Complexity Economics

By Greg Fisher, 10 May 2023 (v 1.0)

This paper describes Complexity Economics (CE), a branch of economics that is changing the paradigm of thought in that field (albeit slowly). For readers unfamiliar with the complexity sciences, this note is best read in conjunction with a separate not entitled *The Complexity Sciences: An Introduction* (referred to below as the Introduction Paper).

When considering social systems from a complexity science perspective, we must be careful when mapping from an abstract conceptual framework that has arisen mostly in the natural sciences, to the social sciences "without a rigorous process of testing for appropriateness and relevance." (Mitleton-Kelly, 2003, p. 25). For example, an important difference between complex systems involving simple, myopic agents and those with humans is that agents in the former are often reactive whereas those in the latter have a greater capacity for imagination and anticipation.

The first section below describes the overall approach taken in CE and it lists eleven key characteristics of that perspective, e.g., the idea of a 'stratified ontology' owing to emergent properties.

Each of these eleven characteristics are discussed and contrasted with the equivalent approach taken in Neoclassical Economics (NCE), which has been the dominant school of thought in economics for decades.

This section ends by contrasting CE and Neoclassical theory in a particular way: by focusing on the different internal consistencies (between their micro and macro features) of the two approaches.

The second section of this paper considers and responds to some of the criticisms of the complexity sciences, including CE.

As a final introductory point, this paper refers to several researchers in the complexity sciences but it places a greater weight on the work of W. Brian Arthur. Arthur was one of the first economists to consider the implications of the study of complex systems not only for economics but for the social sciences more generally. He led the economics department of the Santa Fe Institute for several years after its inception and has been a leading thinker in this field since[1].

1 Complexity Economics

CE is the study of economic behaviour from a complexity science perspective. For books and papers written on this general approach, see Rosser (1999), Colander (2000), Judd (2006), Tesfatsion (2006), Axtell (2007), Colander et al. (2008), Kirman (2010), Colander and Kupers (2012), Epstein (2012), Farmer (2012), Gallegati and Kirman (2013), Arthur (2013), and Arthur (2021).

In the first sub-section (1.1) below we ask whether the complexity sciences are applicable to economics. The second and main sub-section (1) describes the overall approach taken in CE, focusing on eleven general principles (for each we contrast the approach taken in Neoclassical theory).

[1] Also, Arthur was not the first to consider economics in the context of 'complexity', e.g., Friedrich Hayek published a paper in 1964 (Hayek, [1964] 2014) which is broadly compatible with the description of CE in this paper

Section 1.3 briefly discusses how, in broad terms, we can think of CE as economics done in a more generalised way than Neoclassical theory (approximately speaking, if we simplify a CE framing in specific ways, we arrive at NCE); and Section 1.4 looks at how CE, like NCE, offers coherence between its micro and macro levels.

1.1 Should Economies be Viewed as Complex Systems?

One way of framing this question is to ask whether economic systems include the three defining features listed in the *Introduction Paper*: multiple heterogeneous agents, interconnectivity, and time.

It should be clear from the discussions in that paper that economies can indeed be described by these three features: people, firms, and other organisations are typically thought of as economic agents; they exist in networks of relationships; and, in general, they evolve and adapt to each other over time.

From a logical point of view, the statement that economies should be thought of as complex systems represents a syllogism: (i) systems with the three defining features are defined as complex systems (the major premise); (ii) economies include these defining features (the minor premise); therefore, (iii) economies are complex systems.

It would be a mistake, however, to apply the conceptual features of the complexity sciences to economics in an unquestioning way because the former emerged, broadly speaking, from the natural sciences. One must be cautious when mapping from one domain to another.

Most notably, human agents are different to those seen in natural complex systems (atoms, stars, bees, etc.), especially the idea that "humans have the capacity to reflect and to make deliberate choices and decisions among alternative paths of actions." (Mitleton-Kelly, 2003, p. 25). Moreover, the fact that a ground-up view of complex systems is generally advocated by complexity scientists means that if human agents have features that are different to those in natural systems then it is likely that whole systems of these agents will too: different patterns might emerge.

1.2 The Eleven Principles of Complexity Economics

In this sub-section we set out eleven general principles that make up CE. These principles are:

1. Economies are computational in nature;
2. Economies exhibit non-equilibrium and dis-equilibrium features;
3. Economies include the processes of *formation* and *allocation*;
4. Economies have a stratified ontology, resulting from emergence;
5. CE is open to a 'generalized Darwinian' approach;
6. Economies are non-ergodic;
7. Uncertainty is an important feature in economic behaviour;
8. Agents use mental models to make decisions;

9. CE is open to inter-disciplinarity;
10. CE values realism and is sympathetic to instrumentalism; and
11. CE has an affinity with pragmatism.

Each principle is discussed below and then contrasted with the Neoclassical approach. For general criticisms of Neoclassical theory see, e.g., Eichner and Kregel (1975), Nelson (2014), Stiglitz (2002), Blaug (2002), Arnsperger and Varoufakis (2006), and Colander et al. (2008).

Before proceeding, it is worth noting that Complexity Economics is now a maturing field of study, which means that different interpretations and emphases are bound to exist. What follows is one interpretation although it is probably reasonable to say that the only possibly contentious principle listed below is the last, that related to pragmatism. The argument here is that this seems to be a natural extension of the bottom-up orientation of the complexity sciences, and it appears to be implicit in much of Arthur's work, e.g., Arthur (2013).

1.2.1 Economies are computational in nature

In response to the stable, equilibrium-focused world of Neoclassical theory, Arthur (2013) writes:

> A better way forward is to observe that in the economy, current circumstances form the conditions that will determine what comes next. The economy is a system whose elements are constantly updating their behavior based on the present situation. To state this in another way, formally, we can say that the economy is an ongoing *computation* — a vast, distributed, massively parallel, stochastic one. Viewed this way, the economy becomes a system that evolves procedurally in a series of events; it becomes algorithmic. [Emphasis included] Arthur, 2013, p. 6

This quote raises the question of how we define computation, which is an open question even in the field of computational science.

Denning (2010) discusses the history of definitions of computation and offers a "Transformation of Representations" version, which appears compatible with the general usage of the term at the time of writing.

A representation is defined by Denning as "a pattern of symbols that stands for something" (Denning, 2010, p. 7). His proposed definition of computation is of an *information process* driven by a representation, i.e., information is transformed in the act of computation.

In economics we can think about economic agents who receive information that is then processed (transformed) by their mental models. The output might be information also (e.g., a signal to another agent) or actions performed by the agent (including forms of work). These agents need not be humans - they might also be machines, firms, trade unions, etc.

The idea that economies are parallel systems of concurrent computation is compatible with a complex systems approach because it fits well with the architecture of multiple agents interacting over time. In fact, computation provides a framework for describing how agents in the system process information, which is based on a mature body of work.

Computation and Closed Form Solutions

In discussing computation, Arthur (2013) refers to Alan Turing's halting problem theorem (Turing, [1936] 2004). The result of this theorem is that:

> ...there is no analytical method to decide in advance what a given algorithm will do. All we can do is follow the computation and see what it brings. Of course, with simple algorithms we can often see they will settle down to a given outcome. But algorithms don't have to be particularly complicated before we cannot decide their outcomes (Wolfram, 2002, as quoted in Arthur, 2013, p. 6).

This point has substantial implications for the analysis and modelling of computational processes, which Arthur argued included economies. It means that, in general, we must be sceptical about closed form solutions of such processes; rather we must "follow the computation and see what it brings" (ibid).

Implications for Economics

There are two broad implications of this emphasis on computation that are worth highlighting here. First, when framing or modelling economic systems, we must account for their computational nature. If we fail to do this then we run the risk of a framing error.

Indeed, this point seems particularly important for the economics profession which has become highly mathematized in recent decades. A mathematical framing of computational systems represents information compression, which Turing warned against.

Second, the halting problem has significant implications for our understanding of how agents process information, including questions about 'rationality'. We must ask ourselves how agents process information and achieve any goals if the environment in which they exist is not 'solvable' in any way.

Comparison with Neoclassical Theory

Historically, NCE has not treated economic systems as computational in nature. There is a substantial literature looking at the formal approach taken by Neoclassical theory, e.g., Arthur (2013) discusses this and how it relates to equilibrium conditions.

Arthur (2013) argues that for certain features of the economy, equilibrium-like conditions might well exist. Furthermore, "[w]e can often do much useful pre-analysis of the qualitative properties of nonequilibrium systems" (ibid, p. 6). As a result, the standard analytical techniques in Neoclassical theory can be useful. However, for

> highly interconnected systems, equilibrium and closed-form solutions are not the default outcomes; if they exist they require justification. And computation for such systems should not be regarded as the avoidance of analytical thinking; rigorously speaking, it may be completely necessary. Arthur, 2013, p. 6

Here, Arthur is arguing that if the economy is a computational process then computational modelling is a suitable technique for analysing such systems. The standard mathematical techniques of Neoclassical should be viewed as approximations that are useful only under certain conditions. To reinforce this point, Arthur writes "computation ... allows us to see phenomena that equilibrium mathematics does not." (ibid, p. 8).

This point should also lead us to query the assumption of substantive rationality in computational systems: historically, NCE has been oriented around agents solving a utility maximization problem under known conditions. The halting problem means that in computational systems, this type of maximization is questionable.

1.2.2 Economies exhibit non-equilibrium and dis-equilibrium features

The computational view of economics described above helps us appreciate how the economy, or parts of it, can exist in states of non- or dis-equilibrium. This perspective "shows us an economy perpetually inventing itself, perpetually creating possibilities for exploitation, perpetually open to response. An economy that is not dead, static, timeless, and perfect, but one that is alive, ever-changing, organic, and full of messy vitality." (Arthur, 2013, p. 19).

This dis-equilibrium view was emphasised in Farmer's (appropriately entitled) paper, 'Economics Needs to Treat the Economy as a Complex System':

> ...in many situations there is no unique equilibrium. When there are multiple equilibria it may be difficult to predict which agents will converge to; in other circumstances they may fail to converge to any equilibrium at all. Farmer, 2012, p. 8

Comparison with Neoclassical Theory

Arnsperger and Varoufakis (2006) argue that NCE is comprised of three underling axioms. One of these is 'methodological equilibration', which is the idea that markets (and economies more generally) tend to equilibrium.

There is an important question here about why Neoclassical theory has taken this approach. One explanation, shared by many of NCE's critics, is due to the analytical techniques available to economists for most of the 20th Century that for the most part were mathematical in nature. Economists looking to formally determine how economies worked, who were restricted to these analytical techniques, built models orientated around equilibrium outcomes and microeconomic behaviour that was consistent with equilibrium. This approach has been taken in various parts of Neoclassical theory, including the theory of the firm, international trade, and financial markets (Arthur, 2013, p. 2).

It should be clear, however, that the development of computational approaches and the acceleration in processing power since the 1970s, both mean that these restrictive mathematical techniques are no longer the only tools available to economists. Computational modelling of economies offers a way of increasing our understanding of non- and dis-equilibrium phenomena.

1.2.3 Economies include the processes of *formation* and *allocation*

Economics is often defined as the study of the *allocation* of scarce resources. Moreover, Neoclassical theory has focused heavily on this issue to the extent that Arthur (2013) writes that of the two great problems in economics, "[t]he allocation problem is well understood and highly mathematized." (p. 17).

The second major problem in economics Arthur refers to is about *formation* within the economy. It is tempting to think of this in a conventional way, as being about stocks of assets, including capital, labour, and natural resources. However, Arthur argues that the issue is more about how the economy structures and re-structures itself over time. Formation is about:

> how an economy emerges in the first place, and grows and changes structurally over time. This is represented by the ideas about innovation, economic development, structural change, and the role of history, institutions, and governance in the economy. Arthur, 2013, p. 17

This idea of economic re-patterning mimics the language used by other complexity scientists. It is often used to refer to the relationships between parts of systems: the network of relationships in an organisation, circuit board designs, how the various parts and processes of an organism work to sustain its life, etc. (e.g, Boulton, 2019).

Moreover, if we stand back and consider the economy as both formed / re-forming patterns *and* allocation, this helps us visualise the economy as both a stock of networked (or patterned) resources *and* as a flow of resources across that network.

When it comes to understanding what types of pattern exist in the economy, Arthur (2013) refers to "institutions, arrangements, and technological innovations." (p. 1). Institutions include social norms; arrangements can refer to a variety of phenomena, including management structures in organisations; and technological innovations are about how materials and energy are arranged to achieve tasks. Of these three patterns, Arthur's own research has been focused on technology, most notably in Arthur (2009).

Comparison with Neoclassical Theory

Arthur's view is that Neoclassical theory has focused on the allocation problem at the expense of understanding formation.

If we consider the formal modelling technology on which Neoclassical theory has relied, this is not surprising. Formation is not simply about the accumulation of stocks of resources, which can be handled by differential equations; it is about two important issues: the *creation* of networks of relationships and how matter, energy, and information are *processed* across those networks. This distinction corresponds to structural and dynamic patterns, discussed in the *Introduction Paper*.

The standard analytical techniques of Neoclassical theory, which are largely based on classical physics, are not well suited to modelling patterned phenomena. However, they can be modelled computationally, including via agent based modelling. This approach has been used for decades in the complexity sciences to model patterns of relationships and how resources and information can be processed across such networks.

1.2.4 Economies have a stratified ontology

This principle arises from the concept of emergence, which was discussed in the *Introduction Paper*.

The reference to 'stratified' comes from the idea that system-wide phenomena can emerge from the interaction of the system's parts. These system-wide phenomena are framed as if they are 'above' the parts / agents in some hierarchy, hence 'stratified'.

An important point that distinguishes the complexity sciences, which are open to emergent properties, and reductionist perspectives ('reductionism' is defined below) is the view of the former that accords a different ontological status to emergent properties. For complexity scientists, emergent properties are ontologically 'new' and the properties of these phenomena are not reducible to the parts / agents from which they arose. Furthermore, the ontological 'newness' of emergent properties allows for 'downward effects' whereby these properties act on the very agents that gave rise to them.

A classic way of describing this stratification in the complexity sciences is to point out that atoms emerge from the interaction of sub-atomic particles; chemicals emerge from the interaction of atoms; biological entities emerge from the interaction of chemicals; and so on, until the properties of galactic superclusters emerge from the interaction of their constituent galaxies.

Researchers who take a reductionist approach to analysis can also recognise a type of stratification in the sense groups of agents can give rise to system-wide properties. The difference, however, is that these properties are not seen as ontologically 'new' - they are reducible to the parts / agents of the system.

One point worth emphasising is that the claim here is not that all phenomena must be explained through the concept of emergence. There are a wide variety of phenomena that <u>are</u> explainable through reductionism, e.g., if we wish to understand the trajectories of balls on a snooker table; or if we wish to model a satellite in orbit around the Earth. A stratified ontology means we are open to the idea of emergence; it does not mean we reject all reductionist explanations.

Reductionism

The Oxford English Dictionary (OED) defines reductionism as the "practice of describing or explaining a complex (esp. mental, social, or biological) phenomenon in terms of relatively simple or fundamental concepts, especially when this is said to provide a sufficient description or explanation..." (Oxford English Dictionary, 2023).

This is a relatively simple definition which is sufficient for our purposes here. The subject is, however, much deeper than this definition implies and it is an important topic in the philosophy of science. See, for example, the discussions of ontological, methodological, and epistemic reductionism in The Stanford Encyclopedia of Philosophy (2023).

Comparison with Neoclassical Theory

Arnsperger and Varoufakis (2006) point to NCE's reductionist leanings in one of the three axioms they associate with Neoclassical theory:

> To the neoclassical economist ... individual agents ... are to be studied, like the watchmaker's cogs and wheels, independently of the social whole their actions help bring about.

Arnsperger and Varoufakis, 2006, p. 8

This axiom is referred to as *Methodological Individualism* in Arnsperger and Varoufakis' paper but it also corresponds to the definition of reductionism stated above.

NCE has followed a reductionist strategy in a number of ways. First, the interaction of agents in Neoclassical models is typically very limited; and, second, the mental models of the agents have historically been restricted to substantive rationality and exogenous preferences. These two features are typically combined within a mechanistic framing (and mathematics) that exist at the same ontological 'level': there are no emergent properties and the agents behave in a deterministic way.

However, while Neoclassical economists have historically taken a reductionist stance, they have also acknowledged that "social variables, not attached to particular individuals, are essential in studying the economy or any other social system" (Arrow, 1994, p. 8).

This begs the question of how Neoclassical theory explains social structures if, as Kenneth Arrow states, "such categories are in fact used in economic analysis all the time." (p. 1). In this paper, Arrow uses the examples of prices in general equilibrium analysis and the rules assumed in game theoretic analyses to support his argument.

The problem is that Neoclassical explanations of social structures are poor when judged against empirical evidence. They are based on as-if simplifications (following Friedman, 1953) that render them too far removed from reality to be convincing[2] or useful in practical situations.

Perhaps the best example of the Neoclassical approach here is the use of game theory[3] to 'explain' the emergence of organic institutions (conventions and social norms) in economics. Hodgson (2007) points to Field (1979, 1981, 1984) as providing crucial arguments for why such explanations are insufficient: game theorists over-claim their relevance - they are only valid in a very narrow set of circumstances.

Overall, Neoclassical theorists have attempted to explain some emergent properties (and, with it, a stratified ontology) via reductionism but this is futile because the two are incompatible.

1.2.5 Complexity Economics is open to 'generalized Darwinism'

Here, 'Darwinian' is defined by the three features of *variation*, *selection*, and *durability*[4].

There is a substantial literature concerned with whether Darwin's theory of evolution by natural selection applies to social systems, and a comprehensive survey of it is beyond the scope of this paper. Nonetheless, an important question in this literature is whether or not to interpret the above three principles in a very narrow sense, where variation is due to random genetic mutation; selection is about the survival of an organism in some environment; and durability is viewed as inheritance from parent to offspring. If we accept this interpretation then we would clearly reject the use of Darwinian evolution, so defined, for explaining social phenomena.

[2] This is discussed in the context of instrumentalism and realism in Section 1.2.10 below.

[3] Arrow (1994) describes game theory as "[t]he current formulation of methodical individualism" (p. 4).

[4] Different versions of these three principles exist. For example, Hodgson (2002b) and Hodgson and Knudsen (2006) use variation, selection, and inheritance; and Stoelhorst (2007) uses "retention" in place of inheritance because it "takes us further away from the genetic overtones of the term inheritance." (Endnote 1, p. 251).

However, these three principles can be generalized in two dimensions (consistent with "generalized Darwinism" as discussed in Hodgson and Knudsen, 2006): regarding abstraction in the meaning of the three principles, and the 'level' of any Darwinian explanation.

In terms of the first generalization, the three principles can be interpreted as follows:

- variation includes adaptation on behalf of some agent for whatever reason, including via reinforcement learning or conscious deliberation;
- selection refers to "a process of sifting and preservation of fortuitous adaptations." (Hodgson, 2003, p. 89); and
- durability is related to the concept of path dependence, which ensures "that much of the pattern and variety is passed on from one period to the next." (Hodgson, 2003, p. 89).

Consistent with this higher level of abstraction, Hodgson and Knudsen (2006) write "[i]t is not that social evolution is analogous to evolution in the natural world; it is that at a high level of abstraction, social and biological evolution share these general principles." (p. 14).

The second dimension in which the three principles of Darwinism can be generalized relates to the stratified ontologies discussed above. Consistent with this, Hodgson (2002a) writes that it "is possible that some of the reaction against 'biological analogies' is grounded on a mistaken view that theories operate on the one level only." (p. 273). Instead, "Darwinism biology invokes multi-levelled explanations, in which the theory of natural selection is the over-arching and organising theoretical framework." (ibid). This includes the notion of "group selection", i.e., where group-wide phenomena supports the aims (including survival) of the group.

The important point here is that CE is open to the idea of generalized Darwinism, which includes both the abstract interpretation of Darwin's three principles and multi-level explanations.

However, as was the case with emergence above, this use of a Darwinian perspective does not mean that every aspect of an economic system should be explained by these forces. Rather, our analysis is *open* to framing agent behaviour and social change in this way. Also, as Hodgson and Knudsen (2006) argue, generalized Darwinian theories should be viewed as necessary but not sufficient for explaining certain phenomena: we also require a coherent explanation of them.

Comparison with Neoclassical Theory

In addressing this issue, it is important to distinguish between free market economics and Neoclassical theory.

The broader approach to Darwinian evolution as outlined above is compatible with the idea that firms operate in competitive free markets. Firms could be viewed as equivalent to organisms in an ecosphere; they might intentionally adapt to changes in consumer demand; these changes might be sustained for some time; and a firm will 'win' relative to other firms if its adaptation is commercially successful. Firms that do not adapt will 'lose' and might therefore fail.

However, Neoclassical theory is not the same as free market economics. Broadly speaking, NCE's emphasis on stable, equilibrium conditions means it sits awkwardly with generalised Darwinism. As mentioned above, Arthur referred to the Neoclassical approach as "dead, static, timeless, and perfect." (Arthur, 2013, p. 19)[5].

Moreover, it is curious that a number of economists associated with the Neoclassical school had affiliations with socialism. For example, Kenneth Arrow states in Klein (2013) that he had been a socialist in his youth and sustained these views until he entered graduate school, after which "his work was shaped by a deeply leftist sensibility" (p. 268). Furthermore, Klein and Daza (2013) refer to the "market socialists of Abba Lerner and Oskar Lange", two economists who took a broadly neoclassical stance in their work. Lange and Taylor (1938) went as far as to equate Marxist Economics with Neoclassical theory.

Co-Evolution and Co-Adaptation

In the context of 'evolution', it is helpful to be clear about the meaning of *co-evolution* as well as the similar notion of *co-adaptation*.

Janzen (1980) writes that co-evolution "may be usefully defined as an evolutionary change in a trait of the individuals in one population in response to a trait of the individuals of a second population, followed by an evolutionary response by the second population to the change in the first." (p. 611).

This definition pertains to multiple groups of organisms evolving in response to each other.

By contrast, let us refer to *co-adaptation* as the adaptation of two or more agents to each other. More specifically, let us define co-adaptation as "adaptation involving reciprocal changes in two or more agents that affect their interactions." The word "reciprocal" is used here to emphasise the iterative nature of co-adaptation.

In the complexity sciences it is common to refer to agent-to-agent co-adaptation as 'co-evolution'. However, it seems preferable, in a general sense, to distinguish between these two processes in order to minimise confusion and to sustain two different mechanisms in our lexicons.

1.2.6 Economies are non-ergodic

As mentioned in Davidson (1996), "[e]rgodic theory was explicitly expounded as part of the development of the theory of stochastic processes ... In a broader sense, however, ergodicity means the presumption of a preprogrammed stable, conservative system where the past, present, and future reality are predetermined whether the system is stochastic or not." (p. 480).

North (2005) takes an equivalent view, stating explicitly that the economy is non-ergodic in nature:

> An ergodic economy is one in which the fundamental underlying structure of the economy is constant and therefore timeless. But the world we live in is non-ergodic - a world of continuous novel change; and comprehending the world that is evolving entails new theory, or at least modifications of that which we possess. North, 2005, p. 16

North's reference to the economy being non-ergodic can be linked to Arthur's (2013) emphasis on how the economy is a combination of micro-economic behaviour and pattern formation and re-formation.

[5] Related to this, Veblen wrote a paper that asked (and was entitled) "Why is Economics Not an Evolutionary Science?" (Veblen, 1898).

It would be a mistake, however, to believe that complex systems are always re-patterning themselves in an unstable way. Such systems can exhibit epochs of stability, with any re-patterning occurring infrequently.

Comparison with Neoclassical Theory

North's view was that Neoclassical theory is strictly ergodic in nature, stating "the ergodic hypothesis is implicit in much of current economic theory." (North, 2005, p. 19). For North, this meant that "the ergodic hypothesis is a-historical" (ibid), i.e., it runs counter to empirical evidence.

1.2.7 Uncertainty is an important feature in economic behaviour

In economics, the traditional way of describing uncertainty is to refer to Frank Knight's distinction between risk and uncertainty in Knight (1921):

> For Knight, risk was a condition in which it was possible to derive a probability distribution of outcomes so that one could insure against such a condition. Uncertainty according to Knight was a condition in which no such probability distribution existed. Theorizing under the condition of uncertainty therefore was not possible, according to eminent theorists such as Kenneth Arrow (1951) and Robert Solow (1981). North, 2005, p. 13

This distinction between risk and uncertainty is useful but the idea that the latter is concerned only with a lack of probability distribution is not sufficient if we wish to examine *how* uncertainty arises in complex social systems. For example, is a distribution knowable in principle but we just do not know what it is now? Or is the distribution not knowable in principle?

We can also consider different 'sources' of uncertainty. In his research, North referred to three information-based sources: data, knowledge, and limited human cognition. We might also add a fourth, which is when agents' decisions are mutually contingent and an infinite regress problem exists as a result of the agents trying to anticipate each other's actions.

Here, we simply state that CE is open to all forms of uncertainty that exist in the economy.

Comparison with Neoclassical Theory

In the quote above, North (2005) refers to Arrow and Solow who believed that theorizing "under the condition of uncertainty ... was not possible." (p. 13). Furthermore, regarding uncertainty, North writes:

> Economists have themselves displayed a good deal of ambiguity on the subject, largely proceeding as though uncertainty was an unusual condition and therefore the usual condition, certainty, could warrant the elegant mathematical modelling that characterizes formal economics. But uncertainty is not an unusual condition; it has been the underlying condition responsible for the evolving structure of human organization throughout history and pre-history. North, 2005, p. 14

While North refers to "Economists" here, his critique appeared to be directed at Neoclassical economists.

Note that North's reference to "elegant mathematical modelling" points to a conflation about theorizing and the use of mathematics in Neoclassical economics. In general, mathematical techniques can incorporate risk (including stochasticity and probability) but they are not compatible with uncertainty, which might explain why Arrow and Solow thought uncertainty prohibits any theorizing.

However, theorizing does not necessarily have to involve mathematics: it can be conceptual in nature and it can also involve computational models. As Arthur notes, "[t]he objective, we should remember, is not necessarily to formulate equations or to arrive at necessary conditions. The objective, as it is with all theory, is to obtain general insights." (Arthur, 2013, p. 7).

1.2.8 Agents use mental models to make decisions

The complexity sciences generally focus on localised behaviour by agents in complex systems, which means there is typically a focus on how agents receive and process information and make decisions. As a result, complexity scientists are interested in agents' mental models. CE adopts the same approach.

Furthermore, the economic ontology we are interested in includes uncertainty, hence in this paper we take a strong interest in human mental models working under conditions of uncertainty.

In Neoclassical theory, the standard assumption is that agents use substantive rationality to make decisions. The problem we face is that such reasoning is not suitable under conditions of uncertainty:

> To the degree that outcomes are unknowable, the decision problems they pose are not well defined. It follows that rationality — pure deductive rationality — is not well-defined either, for the simple reason that there cannot be a logical solution to a problem that is not logically defined. It follows that in such situations deductive rationality is not just a bad assumption; it cannot exist. Arthur, 2013, p. 4

This raises the question of how human agents reason under conditions of uncertainty. For Arthur, the answer is that people use pattern recognition and simple models to help them make decisions when uncertainty is prevalent:

> Indeed, as Shackle (1991) puts it, "The future is imagined by each man for himself and this process of the imagination is a vital part of the process of decision." One way to model this is to suppose economic agents form individual beliefs (possibly several) or hypotheses — internal models — about the situation they are in and continually update these, which means they constantly adapt or discard and replace the actions or strategies based on these as they explore. They proceed in other words by induction (Holland et al. (1986); Sargent et al. (1993); Arthur (1994)). Arthur, 2013, p. 4

It is important to note here that the word 'induction' has a variety of meanings across different literatures. Arthur (1994) very clearly aligns this word with the broad notion of pattern recognition, which is different to (for example) induction as 'making generalizations from the particular' and from making inferences from data alone. Moreover, Arthur's meaning appears consistent with Holland et al.'s (1986) use of the term.

Comparison with Neoclassical Theory

The approach taken in Neoclassical theory was mentioned briefly above: the default assumption is that agents use substantive rationality to make decisions. This can be viewed as a form of mental model.

Here it is useful to distinguish between two different forms of reasoning: *substantive rationality* and *procedural rationality*, following Simon (1976).

Substantive rationality is used "when it is appropriate to the achievement of given goals within the limits imposed by given conditions and constraints" (ibid, p. 66). This approach is suitable when agents have fixed preferences and a goal like utility maximization: substantive rationality deduces the agents' choices that achieve their goals. In this type of challenge there is no uncertainty[6].

By contrast, "[b]ehaviour is procedurally rational when it is the outcome of appropriate deliberation. Its procedural rationality depends on the process that generated it." (ibid, p. 67). Herb Simon noted that when psychologists use the term 'rational', they are typically referring to procedural rationality. This type of rationality can work under conditions of uncertainty.

Simon also used the assumptions of Neoclassical economics to show how the field achieved analytical reductionism:

> ... the assumptions of utility or profit maximization, on the one hand, and the assumption of substantive rationality, on the other, freed economics from any dependence upon psychology. Simon, 1976, p. 66

Overall, therefore, NCE is focused on a narrow type of mental model: substantive rationality operating under conditions of certainty.

1.2.9 Complexity Economics is open to inter-disciplinarity

One rationale for an inter-disciplinarity strategy is CE's link to stratified ontologies, which were discussed in Section 1.2.4 above. With this in mind, we find that, unlike Neoclassical theory, complexity economists take an interest in psychology, e.g., when understanding agents' mental models. The interest would not stop there: neuroscience and the cognitive sciences would also be of interest in making sense of how people process information, including under conditions of uncertainty.

Equivalently, if economics is (or should be) about identifying social phenomena (e.g., institutions), it would be natural to look at how sociologists think about such things. In the context of a stratified ontology, we might consider the rationale for looking at psychology, cognitive science, neuroscience, and sociology as 'vertical' in nature.

However, we can think of inter-disciplinarity in the 'horizontal' sense also. As mentioned previously, the complexity sciences grew out of the natural sciences, and this has included a range of abstract concepts that relate to complex systems in different disciplines. As emphasised above, we should be

[6] Arnsperger and Varoufakis (2006) referred to substantive rationality as *methodological instrumentalism*. This was the second of the three axioms of Neoclassical theory they identified.

careful mapping between domains but abstract concepts like self-organisation can be useful even if they merely provide inspiration to ask different questions.

Furthermore, other disciplines can be used to help us understand how other researchers have looked at the same - or similar - phenomena. For example, the agency / structure debates in philosophy and sociology appear related to how economists have looked at institutions in economics.

Comparison with Neoclassical Theory

This has been covered in earlier sections: Neoclassical theory is essentially reductionist in nature (recall the quote from Simon above that showed how utility maximization and substantive rationality have been used to "free" economics from any dependency on psychology). As a result, Neoclassical theorists have historically shown little interest in other fields of study.

1.2.10 Complexity Economics values realism and is sympathetic to instrumentalism

We argue here that in complex, non-ergodic systems, instrumentalism has a place but theories that emphasise realism are (i) necessary if we want to bring about change in the real world; and (ii) more likely to prove accurate when faced with novel change than theories that do not.

The debate concerning instrumentalism and realism is extensive within the philosophy of science literature and a detailed evaluation of the many arguments is beyond the scope of this paper. This debate extends as far back as John Dewey who developed instrumentalism in the late 19th Century / early 20th Century as part of his pragmatist philosophy[7]. The Stanford Encyclopedia of Philosophy (2023) contains a more detailed discussion of these origins, under the entry "John Dewey".

It is, nonetheless, helpful to understand some parts of this debate and to consider them in the context of the complexity sciences.

Let us start by defining what we mean by instrumentalism and realism.

> The **instrumentalist thesis** states that theories should be properly considered as just tools or instruments for making observable predictions. Thus, the question of whether a predictive theory is true or false or whether its theoretical terms refer is of little moment for the pure instrumentalist. The usefulness of a theory is determined, therefore, by its predictive scope or range of applicability. Keita, 1983, p. 79-80, emphasis added, footnote 2 removed

By contrast:

> The **realist thesis** ... states that science aims at giving a true picture of the world, and that the theoretical terms of successful and well-confirmed theories which purport to refer to existent entities actually refer to existent entities. Furthermore, acceptance of a scientific theory implies that what the theory states is true. Keita, 1983, p. 80, emphasis added, footnote 3 removed

[7] Pragmatism is discussed further below.

Instrumentalism

Dewey's instrumentalism originated in part from his emphasis on each individual's limited range of experiences in the world, e.g., in Dewey (1925), which is entitled *Experience and Nature*. Our experiences are not only limited: they arise from our own personal histories, which are idiosyncratic.

We can add to this two further limitations, due to cognition and observation. The former emphasises the distance between restricted human cognition and reality[8]. The latter recognises that many phenomena are beyond our ability to observe, e.g., atoms prior to the invention of powerful microscopes; and neurological processes prior to Magnetic Resonance Imaging.

We can contrast these various limitations with a reality that is, from a complexity science point of view, fine-grained[9] and non-ergodic.

This tension between myopic, subjective agents and a complex reality means that simplifications are inevitable in human cognition, e.g., narratives, metaphors, reifications, heuristics, and abstract concepts are used as simplified forms of sense making. Furthermore, in his earlier work, Dewey argued that a broadly Darwinian process (which appears to fit with the generalised Darwinism described above) exists within the mind, resulting in the selection of those simplifications that prove the most accurate[10].

Given the discussions in previous sections of the subjectivity of mental models, non-ergodicity, generalised Darwinism (and the discussion of pragmatism below), we can state that, overall, CE should be sympathetic to instrumentalism as described by Dewey. Furthermore, it should be clear that the combination of simplification and the value of prediction is as relevant in scientific research as it is in our daily lives. All theories are heuristics to some degree.

Before we discuss realism in more detail, it is helpful to frame the difference between instrumentalism and realism via a black box analogy.

Instrumentalism means that the aim of theories is to generate accurate predictions: the patterns within (or components of) the theory, which is like a black box, do not have to correlate with the patterns of the target domain; only the theory's predictions do. We can contrast this instrumentalism with realism by adjusting the black box analogy: the patterns inside the box should describe (thereby correlating with) reality[11].

Realism

Here we look at two arguments in support of realism in economics (and the social sciences more generally).

The first argument is that if a theory is used to bring about change in real world human social contexts, then it is strongly preferable for the corresponding theory to be realistic. The problem with instrumentalism in this regard is mixing causation with correlated patterns.

[8] Heiner (1983), for example, discusses this gap in the context of an agent's *competence* versus the *difficulty* of selecting between preferred alternatives (his 'CD gap')

[9] Related to this, Gell-Mann and Hartle (2007) refer to coarse-grained cognition in contrast to a fine-grained reality.

[10] This appears to overlap with both Hayek's theory of mind (Hayek, [1952] 2012) and Holland's classifier systems (Holland et al., 1986).

[11] This raises the question of whether it is possible to directly describe reality. Addressing this question in detail is beyond the scope of this paper; however, let us agree that we can recognise *degrees* of realism by common sense, e.g., describing a 'lion' as a cat is more realistic than referring to it as a 'planet'.

Consider game theoretic explanations for organic institutional emergence, including one group that frames such institutions as equilibria in games, e.g., Calvert (1995). The equilibrium 'output' of such games appears to correlate, approximately, with organic institutions we see in the real world; however, the mechanisms assumed within Calvert's (1995) equilibria include substantive rationality as a mental model in addition to a range of game-related constraints[12].

Now consider cryptocurrencies as a live example of an institutional 'problem space'. A theory of institutions as equilibria is surely of no use to people managing and developing cryptocurrencies who want pragmatic institutional solutions to the various problems seen in this domain (e.g., fraud and volatility). What is required instead is a theory that is grounded in realistic mechanisms that explain how institutions emerge, to help guide change in that domain.

We can reflect further on the problem here in the context of the black box metaphor above: attempting to bring about change in a social context is like tinkering inside the black box.

If the box contains reasonably realistic mechanisms, we stand some chance of predicting the likely (and desired) outcome but if the mechanisms are non-realistic then we run a risk related to trying to use correlated relationships in a causal manner. This resembles Goodhart's law, which states that "when an empirical regularity starts to be exploited as a basis for economic policy, it is liable to break down" (Black, Hashimzade and Myles, 2009).

Attempting to bring about change in the real world requires real causal mechanisms.

The sensible response to the above argument is that non-realistic theories should not be used in this way. Unfortunately, however, the use of such theories and models (notably those employing substantive rationality) is widespread in Western public policy. See Colander et al. (2008) for a discussion of this point. We might note, also, that Goodhart's law originated precisely because of the attempt to exploit correlated relationships to determine some output (inflation).

The second argument in favour of realistic theories is that, from a complexity science point of view, the value of instrumentalism is limited by the problem of prediction in complex systems. This probably applies less to realistic theories (provided, of course, they are accurate to some degree).

Instrumentalism is compatible with ergodic systems (as defined by North above) because the patterns of such systems do not change, which makes prediction reliable[13]. We can imagine a competitive, scientific, process in which the best predictors are selected over time.

A fundamental problem arises with instrumentalism when a system changes in a novel way, which is to say it is re-patterned in an unpredictable manner. This highlights an inherent tension between pre-conceived non-realistic theories and novel change: the former are meant to predict outcomes and the latter is an unpredictable structural change. Note the problem is not so much about the inability of a non-realistic theory to predict novel change; it is about the resulting re-patterning and (likely) decline in predictive power. The implication is that non-ergodicity leads to non-realistic theories having a shelf-life.

[12] In the case of Calvert (1995) the problem is more serious because his model only demonstrates the conditions under which equilibria exist. He is clear that his model is not concerned with the mechanisms of emergence but this does not stop him from declaring that "*Institution* is just a name we give to certain kinds of equilibria." (p. 74, emphasis included).

[13] Note that non-ergodic systems are not necessarily static: patterns can also be inter-temporal such that these systems change, predictably, over time. Furthermore, non-realistic theories can handle such dynamics: systems of differential equations are a case in point.

A good example of the problem here is provided by standard Value At Risk models in finance, which are used to manage risk in asset portfolios. These models typically use historical data to derive a variance-covariance matrix between the prices changes of the assets in a portfolio. The efficient markets hypothesis leads to an assumption that this matrix is approximately accurate and can be used to choose how much risk a portfolio is exposed to. The problem, however, is that in times of stress, these backward-looking matrices no longer reflect reality and portfolio values can fall much more than was previously deemed likely[14]. Put another way, the patterns assumed inside the VAR ‘black box’ are rendered obsolete by novel changes in the system.

This problem of novel change also applies to realistic theories. However, the proposition here is that such theories are likely to be more robust (or less inaccurate) in the face of novel change. This means they are likely to perform better vis-à-vis predictions in non-ergodic systems than their non-realistic counterparts and, also, they are probably easier to update after some structural change.

Whether this is true, however, will depend on various factors, notably the realism of the pre-existing theory and the nature (and magnitude) of the novel change. A highly realistic theory which is rendered slightly less realistic by some minor change is likely to perform better (and is more easily updated) than a less realistic theory faced with radical change.

The problem mentioned above, that reality might not be sufficiently observable and knowable, is an important qualification here. An ability to observe reality hampers the building of such realistic theories.

To summarise the above discussions, we can say that CE is sympathetic to instrumentalism but, ultimately, there are important reasons for theories to be realistic, notably their use to bring about change in social systems.

Comparison with Neoclassical Theory

It is not possible to firmly align Neoclassical theory with either instrumentalism or realism: the relevance of ether approach differs between researchers and individual theories. Indeed, it is hard to imagine even the most hardened advocate of Neoclassical theory rejecting realism on its own merit.

However, it is probably reasonable to state that Milton Friedman’s famous perspective (which is firmly associated with instrumentalism) has been influential among Neoclassical (and other) economists. The classic text is Friedman (1953) where he uses the example of billiard players to make his case:

> Consider the problem of predicting the shots made by an expert billiard player. It seems not at all unreasonable that excellent predictions would be yielded by the hypothesis that the billiard player made his shots as if he knew the complicated mathematical formulas that would give the optimum directions of travel, could estimate accurately by eye the angles, etc., describing the location of the balls, could make lightning calculations from the formulas, and could then make the balls travel in the direction indicated by the formulas. Our confidence in this hypothesis is not based on the belief that billiard players, even expert ones, can or do go through the process described; it derives rather from the belief that, unless in some way or other they were capable of reaching essentially the same result, they would not in fact be expert billiard players. Friedman, 1953, p. 21

[14] During the 2007-8 financial crisis, some risk managers talked about asset price volatility that should not have been observed over the lifetime of the known universe.

From a complexity science perspective, we can interpret Friedman's argument as proposing a reductionist strategy for making sense of systems that are simple, mechanistic, and ergodic. Such a strategy would be reasonable for these types of system because they can be broken down in to constituent parts (players, table, balls, etc.) with known, predictable relationships. Furthermore, as-if assumptions can be used to approximate how players play the game provided one's aim in understanding is not subverted by these approximations, e.g., simply knowing the trajectory of the balls.

However, given the defining features of complex systems in the *Introduction Paper*, Friedman's description of billiards is a terrible metaphor for economic systems[15], i.e., the premises on which his analysis is based are flawed. Imagine instead if billiards is played by many players, each adapting to each other's style of play, when the balls, table, rules, and aims were also evolving, all simultaneously.

The distance between complex economic systems and Friedman's billiards analogy tells us that instrumentalism should be used in economics with care. This is particularly true in light of the arguments in support of realism set out above.

1.2.11 Pragmatism

The final principle of CE is an association with pragmatist philosophy as depicted by Charles S. Peirce (e.g., Peirce, 1905), William James (e.g., James, 1890), and John Dewey (e.g., Dewey, 1938).

There is an enormous literature on pragmatism versus Cartesian philosophy and positivism; and these approaches span many academic domains. What follows are concise summaries of pragmatism and positivism and short discussions of their relationship to economics.

The underlying assumptions of pragmatism include the ideas that perception is subjective, that reality is socially constructed, and that observers are an integral part of what is being observed. Furthermore, each mind is an assemblage of habits and beliefs; and the idiosyncrasies of personal histories means that minds are heterogenous.

The consequences of these assumptions can be divided into: (i) the implications for our understanding of phenomena; and (ii) the process of research. Regarding the former, our understanding of reality has to be aware of context and also reflexive in that observers should attempt to be aware of their impact on a situation. Multi-perspectivalism is generally valued in light of the heterogeneity of minds.

In general, pragmatists accept that the process of research is influenced by human interests and that in practice it is a human act: within literatures there is a social construction of understanding. Furthermore, qualitative and quantitative modes of research are both valued, and Peirce originated the notion that ideas are developed through *abduction*, which is "the process of forming an explicit hypothesis." (Peirce, [1903] 1998).

There is a comfortable affinity between CE and pragmatism because they have similar ontologies. Most notably, Dewey's pragmatism emphasises a grounded-ness to understanding reality which fits neatly with the bottom-up orientation of the complexity sciences. Related, Blumer (1986) writes that no "theorizing, however ingenious, and no observance of scientific protocol, however meticulous,

[15] Archibald, Simon, and Samuelson do not hold their punches when they write that "[t]he expressed purpose of Friedman's principle of unreality (or as-if hypothesis) is to save Classical theory in the face of the patent invalidity of the assumption that people have the cognitive capacity to find a maximum" (Archibald, Simon and Samuelson, 1963, p. 230).

are substitutes for developing a familiarity with what is actually going on in the sphere of life under study." (p. 39). Also relevant is Commons' (1990) reference to pragmatism in economics as "the scientific investigation of economic relations of citizens to citizens" (p. 157).

Furthermore, the social construction of institutions (including, most importantly, language) and the subjective nature of sense-making both point to a reality which is perceived differently by agents.

Importantly, an affinity with pragmatism should not be mistaken for a wholly incorrect interpretation of this paradigm as anti-scientific, notably as devaluing verification of hypotheses. In fact, by appreciating a range of qualitative information such as interviews, it can be argued that pragmatists have a greater appreciation of verification than positivists.

Pragmatism is frequently contrasted with positivism, which contains a Cartesian duality: the separation of an independent observer and an objective, external reality. In terms of helping us understand phenomena, in principle this reality is comprehensible in the same way to all observers, i.e., a homogenous understanding of the truth is available. There is generally an emphasis on data and quantification given the ambiguity of qualitative information.

In terms of the process of science, the aim of the positivist is to find the objective truth. Moreover, Comte's positivism emphasised simplification, reductionism, and the attainment of laws that demonstrate a causal relationship between phenomena.

Comparison with Neoclassical Theory

NCE is closely associated with positivism (e.g., Katouzian and Katouzian, 1980; Bromley, 2006; Aligica, 2013). Bromley (2006) argues that the problem with this approach is that it is narrow: the "'explanation' of a phenomenon is always bound to the limits set up by axioms and assumptions" (Aligica, 2013, p. 183). Given the association of NCE with "rationality, self-interest, and utility maximization" (ibid), explanations of economic behaviour are constrained by these phenomena.

1.3 Neoclassical Economics as Restricted Complexity Economics

Given the descriptions in the last section, we can interpret NCE - approximately speaking - as a special case of CE. Put another way, if we constrain our approaches in the eleven categories in particular ways, we arrive at CE:

1. Agents in Neoclassical theory use a restricted form of mental processing - utility maximization - whereas CE is open to other forms of cognition, including Simon's bounded rationality.
2. Neoclassical economics is focused on equilibrium systems whereas CE is open to non- and disequilibrium phenomena, in addition to equilibrium.
3. Whereas CE considers the formation of, and allocation within, the economy, Neoclassical theory is focused on the latter.
4. CE is open to a stratified ontology in addition to reductionist explanations, whereas NCE is reductionist in nature.

5. In Neoclassical theory, the economy does not evolve: it is static, or "dead". In CE, the economy evolves over time in a way that is open to generalized Darwinism, although CE recognises that patterns might be stable for periods of time.

6. Included in our understanding of CE is the idea that economies are non-ergodic, i.e., the idea the economy re-patterns itself. By contrast, Neoclassical theory treats the economy as ergodic, i.e., fixed and static.

7. CE is open to uncertainty (and various types and degrees of certainty) whereas Neoclassical theory appears to avoid uncertainty and embraces risk (as defined above in the quote from North, 2005).

8. As will be discussed further below, the mental models mostly used in Neoclassical theory (substantive rationality) are restricted to create stable macro patterns (equilibrium conditions) for which they are also an appropriate response. In CE, mental models can be broader than this, e.g., pattern-based reasoning under conditions of uncertainty.

9. Neoclassical economics is less open to inter-disciplinarity than CE because of its reductionist stance.

10. Neoclassical theory appears to emphasise instrumentalism more than realism, approximately speaking, whereas CE is comfortable with both.

11. NCE's positivism should not be viewed as a subset of pragmatism because the two do not share underlying assumptions of reality. However, pragmatists can incorporate much of the positivists practical ways of doing research, e.g., hypothesis testing and the use of quantitative data.

Consistent with these comments, when contrasting it with Neoclassical theory, Arthur (2013) argues that "Complexity economics, we can say, is economics done in a more general way." (p. 19).

1.4 Internal Consistencies: Complexity Economics and Neoclassical Theory

One of the most important and valuable features of NCE is the internal consistency it demonstrates between its micro and macroeconomic approaches. Arthur (2013) writes:

> economics early in its history ... asked ... what behaviors (actions, strategies, expectations) would be upheld by - would be consistent with - the aggregate patterns they caused. It asked in other words what patterns would call for no changes in micro-behavior, and would therefore be in stasis, or equilibrium. Arthur, 2013, p. 2

The framework created by Neoclassical theory is one of agents maximizing their utility via deductive reasoning (substantive rationality) within a macro environment that contains no uncertainty. Importantly, the agents' combined behaviour generates a macroeconomy in equilibrium *for which each agent's choices are appropriate*. Arthur (2013) notes this is true of general equilibrium theory, classical game theory, and rational expectations economics (p. 2). We can say, therefore, that NCE demonstrates a healthy internal consistency between its micro and macro theories.

The overarching ontology of CE is different to Neoclassical theory in all of the ways listed in Section 1.2 above. Arthur (2013) writes:

> Complexity ... asks how individual behaviors might react to the pattern they together create, and how that pattern would alter itself as a result. This is often a difficult question; we are asking how a process is created from the purposed actions of multiple agents. Arthur, 2013, p. 2

However, even though the ontologies differ, it appears CE also includes internal consistency between micro behaviour and macro patterns, i.e., it provides a coherence equivalent to that seen in Neoclassical theory. We can characterise this in the following way:

- Agents operate under conditions of uncertainty and use mental models to make sense of their environment and to make decisions;
- Micro interactions between agents give rise to patterns (which might or might not be stable); and
- The nature, adaptation and co-adaptation of other agents' mental models, and the emergence of macro patterns, all contribute to the uncertainty that the mental models are an appropriate response to.

If we contrast the two approaches, however, the coherence of Neoclassical theory appears much more fragile than that of CE. If we change the rationality assumption of NCE (even very slightly) the equilibrium outcome would most likely fall apart and it is unlikely that this changed behaviour assumption would be an appropriate response to whatever macro phenomena were then seen. By contrast, CE is open to different mental models being suitable to varying environments and it is open to non- and dis-equilibrium states. In fact, we would expect the agents themselves to adapt their mental models to whatever macro environment they face via a continuous process of pattern recognition.

Finally, it should be clear that the internal consistency of CE is compatible with stable and unstable economic systems (in the latter, patterns are ephemeral and outcomes volatile). Understanding the patterns Arthur referred to (including institutions), their stability, and their relationship with agents' cognitive processes are important challenges that CE appears better suited to than Neoclassical theory.

2 Criticisms of The Complexity Sciences & Complexity Economics

So far this paper has promoted CE as more robust than NCE. Here we turn our attention to criticisms of the complexity sciences and CE.

There appear to be five main criticisms (following Horgan, 1995; Horgan, 1997; and Rosser, 1999):

1. The complexity sciences have not delivered relative to the hype or the promise of / desire for a unified theory of everything.

2. Complexity science is the latest version of three previous fads: cybernetics, catastrophe theory, and chaos theory.

3. Complexity science is too loosely defined - there is no consensus definition of what it is.

4. Evaluation via empirical evidence is very difficult if we treat the economy as a complex system.

5. Complexity science is not necessary in economics: orthodox economics does a good enough job.

The first criticism is articulated in Horgan (1995), repeated in Horgan (1997), and referred to in Rosser (1999). Given Horgan's criticism first appeared in 1995 when the complexity sciences and CE were in their infancy[16], it seems reasonable to ask how such expectations could have been met in a relatively short space of time (versus approximately 200 years of largely reductionist science since the Enlightenment).

Furthermore, this is a relative criticism (delivery versus hype / promise) so it could equally be levelled at those responsible for raising expectations. Some complexity scientists themselves are probably guilty of this, which is perhaps not surprising given they are promoting a new subject in an overcrowded funding landscape. However, popular books like "Complexity" (Waldrop, 1993), while interesting and informative, have probably contributed to the hype[17].

The second criticism was also set out in Horgan (1995) and referred to in Rosser (1999). The premises of this criticism are: (i) complexity science is essentially the same as cybernetics, catastrophe theory, and chaos theory; and (ii) these subjects were correctly found out to be fads by the academic community. The first of these premises is easily rejected by comparing descriptions of the four fields: there are a number of commonalities but they are not identical to each other.

The second premise can be challenged by arguing that cybernetics, catastrophe theory and chaos theory have made useful contributions to research, including ideas like the sensitivity of results to initial conditions. If these fields are to be viewed as fads then it is more likely because they delivered less than people expected, which would make the second criticism identical to the first.

Overall, the criticism that the complexity sciences are the latest manifestation of previous incarnations that proved to be fads appears very weak.

The third criticism is not unreasonable, e.g., Seth Lloyd identified over 45 definitions of 'Complexity' (listed in Horgan, 1997, p. 303, footnote 11). However, the complexity sciences represent a relatively new field / movement that is being used across multiple subjects, which means that, perhaps, this should be expected.

Furthermore, if we align the complexity sciences with multiperspectivalism then this diversity of definitions could also be viewed as a strength rather than a weakness (related to this, Cilliers, 2002 looks at the overlap between the complexity sciences and postmodernism).

The fourth criticism, regarding the problem of empirical evidence in the complexity sciences, relates to the discussions in Section 1.2.10 above. Rosser (1999) notes:

[16] For example, the Santa Fe Institute was founded in 1984 and its economics department in 1988.

[17] The back cover of Waldrop (1993) begins "In a rented convent in Santa Fe, a revolution has been brewing...".

> More generally, some argue that complexity implies a need to seriously rethink the nature of empirical testing in economics. Such a project threatens to lead into deeply philosophical issues such as induction versus deduction, objectivism versus subjectivism, and other difficult conundrums. Rosser, 1999, p. 185

It is difficult to know precisely what Rosser means by this quote but the implication appears to be that delving into the philosophical issues he mentions would necessarily be a bad thing.

One counter-argument to Rosser's point is simply that orthodox economics appears unable to explain a range of empirically-observed phenomena, including the formation of the economy and organic institutional emergence.

The approach taken in this paper is that the economy does resemble a complex system; that the complexity sciences would be useful in developing economic research (if done carefully); that empirical testing does require a "serious rethink" as Rosser put it; and that if this opens up "deeply philosophical issues" then so be it if this is a reasonable consequence of framing the economy as a complex system. A preference not to open up particular philosophical arguments is not a good rationale for not treating the economy as a complex system.

The fifth criticism, that the complexity sciences are not necessary in economic research, was discussed in Section **??** above so it will not be repeated here. As mentioned in that section, the complexity sciences deal much better with a variety of phenomena, including structural change, innovation, technology, formation, and organic institutional emergence, than orthodox economics.

Overall, it is telling that none of the five criticisms discussed above are conceptual in nature: in fact, it is noteworthy that critics of CE have failed to criticise through reasoned arguments about abstract concepts. Indeed, we can think of CE as providing a range of new concepts (like those listed in Section **??**) *and* being more generalised than Neoclassical theory. In a sense, it appears *pareto superior* to NCE.

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