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Quantum Economics

David Orrell, Systems Forecasting, Toronto, Canada
dorrell@systemsforecasting.com

Abstract

A decade after the financial crisis, there is a growing consensus that the neoclassical approach to economics has failed, and that new approaches are needed. This paper argues that economics has been trying to solve the wrong problem. Economics sees itself as the science of scarcity, but instead it should be the science of money. Just as physicists' ideas about quantum matter were formed by studying the exchange of particles at the subatomic level, so economics should begin by analysing the properties of money-based transactions, which like quantum entities have a fundamentally dualistic nature. By building on ideas from quantum money, quantum finance and quantum social science, this paper shows that the economy is an archetypal example of a quantum social system, complete with its own versions of measurement uncertainty, entanglement, and so on. This leads to a proposal for a quantum economics, which is to neoclassical economics what quantum physics is to classical physics.

Keywords: money, quantum social science, quantum finance, quantum economics

JEL: A12, B41, B50, E40, G01

1. Introduction

It is now widely accepted that, by nature of their design, the models developed by neoclassical economists to simulate the economy – from models of financial risk used by banks, to the macroeconomic models used by policy makers – failed to predict, or even properly explain, the events of the 2007/8 financial crisis. In fact they even contributed to the crisis by creating a false sense of security. This paper argues that the reason these economic models broke down is because neoclassical economics – whose 19th-century founders were inspired by classical physics – had failed to heed the teachings and insights of quantum physics, which revolutionised physics in the early 20th century. This does not mean that economics should directly mimic quantum physics, or that all modellers need to literally adopt the formalism of quantum mechanics. Instead, the economy should be viewed as a quantum social system on its own terms, with its own versions of duality, measurement, uncertainty, entanglement and so on.

A number of papers and books have been written that suggest different versions of a quantum economics. In his 1978 paper 'Quantum Economics', the mathematician Asghar Qadir pointed out that quantum mechanics seems a better fit than classical mechanics to modelling the vaguaries of economic behaviour, given that it was developed to handle situations where a variable does not have a single 'true' state (Qadir, 1978). The fields of quantum cognition (Aerts and Aerts, 1994) and quantum social science (Haven and Khrennikov, 2013) indeed show how our decision-making, at the individual or societal level, follows a kind of quantum logic, similar in spirit to that which applies at the subatomic realm. Many (but not all) authors take pains to distance themselves from the idea that the human brain – like a wet version of a quantum computer – itself employs quantum cognitive processes, though this question is not settled (Wendt, 2015, p. 30). A number of authors working in the area known as quantum finance, meanwhile, have shown that, for certain topics, it is possible to translate existing theorems used in quantitative finance into the formalism of quantum mechanics (e.g. Shubik, 1999; Schaden, 2002; Baaquie, 2007).

This paper takes a somewhat different or complementary approach, which is to follow the lead of quantum physicists and start with the idea of quantum (Latin for 'how much') but applied to money instead of energy. It then reconnects with the more general area of quantum social science by considering how people and institutions interact with money. Comparisons are made with neoclassical economics throughout. The aim is not to provide a survey of the quantum approach in related fields, but to show that, by building on findings from these areas, quantum economics provides a genuine alternative to the neoclassical approach.

The plan for the paper is as follows. Section 2 discusses how money effectively went missing from mainstream economics, and Section 3 introduces the quantum approach. Sections 4 and 5 go into more detail about money's roles in measurement and entanglement, and Section 6 explores the process of money creation. Section 7 discusses the relationship between quantum money and quantum social science, Section 8 considers how the quantum view of the economy differs from that presented by neoclassical economics, and finally Section 9 summarises the key results. An appendix presents some of the relevant mathematical tools.

2. The Science of Money

Economics is commonly known as the 'science of scarcity' after 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' (Robbins, 1932, p. 15). But it seems more natural to define economics as the study of transactions that involve money – even if the topic plays a surprisingly small role in mainstream theory.

In standard textbooks, money is usually treated as an inert chip, or as a kind of metric, rather than as a substance with special properties. This goes back at least to Adam Smith, who argued that money was a distraction from what really counted, which was the exchange of goods (Smith, 1776). The economist Jean-Baptiste Say, who popularised Smith's work in France, summed this up in his statement that 'money is a veil'. Or as Paul Samuelson later put it, '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' (Samuelson, 1973, p. 55).

Key to this assumption was that money was not a force in itself, but only a measure of some other quality. For Smith, it was the labour that had been used to produce a good; for neoclassical economists, it was defined as utility (Jevons, 1957, p. 1). In either case, since money had no important qualities of its own, one consequence was that it could be safely omitted from models. For example, the famous Arrow-Debreu model from the 1950s, sometimes known as the 'invisible hand' model because it showed that an idealised market would attain a kind of optimal equilibrium, excluded money and the financial sector altogether (Arrow and Debreu, 1954). Modern dynamic stochastic general equilbrium (DSGE) models follow this example (Keen, 2017), as do standard risk models used in quantitative finance (Wilmott and Orrell, 2017). The economy is viewed as a giant barter system, where money and finance play no central role. Nowhere is this more true than in the pivotal topic of credit creation by banks, which – as discussed below – was ignored by most economists until very recently.

The failure of this approach was brought home during the crash, when models which did not include money or credit could not predict, or even understand, the effect of a credit crunch. Quantum economics argues, however, that money is much more than just an inert chip; instead it is a dynamic substance with complex dualistic properties that feed into, and in many ways define, the economy. Recognising this fact promises to have a similarly disruptive impact on neoclassical economics, as quantum physics did on the orthodoxy of its day.

3. Quantum Money

Neoclassical economics was explicitly based on mechanistic, classical physics. Economists such as Irving Fisher tried to show how individuals mapped to particles, utility to energy, and so on (Fisher, 1892). The central idea was that rational economic man, through the magic of Smith's invisible hand, would guide prices to a stable equilibrium which represented the optimal result for society. Quantum economics, in contrast, treats the economy as a quantum social system in its own right. Just as quantum physics grew out of studies of energy transactions between particles, quantum economics starts by examining the complex properties of money objects.

As discussed in previous works (Orrell, 2016; 2017; Orrell and Chlupatý, 2016), money objects – be they coins or bitcoins – combine the properties of abstract numbers, with the properties of objects. The fact that numbers and objects are very different – for example, you can own an object, but you can't own a number – means that money is fundamentally dualistic, and has properties not unlike those of quantum matter.

It is often said that quantum physics is highly counterintuitive. 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 uncertain – and their values are, in a sense, determined during the measurement procedure. Particles can be entangled so that a measurement on one instantly determines the state of the other. They can magically appear out of nowhere, and then disappear back into the void. Quantum physics, at first glance, seems to present a universe that is utterly alien to our way of thinking.

However, these properties only seem strange when we think of things like objects moving in space. When we talk about money, they are completely natural and obvious. For example, 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 is has become something of a cliché to say that 'money is not an object' but its properties certainly resemble those of a quantum entity, which has both wave and particle attributes, and for which neither description is complete. The historic argument over whether money obtains its value because of its link to precious metal (the theory known as bullionism), or because its value is based on virtual credit that is backed by the state as in chartalism (Knapp, 1924, p. 32) resembles the debate stretching back to the ancient Greeks over whether light is made of real particles or virtual waves, and which was only settled in the early 20th century when it was found that it was both.

The quality known as value is intrinsically fuzzy and indeterminate, and only takes on a fixed and settled amount at the time of a monetary transaction (you don't know exactly how much your house is worth until you sell it). Money, therefore, acts as a kind of measurement device, that puts a number on the concept of value, just like the observation process in quantum physic. Money also acts as an entanglement device, for example, between debtor and creditor. And 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. Money objects are our contribution to the quantum universe. The next three sections go into their properties in more detail.

4. Transactions as a Measurement Process

In neoclassical economics, price is said to be determined by the intersection of supply and demand curves, which are assumed to exist as fixed and independent entities. In practice, however, supply and demand curves can never be observed – all we have is plots of price for particular combinations of supply and demand, so the separate curves are not identifiable from the data (McCauley, 2004, p. 25). Also, given that supply and demand are dynamic and affect one another, there is no reason to believe that these curves generally exist. In quantum economics, prices are determined by the exchange of money objects, just as the position or momentum of a particle can only be determined through a measurement process which affects the particle.

As an illustrative example, consider the purchase of something like an artwork at auction. When the owner first decides to sell the piece, they will only have a fuzzy idea of how much it is worth. The price will depend on sales of works by the same artist, sales by similar artists, trends in the marketplace, the mood during the auction, the nature and quality of the particular piece, whether it captures the eye of a wealthy investor, and so on. But there will be no exact 'correct' or 'intrinsic' value – the painting doesn't come with a price tag on the back. Instead the price will be discovered during the auction process. The fundamentally indeterminate value of the artwork will therefore 'collapse' down to a single number, just like the measurement process in quantum physics, where the wave function describing the location of a particle collapses to a single number.

Of course, many things do come with a (temporarily) fixed price tag; but even here, the transaction acts to confirm the price. You might try to order a plane ticket at a particular price, only to find that by the time you have submitted your credit card details the price is no longer available. And even supposedly fixed prices are usually open to change at short notice.

Just as in quantum physics, this measurement process also has an effect on the system being measured. In physics, measuring the position of an electron by bouncing photons off it imparts momentum to the electron, so the more accurately position is known, the more uncertainty there is in the momentum (Wheeler and Zurek, 1983, p. 64). (More generally, Heisenberg's uncertainty principle states that it is impossible to know both position and momentum perfectly, not because of technical limitations, but because these quantities are indeterminate until measured.) In the same way, the purchase of something like an artwork provides a new data point for similar works, which in turn affects future prices.

As shown by the area of quantum finance, a similar effect is seen in stock markets, where uncertainty in price is resolved only at the exact time of a transaction (see Appendix A.2). More generally, it is possible to use the formalism of quantum mechanics to model hypothetical markets and deduce an explicit equation for the uncertainty. For example, Baaquie shows that under certain conditions the uncertainty in price, multiplied by uncertainty in momentum, is greater than, or equal to half, the variance (Baaquie, 2007, p. 99). However this formula relies on the idealised assumption that the price data follows a random walk with constant variance (see discussion of this assumption in Wilmott and Orrell, 2017, p. 53). One advantage of the quantum finance approach is that it allows a degree of flexibility to relax assumptions such as perfect information (Haven and Khrennikov, 2013, p. 223).

5. Entanglements

Because mainstream economists see money as an inert chip, it pays little attention to the concept of debt. The traditional view, as summarised by Bernanke, was that debt is 'no more than a redistribution from one group (debtors) to another (creditors)' (Bernanke, 1995). In this linear view of the economy, debts and credits cancel out in the aggregate (Krugman, 2012, p. 112). As Keen points out, this is one reason central banks have been content to allow debt levels to reach unprecedented heights (Keen, 2017, p. 110). In 2017 global debt was estimated at $217 trillion, up $50 trillion over the past decade (Institute of International Finance, 2017).

In quantum economics, however, money acts as an entanglement device. In quantum physics, two particles can become entangled so that a measurement of one acts as a measurement on the other, even if the two particles are separated by vast differences – a phenomenon which Einstein famously called 'spooky action at a distance' (Einstein, Born and Born, 1971, p. 158). The field of quantum thermodynamics shows that whenever particles interact, they become entangled to a degree, effectively sharing their wave functions, which has implications for things like entropy (Linden, et al. 2009). In the same way, financial instruments such as loans, bonds or investments, act as contracts between two parties, which means that a change in one, instantly affects the other (see Appendix A.3). The debt/credit relationships in the economy, therefore, act to create an intricate web of entanglements.

These entanglements are not just numeric things which cancel out in the aggregate, but represent a power structure in the economy, which can be mapped using techniques from complexity science. One 2011 study by scientists from the Swiss Federal Institute of Technology (Vitali, Glattfelder and Battiston 2011), for example, analysed the direct and indirect ownership links between 43,000 transnational corporations, and found that fewer than 1 per cent of the companies controlled 40 per cent of the network. Another type of power relationship is that between debtor and creditor. A basic feature of debt is that it is governed by mathematical rules, such as compound interest. Being on the wrong side of this has historically been a major cause of people falling into slavery or peonage (Graeber, 2010, p. 8). Financial derivatives, such as options or credit default swaps, create another layer of financial entanglements, whose complexity defies analysis.

What distinguishes these entanglements from classical network links, is that they represent ties between abstract numbers and real assets. A debt owed on a house grows exponentially, but the house itself is located in the real world, and is subject to things like depreciation and decay. This tension between the virtual debt and the entangled real asset, and between number and the fuzzy concept of value, scales up the inherent quantum tension between the real and virtual sides of money (Orrell, 2016).

6. Money Creation

The entanglement process is seen most clearly at the moment that money is created. As a graphic example, consider the tally sticks that were a main form of payment in e.g. medieval England. This consisted of a wooden stick that was notched to indicate an amount, and then split down the middle. One part, known as the stock, was held by the state, and represented a credit. The other part, known as the stub or foil, was given to a tax collector, and represented a debt that needed to be paid. If the state wanted to pay a supplier, it could give them the stock, which granted the holder the right to collect the debt. Tallies therefore began to circulate as money objects. But because they came in two parts, they directly entangled the debtor and the creditor; if, for example, a stock was lost or destroyed, then so was the record of the debt.

In neoclassical economics, there is little attention paid to how money is created. The main focus tends to be on quantity theory, which says that money supply should be tuned to reflect economic growth. In the conventional picture, the money supply is controlled by a central bank using fractional reserve banking: the central bank creates money by, for example, buying a government bond using made-up money. This money then goes out into the economy and ends up being deposited in private banks, which can then lend out more money, subject to a reserve requirement.

In this picture, the central bank is seen as a kind of central command node, consistent with a mechanistic viewpoint. In recent years, however, there has been a reassessment of how the process really works. The Bank of England wrote in 2014: 'The reality of how money is created today differs from the description found in some economics textbooks… the central bank does not fix the amount of money in circulation, nor is central bank money "multiplied up" into more loans and deposits' (McLeay, Radia and Thomas, 2014). Adair Turner similarly noted that 'Economic textbooks and academic papers typically describe how banks take deposits from savers and lend the money on to borrowers. But as a description of what banks actually do this is severely inadequate. In fact they create credit money and purchasing power' (Turner, 2014). The economist Richard Werner performed an empirical analysis and concluded that 'The money supply is created as "fairy dust" produced by the banks individually, "out of thin air"' (Werner, 2014).

Today, indeed, the vast majority of money (in the UK, about 97 percent) is created by private banks lending money for things like mortgages on houses (Werner, 2005; McLeay, Radia and Thomas, 2014). The money is created in the same manner as tally sticks: money is deposited in the account of the seller, but the bank retains a record granting it title over the property (the difference here is that the money is the thing which acts as the stock, while the title represents the debt that needs to be paid). Because these are of equal but opposite value, they cancel out in the aggregate, but the entanglement remains. If the mortgage holder goes bankrupt, the status of the bank's loan is instantaneously changed – even if it doesn't find out until later.

The flip side of money creation is money destruction. Money that is created from debt is destroyed when the debt is repaid, like a particle colliding with its anti-particle. One implication is that if new debts are not constantly being created, the money supply will shrink, leading to recession. Money creation and destruction are therefore at the heart of the business cycle.

Of course, it is not necessary to adopt a quantum viewpoint to refute the neoclassical picture of money creation, since other people have long made exactly the same points. The banking expert H.D. MacLeod wrote in 1856 that 'the business of banking is not to lend money, but to create Credit' (MacLeod, 1856, p. 338). Schumpeter wrote in 1954: 'It is much more realistic to say that the banks "create credit", that is, that they create deposits in their act of lending, than to say that they lend the deposits that have been entrusted to them' (Schumpeter, 1954). However, the quantum version, by focussing on the role of money, naturally draws attention to the way that money is created and destroyed; and its ideas and formalism offer a coherent alternative to the dominant neoclassical orthodoxy, which has long dominated our understanding of the economy, to the exclusion of other approaches.

7. Quantum Economic Person

Neoclassical economics was originally based on the idea that people act rationally to optimise their own utility, or expected utility, when outcomes are uncertain (von Neumann and Morgenstern, 1944). In recent years this picture has been extended somewhat using the insights of behavioural economics, however, the caricature of rational economic man can still be found in many of the models routinely used by economists, and is still taught at university-level courses (Earle, Moran and Ward-Perkins, 2016).

The field of quantum social science offers a very different conception of how people and institutions behave. While a summary of this field is beyond the scope of this paper, the basic insight is that the decision-making process is analogous to the wave function collapse of a quantum system, where the system encompasses the decision maker's mind (e.g. prior beliefs and biases) and their environment. Something like answering a survey question, or accepting a gamble, is therefore a probabilistic process similar to quantum measurement, and can be modelled using the quantum methodology (see Appendix A.1). Prior to their response, people are seen as being in a superposition of states. The measurement process selects a particular state, but also changes the system. This can be seen by the fact that, just as a measurement of a particle's position affects its momentum, so the answers to certain survey questions are affected in a predictable way by the order in which they are asked (Wang et al., 2014). Similarly, the likelihood of accepting a new gamble depends on whether a previous gamble was won or lost (Busemeyer, Wang and Shiffrin, 2015). It might appear that respondents are being inconsistent, but in fact they are following a kind of quantum logic instead of classical logic.

Decisions are also affected by context, and by entanglement. One illustration, which is very relevant for economics, is the well-known psychological experiment called the ultimatum game (Güth, Schmittberger and Schwarze, 1982). Two subjects are offered an award of say ten dollars, but are given an ultimatum: one must decide how to split the money, and the other has to decide whether to accept the offer. If the offer is rejected, all the money is returned, so they both lose. Standard theory, based on rational utility maximising behaviour, would imply that any offer would be accepted, no matter how low, because it is better than nothing. However the game has been performed in many countries around the world, and the results consistently show that people reject an offer that is overly cheap, just to stop the offerer making an unfair profit. Most offers are near to five dollars, and the typical minimum acceptable offer is around three dollars. Viewed from the perspective of quantum social science, which accounts for things like entanglement and context, this result seems less surprising, since any degree of entanglement between the two players means that the offerer can no longer 'maximize her utility' by offering the other person zero (Mendes, 2005).

Further empirical evidence for the quantum approach lies in interference effects, which occur as the result of incompatible concepts. An example is preference reversal, where subconscious preferences – such as risk aversion – interfere with the decision-making process in a manner that depends on context (Tversky and Thaler, 1990). As Yukalov and Sornette (2015) wrote: 'It is the appearance of interference terms that makes the structure of quantum expressions richer than the related classical ones and that allows one to explain those psychological phenomena that, otherwise, are inexplicable in classical decision making.'

Behavioural economists have uncovered a long series of such traits, which are generally viewed as examples of 'bounded rationality', and have devised tweaks to models in order to incorporate them. As Wendt notes, however, this idea of bounded rationality remains rooted in classical decision theory, and reflects a modified version of rational utility maximisation. The quantum approach, in contrast, can be viewed as 'a kind of super – or "unbounded" rationality' in that it transcends classical limits by taking into account effects such as entanglement, interference and context (Wendt, 2015, p. 167). Furthermore, while any model can always be adjusted to fit the data by adding extra variables, the quantum formalism is, in fact, quite parsimonious and robust (Busemeyer, Wang and Shiffrin, 2015) and has the appealing advantage of allowing for a consistent model which can be applied to a range of situations (Wendt, 2015, p. 164). Money can be viewed as a social technology which extends this notion of mental wave function collapse to the societal idea of value.

8. The Quantum Economy

Quantum economics is, therefore, a composite of quantum money, quantum finance and quantum social science – which were developed independently, but together provide a direct alternative to the traditional neoclassical approach. It also makes very different predictions about how the economy should behave.

To summarise the vision presented by neoclassical economics, it sees the economy as being made up of a large number of independent agents, each of whom have roughly similar power, so that it is possible to concentrate on aggregates. It assumes that people make (roughly) rational choices in order to optimise their own utility, and that economic growth will therefore lead to greater societal happiness (Aldred, 2009, p. 22). Prices are represented as the intersection of supply and demand curves, which are further assumed to be fixed (for a time) and independent of one another.

Money is assumed to be an inert chip, and the financial sector is an intermediary. Models, therefore, usually exclude these, along with debt and credit, and treat the economy as an inherently stable barter system. Not only is credit creation by banks not usually modelled, it was only accepted as an empirical fact in 2014 (Werner, 2016). Such models are incapable of simulating things like financial crashes.

The economy is assumed to be fundamentally fair, with rewards roughly proportional, at least on average, to success in the marketplace. Questions of distribution are tackled only by distorting the model, and there is no settled way on how to do this. As Paul Krugman noted in 2016, 'we really don't know how to model personal income distribution' (Krugman, 2016). Olivier Blanchard wrote in the same year, that the derivation of distributional effects 'depends on the way distortions are introduced in the model. And, often, for reasons of practicality, these distortions are introduced in ways that are analytically convenient but have unconvincing welfare implications' (Blanchard, 2016).

The economy is treated as being separate from the environment, and effects such as pollution are handled as 'externalities'. To summarise, then, neoclassical economies predicts an economy which, if freed from 'frictions' such as over-regulation, monopolies and so on, will optimise happiness, is inherently stable, is fundamentally fair and can be viewed to most practical purposes as a closed system. It also lacks the tools to properly explore topics such as financial instability, inequality and environmental damage.

Quantum economics, by drawing attention to the quantum powers of money, draws a very different picture. Instead of rational economic man, we have quantum economic person – interacting with quantum money and other quantum economic people. There is no isolated 'utility function' to be optimised, instead we make choices that reflect complex entanglements. It is not possible to simply aggregate over people's emotions. The questions of happiness and economic growth are therefore separate issues, which are only loosely connected.

Money is assumed to be a substance that is active both psychologically – conflating as it does the properties of rational number and feelings of ownership – and in terms of its own dynamics. Its distinguishing property is that it provides a way of attaching number to the fuzzy concept of value. It acts as both a measurement device, and an entanglement device, which links debtors and creditors in a complex web of relationships.

The financial sector is not merely an intermediary, it is a uniquely important part of the world economy. Unlike most businesses, banks can create money anew by making loans. This is an extraordinary privilege, and one which is highly lucrative, since the money they create through debt is interest bearing. This special role also makes banks immensely powerful. It is no accident that many governments are dominated by people who came out of the financial sector; or, for that matter, that the economics profession has shown a blind eye to the process of money creation, given its own significant entanglements with the financial sector (Carrick-Hagenbarth, 2012; Häring, 2013).

The business cycle is driven, in large part, by the creation and destruction of money during financial booms and busts. Any realistic model of the financial system, therefore, needs to take these factors into account. Quantum economics puts money at the centre of its approach, instead of treating it as a 'veil' which obscures the true nature of trade. Financial bubbles are not anomalies, but expected features of the system.

Quantum economics anticipates the problem of inequality, because the economy is not a barter system and money does not flow to people on merit alone. Money has its own dynamic – in that money makes more money through compound growth and power relationships. (As Benjamin Franklin put it, 'Money is of a prolific generating Nature. Money can beget Money, and its Offspring can beget more, and so on.') On a societal level, it therefore tends to cluster, rather than spread evenly. The reason eight men now control as much wealth as half the world's population does not come down to merit (Oxfam, 2017).

Quantum economics notes that the economy, as currently maintained, is fundamentally incompatible with environmental limits. Our debt-based money system means that new money must constantly be created in order to pay the interest on the old money. This implies the need for permanent economic growth – and the easiest way to make money out of the world is to extract resources and sell them. The conflict between our economy and the environment is, therefore, as fundamental as the conflict inherent in money, between numeric price and real value. The answer is not to attempt to put numbers on nature, but instead to view the economy as a separate human institution, whose limits are ultimately determined by natural forces outside its domain.

Finally, quantum economics recognises that the economy is a reflexive system, so that theories of the economy affect the economy, just as a measurement affects the system being measured. In particular, a theory which views the economy as inherently stable will lead to its exact opposite, by creating a false sense of security, and leading to cutbacks of safeguards and protective regulations.

9. Conclusions

As seen above, quantum economics starts from assumptions that are radically different from those of neoclassical economics, and comes to equally different conclusions. Neoclassical economics is based on a fundamentally reductionist approach which attempts to derive economic models from so-called micro-foundations. The image is of the economy as an intricate machine with many moving parts. However, it achieves this by aggregating over a large number of individuals, so, for example, a country or sector might be simulated through the use of a single representative agent, and prices determined through estimates of average supply and demand curves.

With quantum economics, concepts, such as representative agents or aggregate demand curves, are not very meaningful. It may not, therefore, be appropriate to try to build a model up from micro-foundations, any more than a weather forecaster would base their model on the quantum physics of water molecules. Instead, it makes more sense to take a complexity approach. Prices are not measuring some unique and stable quality such as utility, instead they emerge from financial transactions. A model which is appropriate at the level of individuals, cannot simply be scaled up to the macro level. Rather than attempt to build a reductionist mathematical model of the economy, it is better to take an agile approach which builds smaller models for particular situations (Orrell, 2017). Just as Heiesenberg argued, that physicists should focus on what can be observed, rather than speculate on what goes on inside an atom (Kumar 2008, p. 231), so economists should limit their use of model parameters as far as possible to those that can actually be measured.

In neoclassical economics, so-called 'market failures' such as economic inequality, financial instability and environmental degradation are treated as aberrations or externalities. Quantum economics sees all of these as intrinsic properties of the economic system, that are caused, in large part, by our use of debt-based money. To tackle these issues, we therefore need to examine the money system in more detail and see how it can be improved. One solution which has been proposed by a variety of economists, for different reasons, is that of full-reserve banking, where money is created debt-free by the state (Soddy, 1926). Barring that, private banks should be viewed as money creators rather than financial intermediaries, and regulated accordingly – so that credit is directed towards productive uses, rather than asset bubbles (Werner, 2016).

Because neoclassical economics treats the economy as a mechanistic system, there has been little role for ethics – either as they relate to decision-making in economics, or to the profession itself (DeMartino and McCloskey, 2016). Quantum economics, in contrast, sees the economy as an entangled living system where individuals and institutions have broader responsibilities to each other, and to society. Finally, quantum economics is inherently pluralistic in the sense that, because it does not see the economy as a utility-optimising machine, it is open to different ideas about the kind of choices that will lead to the good society. The aim is not to further mathematicise the subject, or replace the classical mechanics mimicked in neoclassical economics with a quantum version. Instead, it is to treat the economy as a kind of quantum social system in its own right, with modelling tools adapted for its needs.

This paper has only presented the core ideas of quantum economics, and putting these into practice will obviously be a major project. Techniques such as DSGE models will not be compatible with the quantum approach, but there are plenty of suitable options, such as agent-based models (where the agents may be quantum, see Orrell, 2018, p. 201), network models, and nonlinear dynamics models (Bruno, Faggini and Parziale, 2016). In principle at least, the success of the theory will depend on its ability to make accurate predictions. Physicists initially adopted quantum theory, not for its theoretical appeal, or because they could directly observe how subatomic particles behaved, but because they were compelled to do so by its ability to simulate a number of puzzling experimental results. In economics, the situation is much simpler because we *can* directly observe how money behaves (we invented it), and see its effects scale up through money creation and financial entanglement. Instead of deducing the laws of nature from experiments, we are deciding on the correct mathematical framework for a designed social technology or institution. The empirical evidence for something like entanglement through a loan, lies not in subtle statistical signals, but in the wording of the contract.

Empirical backing for quantum cognition, meanwhile, is provided by experimental evidence for things like the order effect. In his 1978 paper – written before behavioural economics had even been founded as a field – Qadir posited that a consumer's choice 'will depend, among other things, on the order in which his requirements for various commodities are found out'. Some 36 years later, an *Economist* article on tests of quantum cognition (whose author was apparently unaware of Qadir's article) could confirm: 'what is clear is that the kind of judgments we make when responding to a survey are not simply read out of our memory, but are dependent on our cognitive state (which may be highly uncertain) and the context in which it is operating (which can be influenced by question ordering, among other factors). In other words, the cognitive equivalent of those puzzling phenomena that led physicists to develop quantum theory in the first place more than a century ago' (Anonymous, 2014).

Of course, factors such as the difficulty of making controlled experiments, mean that the role of prediction is a little different in the social sciences; neoclassical economics has remained in place for a century and a half, without much of a predictive track record to boast of, and failed completely during the recent crisis – which suggests that prediction isn't really the test. Instead a theory is likely to be accepted if it tells a story which benefits a powerful constituency, either within the profession or outside it (e.g. the government, the financial sector). For quantum economics, its natural constituency is perhaps similar to that which fuelled the anti-nuclear protests: people who have lived through the recent financial crisis, and want to prevent it from happening again.

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Appendix: Overview of the mathematics of quantum economics

A.1. The Hilbert Space and Quantum Cognition

This appendix gives a brief introduction to some of the mathematical techniques related to topics discussed in the paper, including quantum cognition, quantum finance and entanglement through debt.

Perhaps the most basic mathematical tool in quantum theory is the concept of the Hilbert space, which is named for the German mathematician David Hilbert (1862-1943). A Hilbert space *H* is a type of vector space whose elements, denoted $|u\rangle$, have coefficients that can be complex numbers. The dual state $\langle u|$ is the complex conjugate of the transpose of $|u\rangle$. The inner product between two elements $|u\rangle$ and $|v\rangle$ is denoted $\langle u|v\rangle$, and is analogous to the dot product in a normal vector space, with the difference that the result can again be complex. The outer product is denoted $|u\rangle\langle v|$, and is like multiplying a column vector by a row vector, which yields a matrix. The magnitude of an element $|u\rangle$ is given by $\sqrt{\langle u|u\rangle}$, and two elements are orthogonal if $\langle u|v\rangle = \langle u|v\rangle = 0$. The Hilbert space can therefore be viewed as a generalisation of Euclidean space, with the difference that there can be an infinite number of dimensions (though conditions apply), the basis need not be simple column vectors, and coefficients can be complex.

An operator $\hat{A}$ is a map which sends one element $|u\rangle$ of *H* to another element $\hat{A}|u\rangle$ of *H*. For example, the projection operator is defined as $\hat{P}_u = |u\rangle\langle u|$, and $\hat{P}_u|v\rangle = |u\rangle\langle u|v\rangle$ gives the projection of *v* onto *u*. Operators $\hat{A}$ and $\hat{B}$ do not generally commute, so $\hat{A}\hat{B} \neq \hat{B}\hat{A}$. A state $|u\rangle$ is an eigenvector of $\hat{A}$ if $\hat{A}|u\rangle = \lambda|u\rangle$ where λ is the associated eigenvalue. For example, $\hat{P}_u|u\rangle = |u\rangle\langle u|u\rangle = \lambda|u\rangle$, so $|u\rangle$ is an eigenvector of $\hat{P}_u$ with eigenvalue $\lambda = \langle u|u\rangle$. The expectation value of a linear operator $\hat{A}$ in the state $|u\rangle$ is given by $\langle u|\hat{A}|u\rangle$, i.e. the scalar product of $\langle u|$ with $\hat{A}|u\rangle$.

A key feature of quantum theory is that observables, such as a particle's position or momentum, are represented by Hermitian operators, which have real eigenvalues.[1] Instead of being passive elements, as in classical theory, they are operators that ask a question of the system. During a measurement of an observable, the system state $|S\rangle$ collapses to one of the eigenvectors of the associated operator, with a probability given by the square of the projection of the state $|S\rangle$ on that eigenvector.

To see the difference between the classical and quantum approaches, in the context of human cognition, suppose that a person has a choice between a certain number of possible options. In classical probability theory, each choice *u* would be treated as a subset of the set *U* consisting of all choices. A person's cognitive state is represented by a function *p* with the probability of choosing *X* given by *p*(*u*). As a simple example, *U* could consist of two choices *u* and *v*, with respective probabilities *p*(*u*) and *p*(*v*), that satisfy *p*(*u*) + *p*(*v*)= 1.

In quantum cognition, a choice in response to a particular question is treated instead as an element (e.g. vector) $|u\rangle$ of a Hilbert space *H*, and a person's cognitive state is represented by an element $|S\rangle$, both of length 1. (The state $|S\rangle$ is sometimes called a wave function, although here it is static rather than time-varying.) Here the associated operator $\hat{P}_u$ is the one that projects vectors onto the vector $|u\rangle$. The probability of the answer to the question being $|u\rangle$ is then given by the magnitude of the projection squared, which is $|\langle u|S\rangle|^2$.

This shift, from sets of elements to geometric projections, allows for more complicated probabilistic effects such as non-commutativity and interference, which are characteristic of human cognition. For example, projecting onto $|u\rangle$, and then onto $|v\rangle$, may not give the same result as when the order is reversed, which compares with the 'order effect' in surveys.[2] The Hilbert space therefore appears to be the natural framework for simulating cognitive phenomena, and researchers have amassed a considerable number of empirical findings to back up that claim (Bruza et al., 2015).

A.2. The Quantum Market

In the same way that a person's cognitive state can be simulated as a member of a Hilbert space, so we can do something similar for the economy as a whole, and model it as a collection of interacting particles in a Hilbert space. As a starting point, we will consider a simplified financial market. Following (Schaden, 2002), suppose that the market consists of a collection of agents (investors) *j* = 1, 2, ..., *J* who buy and sell assets of types *i* = 1, 2, ..., *I*. Each agent holds cash (or debt) x^j. The market can be represented as a Hilbert space *H*, with the basis

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[1] A Hermitian operator is one which equals its Hermitian conjugate, which for a matrix operator is defined as the complex conjugate of the transpose, so $A = A^{\dagger} \equiv (A^T)^*$.

[2] For the 2-D case the coefficients can be assumed to be real rather than complex, see (Moreira & Wichert, 2017). For a worked example, see the web application available at https://david-systemsforecasting.shinyapps.io/ordereffect/.

$$B := \{|x^j, \{n_i^j(s) \geq 0, i = 1,..,I\}, j = 1,..,J\rangle\}.$$

Here $n_i^j(s)$ is the number of assets *i* with a price of *s* dollars that are held by investor *j*.

An individual basis state represents a market where the price of every security, and the cash position of each agent, is known precisely. The basis states are orthogonal in the sense that if the market is in the state $|m\rangle$ then it cannot be in a different state $|n\rangle$, so if $m \neq n$ then the inner product $\langle m|n\rangle = 0$. In general the market state (wave function) *M* is never known this accurately and is instead represented by the linear superposition of basis states $|n\rangle$ in *B*:

$$|M\rangle = \sum_n A_n|n\rangle$$

where the A_n are complex numbers, and $w_n = |A_n|^2$ is the probability that the market is in the state $|n\rangle$. The phases of the A_n are left unspecified at this stage, but are key to understanding effects such as interference.

If we define the ground state $|0\rangle$ to be a market where agents hold no assets including cash, then we can build up a real market by transferring cash and assets to agents. The approach is the same as that used in many-body quantum mechanics to simulate the behaviour of a collection of bosons, so shares are added or removed from an agent's account by the use of the so-called creation operator $\hat{a}_i^{\dagger j}(s)$ and the annihilation operator $\hat{a}_i^j(s)$. Money creation is handled using a translation operator of the form

$$\hat{c}^{\dagger j}(s) = \exp\left(-s\frac{\partial}{\partial x^j}\right)$$

which increases the amount of cash held by agent *j* by *s* currency units. Similarly the Hermitian conjugate operator $\hat{c}^j(s) = \hat{c}^{\dagger j}(-s)$ lowers the cash holding of agent *j* by the amount *s*.

We can build up an arbitrary market state from the vacuum state by using these operators to successively transfer cash and securities to each agent. To study how the market wave function evolves with time, we write

$$|M\rangle_t = \hat{U}(t, t_0)|M\rangle_{t_0}$$

where $\hat{U}(t, t_0)$ is a unitary linear operator. The dynamical behaviour of the system is driven by a Hamiltonian $\hat{H}(t)$, which as in classical physics represents the total energy of the system. This satisfies the Schrödinger equation

$$i\frac{\partial}{\partial t}|M\rangle_t = \hat{H}(t)|M\rangle_t.$$

It is then possible to develop Hamiltonians for things like cash flow, the trading of securities, and so on. As shown by Schaden and other researchers, these in turn can be used to derive statistical properties of markets (see the original paper for details).

The variables of the system can be loosely interpreted in terms of physical analogies. The price *s* of an asset (or more correctly its logarithm) is like position. As in physics, there is an uncertainty relation involving asset price, and the momentum of the price change. The creation of money or assets adds energy (as measured by the Hamiltonian) to the total energy of the system. The same techniques used to study many-body quantum systems can then be applied to make predictions about market behaviour, either in closed form or by explicitly modelling each agent.

As a simple example of a Hamiltonian in finance, consider the case of a savings instrument containing an initial amount of cash x_0 which accumulates at an interest rate *r*. The classical Hamiltonian for this system is

$$H = rxp$$

where (in classical notation) *p* is the conjugate variable of *x*.[3] We then have

$$\frac{dx}{dt} = \frac{\partial H}{\partial p} = rx$$
$$\frac{dp}{dt} = -\frac{\partial H}{\partial x} = -rp.$$

Solving then gives

$$x = x_0 e^{rt}$$
$$p = p_0 e^{-rt}$$

which implies that the Hamiltonian is constant in time:

$$H = rxp = rx_0 e^{rt} p_0 e^{-rt} = rx_0 p_0.$$

Note that changing p_0 doesn't affect the result for *x*, so we can set $p_0 = 1$ which means that $p = e^{-rt}$ is the value of one unit of currency discounted to time $t = 0$.

To quantise the system, we replace the Hamiltonian *H* and classical variables *x* and *p* with operators. Because the Hamiltonian must be Hermitian, we need to write it in a symmetric form as

$$\hat{H} = \frac{r}{2}(\hat{x}\hat{p} + \hat{p}\hat{x}).$$

Standard techniques can then be used to show that the probability distribution of the cash holdings matches that expected from the classical case (as Schaden notes, the quantum approach only comes into its own when future returns are uncertain). In the case of a single cash transfer of a quantity s at time $t = t_0$, the Hamiltonian becomes $\hat{H}(t) = s\delta(t - t_0)\hat{p}(t)$ where the delta function $\delta(t - t_0)$ has the value 1 at $t = t_0$ and 0 at other times.

The cash flow model treats the account as a black box which magically produces money at a fixed rate *r*. There are no inputs or outputs, which is why the Hamiltonian remains constant even as the nominal amount of money increases indefinitely. While such isolated systems do not exist in reality, the simple model is instructive about how inflation occurs in something like a housing market. As emphasised in quantum economics, money is created by private banks every time they issue a mortgage. If we assume mortgage lending continues at a steady rate, then the money supply will grow at some constant rate *r*. If this money is then used to bid up the supply of houses, then house price growth will track money supply growth, even if the real value of homes remains unchanged.[4]

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[3] See e.g. (Bensoussan, Chutani and Sethi, 2009).

[4] As an example, Figure 3 of (Orrell, 2018) shows that both house prices, and a broad measure of the Canadian money supply, grew at an annual rate of about 6.5 percent in the period 1999 to 2017.

An important difference between cash and a security is that while money is a conserved quantity during transactions, a security once bought evolves into a superposition of states, each of different prices, with amplitudes specifying the probability of selling at that price. If markets are assumed to be large and nearly efficient, then the results generally approximate those produced by the classical approach. (Indeed, researchers have so far largely tended to respect classical assumptions such as efficiency, in an attempt to replicate known results.) However quantum effects become more important for markets that are thinly traded, and the quantum approach can also be used to describe markets driven by investor sentiment, where there is a significant degree of entanglement between market participants.

A.3. Entanglement

As discussed in the paper, a key advantage of the quantum approach in economics is that it provides a natural framework for thinking about financial entanglement through loans and derivatives. To first motivate the discussion, consider the physical example of a pair of entangled electrons, denoted 1 and 2, each of which has spin ½ when measured along a particular axis, but in opposite directions. The spin part of their wave function can be written as a superposition of two states:

$$|S\rangle = \frac{1}{\sqrt{2}}|1\uparrow\rangle|2\downarrow\rangle - \frac{1}{\sqrt{2}}|1\downarrow\rangle|2\uparrow\rangle$$

where the arrow indicates the direction of spin of each electron.

The wave function tells us nothing about the direction of spin for either electron, only that they are opposite, so the total spin is zero. Now, suppose that we measure the spin for electron 1. We would expect an equal chance of getting a positive or negative result. If it is the former, then the system must have collapsed to an eigenstate with positive eigenvalue, so is of the form

$$|S\rangle = |1\uparrow\rangle|2\downarrow\rangle$$

A measurement of particle 2 can now yield only a negative result. The reason is that the wave function describes the system, including both particles, so a measurement on one is equivalent to a measurement on the system as a whole.

The financial version of entanglement can be expressed using a similar formalism. Instead of two entangled electrons, consider two people entangled by a loan contract; and instead of spin direction, we will use loan status (i.e. 'default' or 'no default'). As in quantum cognition, the debtor is modelled as initially being in a superposition of two states, with a decision acting as a measurement event. The loan status can therefore be expressed by a wave function of the form:

$$|S\rangle = \alpha\,|1\uparrow\rangle|2\downarrow\rangle - \beta|1\downarrow\rangle|2\uparrow\rangle$$

Here α^2 and β^2 add to 1, and give the probability of default $|1\uparrow\rangle|2\downarrow\rangle$ and no default $|1\downarrow\rangle|2\uparrow\rangle$ respectively, so reflect the debtor's propensity to default at a particular moment. If the debtor decides to default on the loan, that acts as a measurement on the system as a whole. At any time after that, if the creditor decides to assess the state of the loan, the result can only indicate default. The two parties are thus entangled.

Of course, systems can be correlated without any need to invoke quantum effects.[5] However the key point is that we are treating the debtor's state regarding the loan as being in a superposition of the two states 'default' and 'no default'. The state of the loan is therefore indeterminate (we don't know whether the debtor will default) yet still correlated, which is the essence of entanglement.

Another possible objection is that, after one of a pair of entangled particles has been measured, the second doesn't need to check with the first to find out what its state is; while with a loan the creditor does. However the wave function equation applies to the loan agreement, which is an abstract thing that encompasses both parties. So from the point of view of that wave function (which again is what we are modelling) the state does change instantaneously; it is only measurements that take time. The difference between the physics version, and the financial version, then reduces to a question of the nature and reality of such wave functions, which would depend on one's interpretation of quantum theory, and is a topic of debate for both physicists and social scientists.[6] But from a mathematical modelling perspective the two are the same.

One feature of the system is that, unlike for electrons, there is now only one axis of measurement. This means that the behaviour of a loan agreement is much less subtle than the physical version (though some social scientists do argue for rich versions of mental entanglement based on physical principles); and also that it is not possible to reproduce Bell-type experiments, where entanglement is tested by changing the orientation of the axis. However Bell's experiments do not define entanglement, but were devised as a way to tease out entanglement for systems that cannot be queried more directly. For loans, the entanglement is encoded by the terms of the agreement. Again, the equation applies only to the loan agreement, so default may for example be followed by a complex negotiation, but the same is true in a physical system where other forces can also come into play.

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[5] For example, suppose I have two beads, one red and one blue, and I give one to a friend without looking. Then if I check and find that I have the red one, I know that my friend has the blue one.
[6] A widely discussed example is whether Xantippe, the wife of Socrates, became a widow the instant her husband was forced to commit suicide, or only when she found out later. See Wendt, 2015, p. 194.

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