. Even there, we know from quantum physics that position and time are not simple, linear, external quantities. They warp and connect and break into small parts. In other words, they are not like number.

Measurement is a far more complex procedure than appearances suggest – hence the uncertainty principle.

You may have wondered about this as a child. Money seems to be connected to value, but how does it work? Why are the cookies made by your grandmother free, but the ones in the store cost money? Or put another way: if money is measuring something, what is it measuring?

As described in more detail later, economists have long puzzled over this question. One answer (championed by classical economists such as Adam Smith) is that the price is measuring the labour required to obtain the ingredients and produce the cookie. Everything has a cost, except for grandma who works for free. But this raises a host of other questions about, for example, the mark-up of the store owner, the cost of renting the building, and so on, and in any case it just kicks the can further down the road – how do we decide how much to pay for labour?

Another answer (and a defining principle of neoclassical economics, which dates to the late nineteenth century and now dominates the mainstream) is to say that the price measures or reflects utility, which is loosely defined as the pleasure or satisfaction offered by the cookie. But again – how do you put a number on pleasure? It's not like sensations come with a price tag attached.

Finally, a third answer is to say that the price represents economic value.[3] But this is just a circular definition, since economic value is defined in terms of price. And all of these approaches assume that what counts is prices relative to other goods. Money itself is not important, other than as a score-keeping system.

In this chapter, I will argue that these approaches are mistaken and have led to much confusion. Measuring the price is like making a measurement of a quantum system. The result can't be reduced to labour, or utility, or anything else. Instead of grams or amperes, the units are units of currency. When you buy something, you are measuring – money.

To see why this statement is more than a tautology – and why the consequences of viewing the economy this way are actually rather exciting – we need to look more closely at those things you handed over as a child in exchange for the cookie. Just as the quantum revolution came from analysing the properties of energy exchange by subatomic particles, so the secret of money is to be found residing in coins and other such money objects, whose pedigree dates back thousands of years.

Ur-money

The Sumerian city states of ancient Mesopotamia were responsible for many important innovations which we still enjoy today: the wheel, beer, the 24-hour clock. Even the concept of a city state. But perhaps their most remarkable invention was an early version of money. It wasn't quite a quantum computer, but as we'll see, the money system as a whole, in concert with the human mind, does some of the same jobs.

Cities such as Ur, located in modern-day Iraq, were home to many thousands of people, and were surrounded by farms that supplied them with agricultural produce. The temple bureaucrats whose job it was to oversee this complicated society were faced on a daily basis with versions of a single, but very difficult, question: *how much?* If a man does a month's labour for the temple, how much grain or beer should he receive in return? If he rents a room or a wagon for a day, how much should he pay the owner? And if he harms another person in some way, or damages their property, how much should he give in compensation?

For smaller villages, such problems could be addressed perhaps by sharing out produce equally, and coming to agreements on an ad hoc basis. But for the modern and highly-centralised city state, a more organised solution was required. A first step in this direction was clay tokens that represented rations. Later, the tokens were replaced by clay tablets known as cuneiforms, on which instructions were inscribed with a reed (the Sumerians also invented writing). One such tablet from about 3000 BC is a pay stub, about 10 cm across in size, specifying an amount of beer to be paid in exchange for labour. As the British Museum notes, 'Writing seems to have been invented not for letters, literature or scripture, but for accountancy.'[4]

It was around this time that the temple accountants began to use a shekel of silver, about 8 grams, as a standard unit. The word shekel means 'weigh', so a shekel of silver literally represented a weight of value. Other units were based, like the Sumerian number system (they also invented arithmetic), on multiples of 60, so for example one mina was 60 shekels, or about half a kilogram. Prices for other things were then reckoned in terms of these shekels. One shekel would pay about a month's labour, which in turn would buy one gur (or bushel) of barley, or two rations a day.

The fact that prices were reckoned in terms of shekels did not mean that people carried out daily transactions using weights of silver. The shekel was just an accounting device. If someone needed to pay the palace, they could use wool or barley or some other commodity. And many dealings outside the palace were carried out on the basis of credit, so for example a farm worker might be paid in barley at harvest time.[5]

Larger debts were recorded on cuneiforms, which were put inside clay envelopes marked with a seal, and kept by the creditor until the debt was repaid. Sometimes the debt was made payable to whoever held the envelope, meaning that the creditor could sell it on to another person. Such cuneiforms therefore resembled modern paper notes, which promise to pay the bearer on demand a certain sum. But in general terms, the economy ran on credits which were periodically paid off by the delivery of some commodity.

On the surface, then, it might look like the shekel-based monetary system had little effect on trade, other than as a convenience for temple accountants. But in fact the invention of money would go on to have an even bigger impact than the wheel – because it didn't just transport things over roads, it could transport them virtually through space.

The money object

But where was this money, exactly? We have just seen that silver was not widely used for spending. Sure, there was lots of silver in the temple vaults. But how much exactly? If everyone had tried to cash in their rations for hard silver at the same time – a run on the temple instead of a bank – would there really have been enough to go round? Was the worth of a shekel really measuring a weight of silver, or was it more trust in the state, or both?

And how did the system differ from barter? What was the difference between someone paying a worker at a fixed rate of barley measured in shekels, and paying the barley without the mention of shekels? And even if you do pay with silver shekels, isn't that just a different kind of barter?

According to mainstream economics, the answer would be that nothing had really changed. Any barter exchange has to be expressed in terms of some ratio – *x* kilograms of this for *y* kilograms of that. All that had happened was that the shekel was being used as an intermediary, so the barter ratio could be determined from the price of each commodity in shekels. As the economist William Stanley Jevons noted in his 1875 book *Money and the Mechanism of Exchange*, 'Knowing how much corn is to be bought for a pound of silver, and also how much flax for the same quantity of silver, we learn without further trouble how much corn exchanges for so much flax.'[6]

Again, though, this emphasis on money's convenience misses what was really going on – which was that for the first time in history, people had worked out a consistent way to answer the question *how much*.

With barter, this question doesn't make sense except in a very limited way. Imagine that you are back as a child wanting to obtain a chocolate-chip cookie, but this time it is in the playground at school, from a friend. When you ask how much it is, instead of giving a price, your friend asks to look through your bag for something to trade. Maybe they settle for your slightly used pencil case. You now know that in that playground, with that friend, you can get a cookie for a pencil case. Except tomorrow that won't work, because they already have your pencil case. You will have to give them something different. The same is true for any kind of barter, because the prices of goods are always shifting relative to one another. The question *how much* does not give a single answer, it gives a cacophony of different possibilities.

By standardising their accountancy system around this thing called a shekel, the Sumerians had therefore worked out a way to put a number on value. They had found a method to collapse the plurality of possibilities down to a single number – just as a physicist does when they measure the position of a subatomic particle.

But by inventing this answer, they had done something else as well, which was to create a new kind of quantum entity – the money object.

Virtual versus real

It seems strange, in the era of bitcoin, to talk about 'money objects' as if money could somehow be reduced to a physical thing. Today of course we usually make payments electronically, by tapping a credit card or through a bank transfer, so they don't seem to involve objects at all. Even in ancient Sumeria, as we've seen, people might have reckoned prices in shekels but they didn't actually hand over small lumps of silver. Indeed, it has become almost a cliché among some economists and social scientists to point out that money is not a thing.

But one teaching of quantum physics is that objects are not as clearly defined as they were in classical physics – things aren't really things either, at least as we usually think of them. Entities which we perceive with our senses as solid objects – such as a coin, or a book – are really a virtual web of quantum interactions which happen to convey certain attributes such as mass and colour. You see this page because photons scatter off its force field in a particular way. Other particles don't see it at all, such as neutrinos from the Sun – many trillions of which pass through a page in the time taken to read this sentence. The electromagnetic force, which has the rather important role of holding atoms and molecules and objects of any sort together, is transmitted through the exchange of ghostly virtual photons, which are perhaps better described as ripples in the electromagnetic field. And any particle, as we have seen, has complementary wave/particle aspects.

In this quantum spirit, we can define money objects to be transferable entities, created by a trusted authority or body, which have the special property of a defined monetary value, specified by a number and a currency unit. They therefore combine the mental idea of a numerical quantity of money – the virtual wave attribute – with the physical idea of an object that can be possessed or transferred – the real particle attribute. These are numbers that you can keep or spend. So in a quantum framework, it makes sense to see a money transfer of any sort as representing the transfer of an object, real or virtual, from one party to another. Buying a book online might feel different from paying for it by counting out coins and notes at the store, but the net effect is the same. And even bitcoins aren't as virtual as they seem, as we'll see in the next chapter. Conversely, when money objects are used in transactions to purchase something, they collapse the wave-like idea of value down to a single particle-like number. Money objects are therefore a way of mediating between the real and the virtual. While they are naturally suited for use as a medium of exchange or a store of value, and their units are useful for accounting purposes, these properties are a consequence of their design, rather than a defining feature.

When the ancient Sumerians created the shekel as an accountancy device, they were also creating the shekel as a money object. As we saw above, a shekel was a particular weight of silver – a thing that could be exchanged for something else. These shekels could be real – i.e. made of silver – but mostly they were virtual. Either way, the exchange of shekels had the effect of putting a price on value – of reducing it to number.

Sumeria was of course not the only early civilisation to have come up with the idea of money, but it is the best-documented. In ancient Egypt value was expressed in terms of *deben*, which originally referred to a measure, not of metal, but of grain; wheat was deposited in centralised, state-owned warehouses that functioned as banks, and used for payments of debts and taxes.[7] In pre-imperial China, which was relatively less centralised, the most common form of money was cowrie shells, though other instruments such as knotted strings, or notched pieces of bamboo, were also used.

One of the appeals of using a precious metal such as silver as a basis for money is that, unlike most commodities, it has many properties in common with number. Precious metals are stable (they don't rust, rot, or go off), fungible (one ounce can be substituted for another), and easily divisible. This natural correspondence or affinity between number and precious metal led to the next monetary innovation, which represented perhaps the most expressive embodiment of money's intrinsically dualistic nature – the coin.

Electrum

When economics textbooks describe the history of money, if they cover it at all, they usually skip the Mesopotamia phase and go directly to the first coins, which date to the seventh century BC, in the nearby kingdom of Lydia. These were made of a gold-silver alloy called electrum, and were fabricated by placing a blank round of the metal on top of a die, and hammering it down with a punch. The die was embossed with a design such as the head of a lion that certified the coin.

The story goes that the use of these coins grew out of using precious metal in barter. As Aristotle noted in *Politics*, 'the various necessaries of life are not easily carried about, and hence men agreed to employ in their dealings with each other something which was intrinsically useful and easily applicable to the purposes of life, for example, iron, silver, and the like. Of this the value was at first measured simply by size and weight, but in process of time they put a stamp upon it, to save the trouble of weighing and to mark the value.'[8]

Aristotle's explanation of the origins of money was highly influential, and viewed as a kind of energy. By stamping the coins, and asserting its power of ownership, the state was therefore doing a kind of work, which in a sense was as valuable as that of the slaves who dug up the metal in the first place. It is this work which fuses and engineers the two sides of money – the real thing and the virtual idea – into a single money object. A coin, with its abstract stamp embedded in earthly metal, is therefore a graphic representation of the dualistic, quantum properties of money.

While coin money may have been designed primarily for military purposes, it of course had what historian Michael Crawford calls the 'accidental consequence' of boosting the development of markets – and eventually the world economy.[16] And it had other effects as well. By putting a number on things, it turned everyday transactions into a mental accounting exercise – which had profound consequences for our mental development as a species (and even perhaps on the wiring of our brains, as discussed later). The development of money also shaped Western philosophy, with profound implications for the way that we think about – money.

The value of value

The first Greek city to produce its own coins in the sixth century BC is believed to have been Miletus, a city state located in what is now Turkey, adjacent to the kingdom of Lydia. But the city is known just as well for being the 624 BC birthplace of the philosopher Thales, with whom, according to Bertrand Russell, 'Western philosophy begins'. His mathematical discoveries include using geometry to figure out how to compute the height of the pyramids or the distance of a ship at sea. Thales also came up with an early version of a Theory of Everything, arguing that everything was made of water (today, physicists think everything is made of higher-dimensional strings, which will probably also sound pretty funny a couple of millennia from now).

When Thales was an old man, he was visited (it is said) by a young man in his twenties called Pythagoras, from the nearby island of Samos. Pythagoras would go on to found his own school of philosophy which also had a theory of everything, but with a twist. The unifying substance was not a physical material like water, but an idea: number. According to the Pythagorean creation myth, the universe began in a state of unity, which then divided into two opposite components: the limited (*peiron*), which was good, and the unlimited (*apeiron*), which was not ('Evil belongs to the unlimited, as the Pythagoreans surmised', wrote Aristotle in *Ethics*, 'and good to the limited'[17]). These combined to form numbers, which made up the structure of the cosmos (a word invented by Pythagoras).

The emphasis on number was no doubt largely due to Pythagoras' discovery that musical harmony – and the correct spacing of frets on a lyre or today a guitar – is based on mathematics (he would have appreciated

Schrödinger's comparison of quantum states with the 'nodes in a vibrating string', or for that matter string theory). But according to the classicist W.K.C. Guthrie, it was probably also influenced by applications in commerce: it is likely that Pythagoras was involved in the design of coinage for his region in what is now southern Italy, and the impact of the new monetary economy 'might well have been to implant the idea that one constant factor by which things were related was the quantitative. A fixed numerical value in drachmas or minas may "represent" things as widely different in quality as a pair of oxen, a cargo of wheat and a gold drinking-cup.'[18]

The dualistic view of the Pythagoreans was summarised in a list of ten pairs of antitheses, documented in Aristotle's *Metaphysics*, which represented what they believed were the fundamental organising principles of the universe. In many respects their list resembles the similarly ancient Chinese concepts of yin and yang, with the left column being yang and the right yin; however, there is an important difference, which is that while the Chinese saw yin and yang as complementary, the Pythagorean list has a preferred direction, with one column labelled Good and the other Evil.[19] As seen in the box below, this distinction provides an interesting clue about the nature of money.

Pythagorean dualism was tremendously influential on Greek philosophy, and appears for example in the broader split in Greek thought between mind and body, which Plato took to its logical conclusion with his theory of forms. According to Plato, any real-world object is an imperfect version of an abstract form. Unlike real things, which change and decay, forms are static and unchanging and can be known only through the intellect. Numbers live in the world of forms, while measurable physical events and objects live in the real world.

Given that Western science grew out of this dualistic approach – its aim after all is to express the real world by using abstract numbers and equations – it is unsurprising, as I have argued elsewhere, that Pythagorean fingerprints can be found all over it.[20] One reason quantum physics came as such a shock was because it challenged this ancient good/evil dualism, by seeing opposing qualities not as ranked pairs but as complementary aspects of a unified dynamic whole, as in yin/yang. In fact, while Bohr's principle of complementarity was said to be inspired by the idea from psychology that we can hold opposite ideas in the mind at the same time, another influence was Chinese philosophy.[21] When the King of Denmark conferred on him the country's top honour (the Order of the Elephant) Bohr designed his own coat of arms, which featured a yin-yang symbol and a motto in Latin: *contraria sunt complementa*, 'opposites are complementary'.

As we have seen, money is inherently dualistic by design, because it combines the attributes of a number with those of an owned object. This duality is captured in the different senses of the word 'value' as applied to exchange (rather than to principles or standards of behaviour, which are not supposed to be for sale). We value something not just because it serves some mechanical purpose, but because it means something to us. Only a conscious entity can value something else. However, value also has a mathematical definition that refers to a particular number, such as the reading on a gauge, or the value of a parameter in an equation. Money is a way of mediating between these two types of value, the subjective meaning and the objective number. In classical economics, prices had meaning because they represented labour; in neoclassical economics because they represented utility. In quantum economics, prices and meaning are two sides of the same coin, and the same word.

Like a magnet, money therefore encompasses twin poles with opposite properties, and neither is ever seen in isolation; but as with Pythagorean dualism it also has a fixed polarity, because – like science – the whole point of money is to put numbers on things. It is a way to find the value of value. These dualistic properties feed into other financial instruments: the numerical debt owed on a loan is virtual, but the treasured possession supplied as collateral is real.

As noted in my previous book *Economyths*, the same dualism has also shaped the discipline of economics. Mainstream neoclassical economics – with its emphasis on stability (At Rest), symmetry (Square), linearity (Straight), and so on – never strays too far from the first or 'Good' side of the Pythagorean list (see box below), while heterodox approaches tend to take a more left-handed approach. Of course, this is not to suggest that the Pythagoreans somehow intuited the quantum nature of the universe, or that their descendants continue to populate economics departments. However, their number-based philosophy was influenced by the development in Greece of the monetary economy; and as already argued, the economy is a quantum system in its own right, with money having a special role in the measurement process; so in a way they were the first quantum economists. This is why their insights into the dualistic nature of the universe continue to resonate today – and why we still live in a world shaped by Pythagorean duality. As we'll see in the next chapter, nowhere is money's dualistic nature more evident, but also least understood, than in the act of its creation.

Quantum opposites

The tension between the two sides of value – subjective worth and numerical price – resonates in interesting ways with the Pythagoreans' list of opposites (in bold below), which again was created at a time when these concepts were being juxtaposed and brought into conflict by the advent of the market economy.

Limited versus **Unlimited**. A measured price (e.g. an amount that you just paid) represents a fixed, limited quantity. Value is a fuzzy, non-numerical quality that is essentially unbounded (economists may assign numbers to a human life, but a parent could put no price on the life of a child).

Odd versus **Even**. A measured price is stable and unique, while value is more diffuse. (In particle terms, the former would be an odd-spinned fermion, and the latter an even-spinned boson – see Chapter 1.) According to his biographer Iamblichus, Pythagoras similarly asserted that, while even numbers were associated with 'that which is dissolved', odd numbers were associated with stability and unity. One reason is that summing their sequence gives a square number, so for example 1+3+5+7=16 or 4 squared, and the sides of a square always have a fixed ratio of 1.

One versus **Plurality**. A price is a single unified concept. Value depends on viewpoint and is therefore inherently pluralistic.

Right versus **Left**. Numerical prices appeal to our left-brained computational and analytical abilities (see box in Chapter 4). Value is more of a right-brained, context-driven attribute. (Note the left brain controls the right side of the body and vice versa, hence the polarity reversal.)

Male versus **Female**. A price is a virtual symbol (from Latin *virtus* for 'manliness'), while a valued object is a material thing (from Latin *mater* for 'mother') that can be owned and possessed. The gendered language relates to the classical association of ideas and numbers with the male principle, and real-world things with the female principle.[22] An updated version for money would be Virtual versus Real.

At Rest versus **In Motion**. A measured price is fixed and stable, while a valued object mutates and decays.

Straight versus **Crooked**. Numbers are linear and additive by definition, which is why they teach the number line at school, and so are prices. In the real world, when you add two things, or work twice as many hours, the value might not double.

Light versus **Darkness**. Prices are objective, susceptible to the light of reason, and mean the same thing to everyone. Value is more subjective and obscure, so depends on the person and the context. Subjectivity gets a bad rap in science – the political scientist Alexander Wendt (named in 2015 as 'the most influential scholar in international relations over the past 20 years') for example notes that 'in most of contemporary social science there seems to be a "taboo" on subjectivity' – which is awkward since according to some interpretations at least, the individual consciousness plays a key role in quantum physics (not to mention everyday life).[23]

Square versus **Oblong.** The Pythagoreans thought about numbers by arranging pebbles in patterns. They saw square numbers such as 4, 9 and 16 as stable and symmetrical, since they can be arranged to form a square. Prices or costs are symmetrical too, in the sense that positives and negatives cancel out, as in a square deal. A key difference between a monetary economy and a gift economy is that the former is based on symmetric exchange where the accounts always balance, while a gift is supposed to be asymmetric.[24]

Good versus Evil. Because the Pythagoreans wanted to reduce the world to number, they aligned themselves with only one set of these principles – the Good, which is consonant with number. Similarly, money has a polarity because its function is to put objective number on subjective value, not the other way round. It is Pythagorean dualism in action.

Notes

1. Simmel, G. (2004), *The Philosophy of Money* (T. Bottomore and D. Frisby, trans.) (London: Routledge).
2. According to Gallup, 'Half of Americans have substantial financial anxiety'. Saad, L. (20 April 2015), *Americans' Money Worries Unchanged from 2014*. Retrieved from Gallup: www.gallup.com/poll/182768/americans-money-worries-unchanged-2014.aspx
3. See for example: Martin, F. (2013), *Money: The Unauthorised Biography* (London: Random House), p. 52.
4. British Museum (9 November 2017), *The first writing: counting beer for the workers.* Retrieved from: https://www.google.com/culturalinstitute/beta/asset/early-writing-tablet-recording-the-allocation-of-beer/fgF9ioy89DC2Uw
5. Tymoigne, É., and Wray, L.R. (2007), 'Money: An Alternative Story', in P. Arestis, and M.C. Sawyer (eds.), *A Handbook of Alternative Monetary Economics* (Northampton, MA: Edward Elgar), pp. 1–16.
6. Jevons, W.S. (1875), *Money and the Mechanism of Exchange* (New York: D. Appleton and Co.), p. 5.
7. Davies, G. (2002), *A History of Money: From Ancient Times to the Present Day* (3rd edn) (Cardiff: University of Wales Press), p. 52.
8. Aristotle (2000), *Politics* (Mineola, NY: Dover Publications), p. 42.
9. For example: 'All sorts of commodities have been used as money at one time or another, but gold and silver proved to have great advantages ... Before the invention of coins, it was necessary to carry the metals in bulk ... The invention of coinage eliminated the need to weigh the metal at each transaction, but it created an important role for an authority, usually a king or queen, who made the coins and affixed his or her seal, guaranteeing the amount of precious metal that the coin contained. This was clearly a great convenience ...' Ragan, C.T., and Lipsey, R.G. (2011), *Economics* (13th edn) (Toronto: Pearson Education Canada), pp. 672–3.

CHAPTER 3

Quantum creations

I am afraid the ordinary citizen will not like to be told that the banks or the Bank of England can create or destroy money. We are in the habit of thinking of money as wealth, as indeed it is in the hands of the individual who owns it, wealth in the most liquid form, and we do not like to hear that some private institution can create it at pleasure. It conjures up a picture of an autocratic and irresponsible body which by some black art of its own contriving can increase or diminish wealth, and presumably make a great deal of profit in the process.

Reginald McKenna, former UK Chancellor of the Exchequer (1915–16)

Quantum mechanics is magic.

Daniel Greenberger

One of the more mysterious predictions of quantum physics, which has since been amply confirmed by experiment, is that particles can spontaneously appear out of nowhere, and then disappear back into the void. Indeed, such quantum eruptions might explain the sudden appearance of the universe itself. Central bankers have managed a similar trick, through the magic of 'fiat money', which is ushered out of the void at the press of a button. This chapter explores the quantum processes of money creation and destruction, from ancient coins to modern bitcoins.

Where does money come from? In ancient Greece, the answer would have seemed rather obvious – the ground. Coins were made of precious metal, and their value – in terms of both weight and quality – was certified by the stamp. But even there the answer wasn't quite so clear-cut. For example, an Athenian drachma coin would by definition be worth exactly a drachma within Athens, but outside of the city its value would gravitate towards whatever the metal could be traded for locally – normally a little less. The value of a coin depended not just on the weight of the metal, but also on the weight of the state. Money objects may be *designed* to have well-defined numerical quantities, but (unlike with subatomic particles) those qualities tend to deteriorate unless actively enforced.

While neoclassical economics tends to view money as an inert chip, which apart from its made-up nature is not fundamentally different from any other tradable good, money is a complex entity and control of its production has always been loaded with social, political, cultural and economic implications.

This can be seen from its history, where its essential features rearrange themselves in a constantly shapeshifting manner while somehow remaining the same.

The word 'money' is named for Juno Moneta, the goddess in whose Roman temple the first coins were minted. The Roman monetary system was a scaled-up version of the Greek: the army conquered foreign lands, put slaves to work in mines, and stamped out coins to pay themselves with. The state demanded that the conquered populations pay taxes in those same coins, which ensured their circulation.[1] In the mid-second century AD, when a denarius coin contained roughly £1 sterling-worth of silver at today's price (as opposed to an actual pound of silver), imperial spending reached an estimated 225 million denarii per year, with about 75 per cent going to supply the military.[2]

Money played a key role in building the Roman empire, but it was also one of the factors leading to its collapse. A disadvantage of having a currency linked to precious metal is that the quantity of money in circulation depends on the amount of metal being mined. When the empire was expanding, the growing economy was matched reasonably well with the growing supplies of metal. In the third century AD, though, the number of new foreign conquests began to dry up. Rome produced very little itself, so money was continuously draining away to foreign lands, especially once its citizens acquired a taste for exotic goods from India and China. At the same time, the army ballooned in size to 650,000 soldiers, which required more cash (it is always easy to pay people more, rather harder to pay them less, especially when they are armed).[3] The only way to square the circle was to debase the currency – a measure which proved to be quite addictive.

When the denarius, the common coin which was the equivalent of the Greek drachma, was first minted around 211 BC, it contained about 4.5 grams of nearly pure silver, and would pay a day's wages for a soldier or unskilled labourer.[4] Emperors progressively reduced the silver content until 500 years later all that was left was a silver coating on a copper core which tended to rub off with use. Such debasement was popular with emperors because they could pocket the difference between the stamp value and the metal value of the coin, but the increased quantity of money sloshing around the economy also led to runaway inflation. During a spell of just one year in 274–5 AD, prices multiplied by a factor of a hundred.[5]

Symmetrical versus asymmetrical

The dynamics of inflation were nicely explained, though a little late for the Romans, by the Renaissance mathematician and astronomer Nicolaus Copernicus in his 1526 treatise *Monetae cudendae ratio* (On the Minting of Coin), where – in an early version of what economists today call the quantity theory of money – he wrote that 'money usually depreciates when it becomes too abundant'.[6] In one sense, the Roman episode seems proof that money's value is an intrinsic quality, which eventually boils down to the metal content. Remove the bullion, and the currency falls apart. But after the fall of the Roman empire a curious thing happened, which is that the money survived for centuries without any metal at all, in the sense that debts were still calculated in units such as the denarius.

At the same time that the empire was shrinking, and Rome's population of a million people crashed to about 30,000 by 550 AD, the religions of Christianity and Islam rose in power and influence. Metal previously used for coins ended up in religious establishments. But even if the economy was smaller, and more closely regulated by religious authorities, this didn't mean that money was destroyed completely. It was just that the virtual symbol (i.e. the number) took priority over the real material (the metal). Money was returning to its virtual roots – and the region leading the change was the Islamic world, centred again on Mesopotamia.

Markets here flourished, but rather than based on cash transactions they relied, as in ancient times, on credit instruments such as the promissory notes known as *sakk*, or 'checks'. As today, Islamic finance forbade usury but allowed a range of fees, so it was still possible for financiers to make money. And just as the ancient Mesopotamians invented mathematics to keep track of payments, so mathematicians invented a new kind of number to keep track of debts.

As discussed in the previous chapter, a basic property of both numbers and monetary transactions is that they are symmetric, in the sense that for every positive there is a negative. If you exchange one currency for another at the market rate with no commission, then the net gain is zero, because what is gained (a positive amount) in one currency is cancelled by what is paid (a negative amount) in the other. However, until the seventh century AD only positive numbers were recognised. Negative numbers made no more sense than negative coins.

The rules around how to deal with negative numbers appeared for the first time in a book called *The Opening of the Universe* (628 AD), by the Indian mathematician Brahmagupta, who thought about them in monetary terms: positive numbers were 'fortunes', negative numbers were 'debts', and adding a positive with its negative gave zero, which was a number in its own right. These concepts were adopted in the Islamic world through translations of Brahmagupta's work, but took centuries to spread to Europe. They eventually led in the fifteenth century to the development of double-entry book-keeping, in which every transaction was entered in two different accounts, once as a debit and once as a credit. The method helped detect errors, since the sum of credits over all accounts should be balanced by the sum of debits, and also gave a quick picture of profitability.[7]

The invention of negative numbers also revealed a side of money which until then had remained unarticulated; which was that, just as money has real and virtual sides, so it has a positive side and a negative one – the first is owned, while the second is owed. In accounting, this symmetry is expressed numerically through the sign of the number. In ancient Greece or Rome, only the first side of money would have been obvious, but even there, the fact that coins were handed out by the state, but then demanded back as taxes, hinted that debt was involved.

Indeed, it is never possible to talk about 'inherent value' in an absolute sense, because monetary value is always relative and transactional. A lump of gold only takes on value for a person when that person exerts ownership over it, and when others recognise its value. As seen throughout history, the importance of a stamp on a coin is not really to indicate the weight. Instead it is to establish the crown's ownership over the object, and locate its value in a particular monetary space which is maintained by the crown. But where there is ownership, there is its negative, which is debt. The importance of virtual, mathematical debt – and the symmetry at its heart – became clearer still when the state switched to giving out money made of wood.

Wood

During the Early Middle Ages, Christian Europe operated under a feudal system in which the ultimate source of power was the crown, which was God's representative on Earth. The king granted land to his lords, and they in turn granted plots, and a portion of the land's agricultural yield, to their vassals in exchange for loyalty, work on the estate, and (for those in the warrior class) military service.[8] Feudal estates were largely self-contained, so money played little role except as an accounting device. Rents and taxes were usually paid in kind or through labour, rather than in cash.[9] The use of coins was further restricted by the fact that there was little coordination or centralisation. Each king and lord wanted to produce their own version, so that like Roman emperors they could collect the 'seigniorage' (from the Old French *seigneur* meaning lord) which is the difference between the face worth of the coin and its cost of production.

An exception to this lack of centralisation was England, where shortly after ascending the throne in 1100, King Henry I – son of William the Conqueror – introduced a payment system that was based on wooden sticks, known as tallies. The sticks, which were about ten inches long and made of polished hazel or willow wood, were notched to indicate their worth, and split lengthwise into two parts – the stock for the creditor, and the stub or foil for the debtor. The width of the notch varied from 'the thickness of the palm of the hand' for a thousand pounds, down to 'a single cut without removing any wood' for a penny.[10] The stock was also made slightly longer, to differentiate it from the part held by the debtor, who literally had 'the short end of the stick'. When the debt was repaid, the two sides were matched – comparing the grain of the wood made it easy to detect fraud – and destroyed. The tallies therefore functioned as a physical symbol for the debt, which was important when the population was mostly illiterate. A similar technique was used around the same time in China, with the difference that the tallies were made of bamboo.[11]

As with coin money in ancient Greece, but without the need for metal, tallies encoded numerical information whose context depended on the power of the state. Use of the tallies took off in England after King Henry began to use them for the purposes of tax collection. This expanded their use and made it easier for the stocks to circulate as money objects. For example, suppose the state held a stock representing a debt owed to it from a local tax sheriff. Then it could use the stock to pay a supplier, who could either collect from the tax sheriff, use it to pay their own taxes, or sell it at a discount to a broker who would collect the debt when it came due. The foil meanwhile was a kind of negative money object, in the sense that you had to pay to get rid of it.

An interesting thing had therefore happened to money – it had somehow physically bifurcated into two parts. As we have seen, coin money is inherently dualistic in the sense that it combines the properties of numbers and valued objects, but the two aspects come combined in what appears to be a single package. Coins were created by digging up metal from the ground, stamping them with a symbol, and enforcing their value locally through the power of the state. In fact, even here money has two parts joined by an invisible thread – the coin, which circulates as money, and the die for the stamp, which is engineered and controlled by the mint. But with tallies there was no valuable material, only a stick of wood; and together the two parts represented, not a single value, but a positive credit and a negative debit, which sum to zero. The situation is again analogous to quantum physics, where entangled particles with opposite spin can be produced from a single source. In this case, the holders of the two parts of the stick were entangled in the sense that whatever happened to one had implications for the other. For example if the stock was destroyed in a fire, there was no longer a record of the debt; if the monarch debased the currency, then both sides would lose their value.

Of course, this entanglement was not an invention of King Henry or any other ruler – an IOU does the same thing. But tallies also illustrated another feature of money, which is that its creation is not a zero-sum game. Tallies were money objects with a numerical price, just like coins, and their validity was backed by the state. Their creation therefore added to the money supply, even if the effect lasted only until the debt was cancelled. As seen later, this type of money creation can lead to inflation as surely as the debasement of truth they thirsted mightily for gold; they stuffed themselves with it; they starved for it; they lusted for it like pigs.'[17] (While it's hard to imagine anyone getting so excited over wooden tallies, we should note that money has a similar effect whatever form it takes, and not just on conquistadors.) The influx of metal certainly enriched many people, but following Copernicus' quantity theory of money (which was prompted by this episode) it also led to a huge level of inflation. The Spanish economy in particular fell victim to what has become known as the resource curse (similar to the 'trust fund curse' but for countries rather than children).

The lust for gold was the organising principle behind the doctrine known as mercantilism, as first championed by Queen Elizabeth I in England. While England was not blessed with an abundant local supply of precious metal, this was no more a problem for the English than it was for Alexander the Great – it just meant that they had to conquer places which were. The task was largely carried out through private companies, with the largest being the British East India Company. But the true quantum power of money was only unleashed in 1694 with the founding of the Bank of England – which announced a new way of merging the two sides of money, and inverted the relationship between money and the state.

As mentioned above, a problem with metal money was that it was controlled by monarchs who had a tendency to debase the currency or default on their debts. After military defeat by France in the Battle of Beachy Head in 1690, King William III was in urgent need of £1.2 million to rebuild the navy; but his credit was so poor that he found it impossible to raise the money by the normal means. He therefore decided to set up a public–private funding vehicle called the Bank of England. The way it worked was that the bank – acting like a very large goldsmith – gave the government a permanent loan of gold, in return for notes against this debt. As compensation it would receive 8 per cent interest in perpetuity on the original loan, plus a service charge of £4,000 per year, plus whatever it could make from banking services. The subscription was quickly sold out.

The bank's original charter didn't actually mention banknotes, but like other banks of the time – such as the Amsterdam Exchange Bank (since 1609) or the Swedish Riksbank (since 1656) – it gave notes in return for deposits, and also lent them out at interest. Such notes included a promise to pay the bearer the sum of the note on demand, so anyone could redeem them in full or in part for metal coins. Supported as they were by royal approval, they soon began to circulate as money objects. As with the banknotes issued by goldsmiths, the principle behind the Bank of England notes was again similar to that of tallies, in that the notes represented the stock, or a claim on the debt. But now the direction of the debt had changed: as anthropologist David Graeber puts it, 'money was no longer a debt owed to the king, but a debt owed by the king ... In many ways it had become a mirror image of older forms of money.'[18]

The founding of the Bank of England also represented a different kind of bifurcation for money, in the sense that it involved a kind of public–private splitting of functions between the state and the bank. The state was responsible for the symbolic stamping of the money, while the private sector was responsible for stumping up the actual gold (though in fact subscribers also contributed wooden tallies, which muddied the waters somewhat). The success of this arrangement meant that money achieved a new stability and reliability, and the Bank of England became the model for similar central banks around the world.

In the end, money always comes down to a confidence trick. We value something like a banknote because we trust that it can be exchanged or redeemed, which will only be the case if other people also trust in it. Money is therefore a way of entangling people into a kind of belief system – and this level of entanglement reached a new high as banknotes became widely adopted, as the driving force behind the British empire.

Symmetry breaking

As mentioned above, one difference between banknotes and a more straightforward credit system such as tallies is that tallies represented particular verifiable debts which were designed to be cancelled, while the new banknotes were viewed more as a receipt for something tangible that existed in a vault somewhere. They weren't gold, but they served as pointers to gold. But because the gold wasn't physically matched to the note in any way – unlike wood sticks with their distinctive grain, one gold bar is as good as another – this made it easy to loan out the same gold many times over. Goldsmithing was a profitable business, and not because of the actual smithing part.

This system was formalised under the Bank of England as fractional reserve banking, which is traditionally described in economics textbooks as follows. A central bank buys a government bond (e.g. fronts a monarch some cash). The state then spends the money (e.g. on rebuilding the navy) and the money enters the larger economy. But this is just the first stage.

Suppose one such payment to a supplier is for £100. The supplier deposits the amount in their own bank. But that bank doesn't just let it sit there – it holds on to £10 (corresponding to a reserve requirement of 10 per cent) and loans out the other £90 to someone else. That money in turn gets deposited in another bank, which keeps 10 per cent or £9 and loans out £81. When you add up the chain of transactions, the amount of new money in the economy is £100 plus £90 plus £81 and so on, which sums in the limit to £1,000, meaning that the original payment has been scaled up by a factor ten.

According to the textbook picture, money creation is therefore initiated and controlled by the central bank. Private banks play a role as well, by issuing new loans, but the amount is limited by the fractional reserve requirement, which was 10 per cent in the above illustration. As discussed in Chapter 5, this picture is rather misleading, since in reality it is private banks that control the money creation process, with central banks playing more of a reactive role, loaning money as necessary to banks to top up their reserves. But it seems a reasonable interpretation of how things functioned under what became known as the gold standard, where banknotes supplemented the use of coins, but were valued in terms of precious metal and, in principle at least, could be exchanged for coins if requested.

One advantage of the fractional reserve system was that it added flexibility, so for example the money supply could be ramped up by issuing more banknotes during times of economic growth, even when the supply of gold lagged behind. It also made deposits more valuable to banks, which meant savings accounts could earn interest. But there was also an obvious structural problem, which was that if everyone wanted to withdraw money at the same time, there wasn't enough to go round. An important symmetry had been broken, between what is owned and what is owed. Just as physics has its conservation laws, which are subject to the uncertainty principle, so the economy has accountancy rules, but these are subject to human uncertainty. Tallies could be redeemed and the stub and stock destroyed together, but with banknotes it wasn't so simple. In principle, each loan and each note is backed by a corresponding asset, but during a crisis – when the link between real and virtual comes under stress – there can be a collection problem.

Central banks therefore increasingly found themselves to be what the nineteenth-century journalist Walter Bagehot called the 'lender of last resort', responsible for bailing out smaller banks that were subject to such bank runs. Instead of being backed by gold, banknotes were backed by the central bank. After the crisis of 2007–08, the lender of last resort was the taxpayers who bailed out the financial system.

Entangled money

As we have seen with the brief history so far, the dualistic, quantum, shapeshifting nature of money is manifested in the historical record through its myriad forms, including clay tablets, cowrie shells, metal coins, wooden sticks, and paper notes, not to mention the many other forms of money identified by anthropologists, which alternate in emphasis between the real and virtual (see box below). But money has some constant features. One is that money is transmitted by the exchange of money objects, which are inherently dualistic in the sense that they combine the properties of owned objects with the properties of numbers. They are a way of stamping numbers onto the real world, and putting an objective numerical value on subjective social value, through a process similar to measurement of a quantum system.

We return to this measurement process in more detail later, but one thing to note is that because numbers have no inherent scale, it is possible to have an economy function with one set of prices, and also function at a set of prices which is exactly twice (or some other multiple) that of the first. In fact this kind of thing happens all the time because of inflation. This led economists from Adam Smith onwards to think – mistakenly, I will argue – that what counts is relative prices, with money just a distraction.[19]

Another common property, related to the first, is that money creation is based on the concept of ownership (and its negative, debt) which is signified by the stamp. When the ancient Greeks forced slaves to mine silver and turned it into coins, the stamp did more than just serve to certify the weight of the metal, as described by Aristotle and modern textbooks. Instead it was a stamp of ownership, which signified that the gold belonged to the state – and because ownership is relational, a gold coin represents a debt to the state which can be cancelled out by providing a service. With tallies, the role of debt was more transparent, since the stock was literally a receipt for money owed. In modern economies, central banks create money by issuing bonds which are sold to the private sector, and private banks create money by creating loans against assets. Money objects therefore entangle debtor and creditor at the moment of their creation. When the Bank of England loaned the king his money for his war debt, it was like handing him the short end of a tally stick. The stick was then metaphorically shaved off into many thousands of sheets called banknotes. If the state ever repaid the loan, all that money would disappear back into the void. This is one reason governments need to run deficits, because without the debt there wouldn't be money.

The creation of money always involves asserting ownership over a tradable object. This means that every money object has two parts: the object itself, and a record asserting the status of that object (which may in itself be tradable). In every case, there has to be a way of matching the two parts – the object and the record – to test whether the money is counterfeit. For a tally, this was done by literally matching the grain of the wood; for a coin or banknote, it is done through the design of the object; for a bitcoin, it is through cryptography.

In, say, eighteenth-century England a money object might have started off as a tally stick, been exchanged with a broker for gold coin, and then been swapped for a banknote. Money can therefore change its host from wood to metal to paper, even before it is used to buy anything. However, while gold coins and banknotes were backed directly or indirectly by metal, the tallies were produced out of thin air. How did this happen?

The obvious explanation is that with coins or banknotes, it isn't necessary for the sovereign to apply so much force to make the money work, because they are backed by metal – with coins physically, and with banknotes by contract. The hard labour was done by the slaves when they dug the metal up, and the army who controlled the process. But tallies are a different thing, because the sovereign is creating two money objects – the positive stock and the negative foil – and the stock is only worth something if he or she can force or cajole someone into accepting the foil. In the same way that energy can be transformed into mass or vice versa in nuclear reactions, so the sovereign's energy can be used to forge new money objects out of the void. Money objects therefore store a kind of potential energy.

With fractional reserve banking, though, the situation becomes more complicated because deposits can be loaned out multiple times and earn interest for the depositor in return, while banks can charge interest on loans. This means that some of the sovereign's power to create money objects – the seigniorage – has passed to the private banking system. This fact has not been widely advertised: as economist Norbert Häring observes, 'Central bankers never, ever talk about the hugely profitable privilege that the ability to create legal tender means for commercial banks.'[20] Another implication is that the amount of money in the economy has to build over time in order to pay off the interest. The money supply therefore tends to expand in an exponential fashion, and not just because of real economic growth, as discussed further in Chapter 5.

In medieval England the stock half of a tally stick became a money object representing a credit, made up by the king, that could be collected. With the founding of the Bank of England, the direction reversed, so that money was now based on the state's debt to the private sector. With modern fiat currencies[*] that are backed only by the word of the state, the central bank goes a step further and creates money not by loaning real assets to the state, but by loaning made-up funds, produced magically at the press of a button. Of course, this raises a couple of questions. One is that, since anyone can initiate a debt, it isn't clear why the state needs to be involved at all. Bitcoin believers would argue that it doesn't. Another question is, rather than the government borrowing fiat money from the central bank at interest, couldn't it just issue the money as a debt to itself? We return to this in the final chapter.

To summarise, we have seen in this chapter how the creation of money objects always involves two entangled entities which reflect money's dualistic nature: a tradable object which is worth a fixed amount, and a virtual record of that amount. The record – which can be in the form of a government stamp, a tally, or a secure entry on a computer – guarantees that the money object which tallies with it is genuine and belongs to a specified monetary space. The strands which link these separate aspects of money objects braid together to form the complex web of entanglements that characterise the quantum class are unlikely to go away. So where then does the backing for bitcoin come from, if not a weight of metal or the authority of the state or the legal system? The answer is – itself. Or rather, its network.

The first 43,000 bitcoins – the so-called 'Genesis' block – were produced or 'mined' using open-source software by a person going by the name of Satoshi Nakamoto on 3 January 2009. To timestamp the code, Satoshi included a headline from that day's London *Times* newspaper which hinted at his (or her, or their) motivations: 'Chancellor on Brink of Second Bailout for Banks.' The value of the coins was zero, so he handed some out for free to interested parties he met online, along with a paper explaining how they could mine more coins by running the cryptographic code used to maintain the blockchain and keep the network secure.

A community of users began to develop, and in October that year someone set up a website quoting the value of a bitcoin as being equal to the cost of electricity required to mine a coin, which seemed reasonable. At the time it was about 0.08 cents, so a thousand bitcoins was worth about 80 cents. Each time a user was added, the code took a little longer to run, but the price also went up. And up. According to an empirical equation known as Metcalfe's Law, the worth of a network scales roughly with the number of users squared, which seems to work quite well with bitcoin.[31]

So is this money real? Is it a *thing*? And how can value be produced out of nothing? Well, if those 43,000 bitcoins were held in a single bitcoin wallet – say on a detachable drive – and it was lost, then they would be gone for good. So the money would certainly feel real.[32]

As with all forms of money, the real value of the currency is in the network – the power to buy and sell within a community of users. With coin money, the network is maintained by the sovereign, but with cybercurrencies the power is distributed among its users. So bitcoins are a kind of virtual gold adapted for the network age. Its price might be a bubble, susceptible to swings in sentiment, but so is the price of gold – the latter is just a bubble that has lasted a very long time. Now we just need to update our ideas about money for the quantum age.

Notes

1. 'If you consider the whole army of legionnaires and auxiliaries at the time of Augustus, 250,000 men, the total annual requirement of the army for silver denarii (or equivalent copper coins) was at least 75,000,000 per year!' Pense, A. (1992), 'The Decline and Fall of the Roman Denarius', *Materials Characterization*, 29 (2), pp. 213–22.
2. Eagleton, C., and Williams, J. (2007), *Money: A History* (Firefly Books), p. 51.

3. Weatherford, J. (1997), *The History of Money* (New York: Three Rivers Press), p. 52. For comparison, the modern Italian army employs about 180,000.
4. According to Matthew 20:2. Wages for a Roman legionary soldier changed from 225 denarii under Caesar (c. 46 BC) to 1,800 denarii under Maximinus (AD 235–8). Eagleton, C., and Williams, J. (2007), *Money: A History* (Firefly Books), p. 54.
5. Harris, W. (2008), *The Monetary Systems of the Greeks and Romans* (Oxford: Oxford University Press), p. 205.
6. Spiegel, H.W. (1991), *The Growth of Economic Thought* (3rd edn) (Durham, NC: Duke University Press), pp. 88–9.
7. The technique was codified by the mathematician Luca Pacioli in his 1494 book *Summa de arithmetica*, though by that time it had already been in use for over a century. Davies, G. (2002), *A History of Money: From Ancient Times to the Present Day* (3rd edn), (Cardiff: University of Wales Press), p. 235.
8. Bloch, M. (1965), *Feudal Society* (L. Manyon, trans.) (Chicago: University of Chicago Press).
9. Le Goff, J. (2012), *Money and the Middle Ages* (Oxford: Polity Press), p. 115.
10. From the 12th-century treatise *The Dialogue Concerning the Exchequer*.
11. Graeber, D. (2011), *Debt: The First 5000 Years* (Brooklyn, NY: Melville House), p. 268.
12. Polo, M., and Yule, H. (1903), *The book of Ser Marco Polo, the Venetian, concerning the kingdoms and marvels of the East* (London: Murray).
13. When Venetian authorities discovered in 1321 that merchants were practising fractional reserve banking, they passed legislation saying that banks had to be able to meet all requests for withdrawal within three days. Martin, F. (2013), *Money: The Unauthorised Biography* (London: Random House), p. 104. See also: Kindleberger, 1984, p. 51.
14. Fairs were highly organised, and followed fixed schedules over the course of a few weeks, with days for settlement at the end. Kindleberger, C.P. (1984), *A Financial History of Western Europe* (London: Allen & Unwin), p. 36.
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18. Graeber, D. (2011), *Debt: The First 5000 Years* (Brooklyn, NY: Melville House), p. 339.
19. Milton Friedman for example wrote that 'nothing is so unimportant as the quantity of money expressed in terms of the nominal monetary unit ... let the number of dollars in existence be multiplied by 100; that, too, will have no other essential effect, provided that all other nominal magnitudes (prices of goods and services, and quantities of other assets and liabilities that are expressed in nominal terms) are also multiplied by 100.' Friedman, M. (1969), 'The Optimum Quantity of Money', in M. Friedman (ed.), *The Optimum Quantity of Money and Other Essays* (Chicago: Macmillan), pp. 1–50, p. 1.
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29. Chun, R. (September 2017), 'Big in Venezuela: Bitcoin Mining', *The Atlantic.*
30. Or approximately 4 million bolivars.
31. Alabi, K. (2017), 'Digital blockchain networks appear to be following Metcalfe's Law', *Electronic Commerce Research and Applications*, 24, pp. 23–9.
32. Satoshi has not been heard from since 2011, and the digital forensics firm Chainalysis treats his holdings – possibly a million bitcoins in all – as lost. Roberts, J.J., and Rapp, N. (25 November 2017), 'Exclusive: Nearly 4 Million Bitcoins Lost Forever, New Study Says'. Retrieved from *Fortune*: http://fortune.com/2017/11/25/lost-bitcoins/

* From the Book of Genesis: *fiat lux*, let there be light.

CHAPTER 4

The money veil

I don't care who writes a nation's laws – or crafts its advanced treatises – if I can write its economics textbooks.

Paul Samuelson

Neoclassical economics is based on a Newtonian picture of the economy as a mechanistic system, made up of self-interested, atomistic individuals who interact only by exchanging goods and services. Money has no important role and acts primarily as an inert medium of exchange. These assumptions allowed economists to build elaborate physics-like models of the economy. But just as Newtonian physics fails at the quantum level, so this mechanistic approach breaks down when we consider the complex dynamics of money.

In previous chapters we have considered the question of what money is, and where it comes from. The next question would be, what does money do?

For most economists, the answer has long been very simple – nothing special. Money is just an inert chip with no special properties of its own. To understand the economy, economists should not focus on money – in fact, they should do the opposite, and ignore its bewitching and distracting activities. As John Stuart Mill remarked in his seminal nineteenth-century textbook *Principles of Political Economy*, 'There cannot, in short, be intrinsically a more insignificant thing, in the economy of society, than money.'[1]

Of course, this isn't to say that economists omitted money altogether (for example, it was obviously needed as a metric) – only that it was deprived of any kind of life. This attitude was born in part from the Aristotelian creation myth that money evolved as a substitute for barter, so it was just another commodity that could be exchanged like any other. As Paul Samuelson wrote in *Economics*, 'if we strip exchange down to its barest essentials and peel off the obscuring layer of money, we find that trade between individuals and nations largely boils down to barter'.[2] But it also reflected a Newtonian view of the economy as a mechanistic system, in which the two sides of money were collapsed down to a single point, and money became no more than another inert particle to be held or exchanged.

The founding father of economics is usually considered to be the classical economist Adam Smith, who was much impressed by 'The superior genius and sagacity of Sir Isaac Newton' and aimed to put the study of the economy onto a similarly scientific plane. A first step, in his *Wealth of Nations*, was to assert that the value of money was determined only by its weight in precious metal, rather than by the stamp which was rather unreliable: 'Six shillings and eightpence, for example, in the time of Edward I, I consider as the same money-price with a pound sterling in the present times; because it contained, as nearly as we can judge, the same quantity of pure silver.'[3] Similarly the price of goods was equal to 'the quantity of pure gold or silver for which they are sold, without any regard to the denomination of the coin'.

This put economic trade onto a reassuringly Newtonian basis, since everything could be expressed in terms of weights of metal. But in order to complete the mapping from the physical to the economic sphere, Smith needed some kind of social analogue for mass, which he found in stock (i.e. goods or possessions) and labour. Following philosophers such as John Locke, Smith asserted that 'The real price of every thing, what every thing really costs to the man who wants to acquire it, is the toil and trouble of acquiring it.' Value is labour, and money is just a medium of exchange.

Of course, these prices were only relative. The exchange value of labour in terms of metal was not fixed, because it would depend on the cost of obtaining the metal, which in turn would depend on factors such as the 'fertility or barrenness' of mines. But this didn't matter, because what counted was relative prices – or what Smith called 'real' as opposed to 'nominal' prices – which stripped out these confusing effects. The economist Jean-Baptiste Say, who popularised Smith's work in France, summed this up in his statement that 'money is a veil'. According to Say's law, for example, production is the source of demand – when something is sold, the money is used to buy something else – so markets clear and money comes out in the wash.[4]

Finally, Smith needed a rule to specify how prices map onto the specified quantity. He found this with his most famous invention, the invisible hand.

Hard labour

Smith himself used the phrase 'invisible hand' only once in his book, in a section on trade, but it was later popularised by Paul Samuelson as the name for Smith's idea about how markets work. According to this rule, which eventually came to be viewed as the social science version of a Newtonian law, the price of an asset will be guided towards its 'natural price' (i.e. that which corresponds to labour value) by market mechanisms. If a particular good is too expensive, then more suppliers will enter the market, and competition will drive the price down. If the price is too low, then suppliers will go broke or leave the market, and the price will go up. So as Samuelson paraphrased, 'Every individual, in pursuing only his own selfish good, was led, as if by an invisible hand, to achieve the best good for all.'[5]

The invisible hand therefore closed the Newtonian loop between weights of

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