# Quantum Economics

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## 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, the 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.

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## 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 nineteenth century founders were inspired by classical physics – had failed to heed the teachings and insights of quantum physics, which revolutionised physics in the early twentieth century. This does not mean that economics should directly mimic quantum physics, or literally adopt the formalism of quantum mechanics. Instead, the economy should be viewed as a quantum 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. Some of these explore similarities between quantum physics and economics; for example things like uncertainty principle, which seem to apply as well to financial markets as they do to particles. In his 1978 paper 'Quantum Economics' the Pakistani 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). A number of authors working in the area known as quantum finance have indeed 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; Baaquie 2007).

The fields of quantum cognition (Aerts and Aerts 1994) and quantum social science (Haven and Khrennikov 2013), on the other hand, 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).

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 thoughout. 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 remainder of 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.

## 2. The science of money

Economics is 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 exchange of goods (Smith, 1776). The economist Jean-Baptiste Say, who popularized 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 further 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 has 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 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; Orrell and Chlupatý, 2016; Orrell, 2017), 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 can never be known exactly, but are fundamentally uncertain, and are in a sense determined during the measurement procedure. 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. 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 cliche 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 if 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, that was only settled in the early twentieth 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 physics (Orrell 2007). 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, it is not even clear 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 decided 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 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. 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). Or as Krugman wrote 'when debt is rising, it's not the economy as a whole borrowing more money. It is, rather, a case of less patient people – people who for whatever reason want to spend sooner rather than later – borrowing from more patient people' (Krugman 2012, p. 112). In this linear view of the economy, debts and credits conveniently cancel out in the aggregate, and so can be ignored. 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). Global debt is now 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, if a particle and its anti-particle are created in a single event, the two particles remain entangled so that a measurement of one acts as a measurement on the other and affects its state, 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. 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 for example analyzed 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.[1] 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).

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. These consisted of a wooden stick that were 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, know 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

[1] Vitali, Glattfelder and Battiston 2011.

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. Too much money printing leads to inflation, while too little can lead to economic contraction. In the conventional picture, the money supply is controlled by a central bank using fractional reserve banking: the central bank creates money by e.g. 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). In 2017 the German Bundesbank wrote that ‘banks can create book money just by making an accounting entry ... this refutes a popular misconception that banks act simply as intermediaries at the time of lending – ie that banks can only grant credit using funds placed with them previously as deposits by other customers’ (Deutsche Bundesbank 2017).

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 it offers 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 woman

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. A summary of this field is beyond the scope of this paper, but 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. 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 his utility' by offering the other person zero (Mendes 2005).

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 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).

## 8. The quantum economy

Quantum economics can therefore be viewed as a composite of quantum money, quantum finance and quantum social science, which provides 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 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 modelled, it was only accepted as an empirical fact in 2014 (Werner, 2016). The models are incapable of simulating things like financial crashes.

The economy is assumed to be fundamentally fair, with rewards roughly proportional, at least in 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 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 woman (Wendt, 2015, p. 149) interacting with quantum money. 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 a mere 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 (Wilmott and Orrell 2017).

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 center 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. (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.

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. Its defining feature is that it puts money creation, monetary transactions, and the dualistic properties of money at the heart of economics.

One can often tell a lot about a field by asking what subjects are considered off-limits. Wendt writes that 'in most of contemporary social science there seems to be a "taboo" on subjectivity' (Wendt, 2015, p. 19). The economics equivalent is the highly emotional subject of money, and in particular its creation by banks. As Werner notes: 'The topic of bank credit creation has been a virtual taboo for the thousands of researchers of the world's central banks during the past half century' (Werner, 2016). Quantum economics takes the opposite approach of starting with the topic of money, and working its way out.

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 is not therefore appropriate to try and 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, 'market failures' such as economic inequality, financial instability, and environmental degradation are treated as aberrations or externalites. 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 relates 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 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 may need to be discarded, but there are plenty of options such as agent-based models, network models, and nonlinear dynamics models that will be compatible with the quantum approach (Bruno, Faggini & Parziale, 2016). It would be nice to say that the success of this project will depend on the ability to make accurate predictions, but of course this is far from being the case; neoclassical economics has remained in place for a century and a half without much of a predictive track record to boast of. 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 similar to that which fueled 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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