Accepted Manuscript

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PII: S0016-3287(15)30013-6
DOI: http://dx.doi.org/doi:10.1016/j.futures.2016.02.001
Reference: JFTR 2096

To appear in:

Received date: 2-8-2015
Revised date: 4-2-2016
Accepted date: 5-2-2016

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Highlights

- The paper provides a comprehensive discussion of the implications and challenges of complexity science for futures studies
- It discusses the benefits to be derived from a complexity-science perspective on the future
- It begins a discussion as to how futures studies can be adapted to take better account of complexity science

Abstract

Complexity science is increasingly cited as an essential component of a Futures Studies (FS) capable of assisting with the wide-ranging and complex societal problems of the 21st century. Yet, the exact implications of complexity science for FS remain somewhat opaque. This paper explicitly sets out the challenges for FS that arise from six complexity science concepts: 1) irreversibility of time 2) path dependence 3) sensitivity to initial conditions 4) emergence and systemness 5) attractor states 6) complex causation. The discussion highlights the implications of these challenges for FS tools such as horizon scanning and weak signals, and sets out the benefits of overcoming the challenges to create an explicitly complexity-orientated FS. The discussion concludes with a set of questions summarising the challenge for FS from complexity science with the aim of stimulating a discussion as to how they can be met. The concluding remarks make some initial suggestions in this regard.

Keywords: futures studies; complexity science; emergence; horizon scanning; scenario planning; weak signals; uncertainty

1 Introduction

Complexity science is increasingly referenced as an important component of a Futures Studies (FS) capable of grappling with the increasing uncertainties of a highly complex and connected world. For example, Wilkinson et al. [1] argue that incorporating insights from complexity science is a 'must have' for consideration of the highly complex, messy and opaque societal problems and challenges of the 21st century. Similarly, in a series of papers in this journal, Samet [2-5] has provided a broad discussion of some implications of complexity science for FS, identifying different schools of thought, varying complexity-based theoretical standpoints, and a range of different applications of complexity.

However, as the heterogeneity highlighted by Samet [2-5] shows, there are multiple viewpoints when it comes to complexity science and its implications for FS, and little common understanding of the specific challenges, lessons and insights that arise from it. Furthermore, the discussion of complexity science, both in FS and more broadly, may seem highly theoretical and esoteric to those engaged in pragmatic efforts to consider the future of government policy or business strategy. In short, the exact implications of complexity science for FS remain somewhat opaque. This paper addresses this issue by explicitly setting out the challenges for FS which arise from six concepts central to complexity science. While it makes some tentative suggestions with regards to how these challenges can be met, the primary objective is to clarify and render explicit the specific issues arising from complexity science so as to stimulate further debate and discussion.

The six complexity-science concepts are: 1) irreversibility of time 2) path dependence 3) sensitivity to initial conditions 4) emergence and systemness 5) attractor states 6) complex causation. We discuss the interactions between the highlighted challenges, showing how meeting one can render it difficult to meet the others at the same time, thereby illustrating the difficulty of creating a consistent complexity-orientated FS. Nevertheless, the paper also highlights the considerable benefits that could be accrued to FS by meeting the challenges and adopting a more explicit complexity-science orientation. These benefits include the cultivation of a nuanced temporal perspective and a more sophisticated understanding of the origins of uncertainty.

For practitioners, the paper draws out implications for several widely-employed tools from the FS toolkit, such as horizon scanning, weak signals and scenario planning. Through discussion of implications for these specific tools and concepts used by practitioners, we clarify and illustrate the importance of complexity science for the evolution of FS as a discipline, and we render explicit the difficulties associated with overcoming the highlighted challenges. The paper concludes with a set of questions summarising the challenges that must be overcome to develop a FS with an explicit complexity-science orientation. We begin by discussing the challenge and benefits stemming from a complexity-science concept of obvious salience to any consideration of the future: the irreversibility of time.

2 Irreversibility of time

The irreversibility of time, while a seemingly simple concept, is one which nonetheless renders complexity science distinct from the mode of thinking which remains dominant in many social sciences, the most obvious example being mainstream economics. This latter mode of thinking originates in the Newtonian paradigm of mechanics, in which phenomenon can be reduced to a collection of atoms, the movement of which is governed by the deterministic laws of nature [6-7]. Under this approach, because of its inherent determinism, systems are viewed as entirely reversible such that, not only is accurate prediction of the future possible, but also exact knowledge of the path taken to the present through the past. Under this mode of thinking, an accurate knowledge of the past implies an exact knowledge of the future, and vice-versa. Complexity science represents a major departure from this Newtonian-based view of the world. Indeed, one of the central figures responsible for some of the early research that is now part of the foundations of complexity science, the chemist Ilya Prigogine, explicitly stated that the more knowledge we have of the world, the more difficult it becomes to continue believing in the determinism and reversibility implied by the Newtonian mechanical system [8-11].

By incorporating the concept of time-irreversibility, complexity science acknowledges that there is no simple relationship between a past trajectory through time and a present set of conditions, leading to a single, unique future. The absence of any one-to-one relationship linking the past and present to a single, identifiable future is of obvious salience to FS; it is the reason the discipline is called *Futures* Studies, with a plural rather than singular ‘futures’. The simplest, yet perhaps most important, benefit for FS from the adoption of a complexity-science perspective is therefore complexity science’s acknowledgement - and, indeed, emphasis - that there are a multiplicity of possible futures. This brings into sharp focus the full extent of the difficulty associated with consideration of which will transpire. Through its incorporation of the concept of time-irreversibility, in combination with other concepts discussed subsequently, complexity science provides FS practitioners and scholars with an important means to conceptualise the origins of fundamental uncertainty, and for framing the discussion on how to grapple with it. At the most basic level, this is the central benefit which would be accrued to FS from the adoption of an explicit complexity-orientation. Complexity science provides the scientific foundations on which to build a recognition of the plurality of the future and the uncertainty associated with this. While this plurality and uncertainty is already recognised by those working within the FS fold, complexity science provides the underpinning scientific reasoning which lays behind it, lending FS theoretical credibility and helping to shape and direct consideration of the future.

Byrne and Callaghan [12 p.187] use the metaphor of the ‘ratchet effect’ to illustrate the problem of the irreversibility of time in human affairs. A ratchet takes the form of a toothed wheel in which the teeth are smoothly curved on one side and vertical on the other. The wheel engages with a pawl. In one direction of travel it is easy to turn the wheel because the pawl climbs the smooth slope of the tooth. The wheel cannot be turned in the other direction however, because the pawl becomes wedged against the vertical incline. There is therefore only one possible direction of travel. Brumbaugh [13] usefully describes this problem in terms that are highly salient to FS, describing the ‘change of modalities’ that occurs as time unfolds. The past, present and future are ontologically distinct because ‘there are no past possibilities and no future facts’ [13], thus acknowledging time-irreversibility and, related to this, the full extent to which the future is undetermined. In sum, time is a ratchet which turns future possibilities into present options. Present options, once taken or foregone, then become past facts[i], with the direction of turn running only that one way, and with no possibility for it to run the other. The complexity science concept of the irreversibility of time, seen in this way, therefore provides a compelling means to understand the ontology of time that underpins FS.

Beyond this, there are several important implications, challenges and benefits for FS which can be derived from time-irreversibility. Irreversibility of time places a premium on making ‘good’ decisions, because many decisions are of a type which cannot be easily undone. Many economic processes, for example, once underway or implemented, become difficult or impossible to reverse. Ayres and Axtell [15] illustrate this problem in relation to technology designed to address the problem of climate change. The choice of a wrong technology (a wrong ‘option’) now may be impossible to reverse later, since the ‘winner’ (the chosen technology) is likely to lock out unsuccessful rivals. Another prominent complexity theorist, W. B. Arthur, has shown that lock in to a seemingly sub-optimal technological outcome can persist even in circumstances in which the unsuccessful rival technologies are superior [16-17]. Essentially, what irreversibility of time brings into focus then, is the 'crucial' nature of many decisions that must be made about the future. Such 'crucial decisions' are the very bread-and-butter of FS.

The non-mainstream economist G. L. S. Shackle [18-22] placed strong emphasis on the problem of irreversibility in relation to decision-making, making a distinction between decisions that are reversible and decisions which are of a more 'crucial nature' exactly because of their irreversibility. 'Crucial decisions', Shackle showed [18-22], are crucial because they change the very circumstances in which the decision is made, such that no future decision can ever be made in similar circumstances again [18]. Herein we see the irreversibility of time, as emphasised by complexity science. The theory of decision making under uncertainty that Shackle proposed to overcome the problem of irreversibility – Potential Surprise Theory [18-22] – was identified by those working on futures research at Royal Dutch Shell in the 1970s and 1980s, and by Shackle himself [23-25], as in 'essential unity' with the practical FS tool known as 'scenario planning' that Shell then used, and which is widely-used today [26 p.215].

The complexity-science concept of the irreversibility of time, then, set in the context of the problem of 'crucial decisions', can therefore be used to theoretically underpin the practical tools widely-used by FS practitioners for consideration of the future. This is an important benefit to be derived from a complexity-orientated FS. Complexity science is a framework able to provide solid theoretical foundations for the practical techniques employed in FS, for which there is often currently an absence of any underlying theoretical justification - a fact that some in the FS field consider to constrain its development as a discipline [27-28]. A challenge for FS from the concept of time-irreversibility lies firstly in ensuring a sufficient taking-of-account of the ratchet-like closing down of options that occurs over time. Acknowledging this highlights the importance of methods for thinking about the future designed to keep options open, such as real-options reasoning or anti-fragility [26, 29]. Maintaining options, however, does not come for free. Just as in complexity science, in which there is a cost in terms of energy that must be paid to maintain order instead of entropy [30], so it is with the maintaining of options when it comes to the future. Leaving options open as long as possible is itself a form of decision with consequences and opportunity costs. A price must be paid in terms of what is possible in the future in order to maintain the present status-quo. Options of one type can only be kept open, or new options created, by closing down options of another type which are time-dependent and require a decision to be made now in order for their beneficial payoff to be realised at a distant point in the future.

Recognising the problem of crucial decisions which lead to irreversibility, a central tenet of the so-called ‘precautionary principle’ for decision-making about the future is that in circumstances of uncertainty decisions should be postponed until further clarifying information is available [31]. In other words, options should be maintained until there is sufficient information with which to make a ‘good’ decision, which time-irreversibility shows to be important, since changes enacted on many focal systems of interest cannot be easily undone. However, for example, *not* selecting a particular technological path in support of carbon-emissions reduction because of fundamental uncertainty, or *not* sufficiently realigning the economy to be less damaging to the environment for the same reason, are themselves decisions with their own long-term consequences. They essentially represent options *foregone*. Maintaining or creating options can only, then, partially assist in dealing with uncertainty, since maintaining options comes at a cost and usually implies a lack of commitment to any one specific option. The concept of time-irreversibility brings this double-edged problem, with which FS must grapple, into sharp relief, highlighting the full extent of its difficulty. The simple complexity-science concept of the irreversibility of time, and the many implications it implies, brings into focus the full range of problems we must face when considering an uncertain future.

3 Path dependence

The complexity-science concept known as ‘path dependence’ is related to, but not the same as, the irreversibility of time. Its incorporation into FS would have some of the same benefits as the concept of time-irreversibility, and it implies some of the same implications and challenges for FS. However, it also brings its own subtle but important benefits, implications and challenges to the problem that is thinking about the future. Based on its name alone, it could be mistakenly assumed that path dependence implies there to be a single path into the future to which a system sticks rigidly, suggesting the possibility of exact knowledge about the future. This is not so; such path-rigidity is nevertheless a subject to which we return later when considering another complexity-science concept: ‘attractor states’. The implications of path dependence are different to this. However, it can perhaps be a difficult concept to conceptualise the implications of, because it might at one-and-the-same time be considered to emphasise both the indeterminism of the future and that the future is subject to an at least weak determinism.

At its most basic, the concept of ‘path dependence’ simply implies that the past influences the future. This tendency is obvious and evident in all aspects of life. Tensions that exist between different countries in, say, Africa or the Middle East are influenced by the past imposition of arbitrary border settlements by former colonial masters. An individual’s past educational investments affect their future earning potential and career trajectory. And as shown by the complexity theorist R. Axtell, distinctive interaction histories and exchange transactions modify prices and lead to particular societal distributions of wealth over time [32]. Indeed, so obvious is it that the past influences the future that according to P. A. David [33] - the scholar who has perhaps done most to explore the implications of path dependence in relation to economic matters - the denial of this tendency in mainstream economics, with its basis in Newtonian mechanics, is one of the central factors indicating its inaccurate perspective on reality. In contrast to this ahistorical perspective, path dependence, then, implies that the future trajectory of a system depends not only on its present state, but also the path it has taken to reach that present state. However, this is *not* to say that the future trajectory of a system will simply continue along the same path that it has taken to the present, implying an absolute determinism. It is only to say that the trajectory of a system in the future is *influenced* by its trajectory through the past to the present.

At a less basic level, the implications of path dependence for consideration of the future become slightly more difficult to conceptualise, but still more important. From this deeper perspective, the concept also reemphasises indeterminism and reconfirms the uncertainty of the future. Path dependence implies that two systems which have exactly the same present state may have taken very different paths to reach that same present state, and that these very different paths to the present, because they influence the future, imply the possibility for very different future paths regardless of the identicalness of the present state. The full extent of the problems we face in considering the future is brought into focus by the consideration that, since any two identical present states can have come about from very different past trajectories, any particular future state that we consider could also result from multiple possible trajectories from the present to that future state. In other words, the state of a focal system of interest at a particular point in time in the future, which, at that time, will be its ‘present state’, could have come about from any one of a large number of paths from the present (i.e. now). This initially implies a double or compounded uncertainty associated with the future: firstly, we do not know what future states will emerge; secondly, even if we did know, we still would not know what path will be taken from the present to that future state.

However, to temper that somewhat pessimistic (for the usefulness of FS as a discipline) view, path dependence suggests that in many instances in which we consider the future we do not face such an irremediable, absolute uncertainty in which any and all outcomes are possible. The uncertainties we face tend to be bounded exactly because they are influenced by past developments and, for exactly this reason, we can garner clues about the future through an examination of how we have arrived at the present [33]. In this respect, path dependence implies a weak determinism that is of use to FS, rendering it possible to consider and anticipate the future. Taking these basic and deeper perspectives together, path dependence, then, on the one hand reemphasises the difficulty faced by those considering the future and stemming from its inherent uncertainty; however, it also emphasises that we can ameliorate this uncertainty through examination of the past. The specific challenge for FS lies in taking sufficient account of the past while ensuring that our consideration of the future is not dominated by it. Overly-focusing on how past developments have led to the present renders it difficult to think about how the future may develop in unexpected ways. However, conversely, focusing too much on the latter (potentially unexpected developments) results in our considerations of the future appearing disconnected from the present and past from which it emerges. Complexity science, especially through the concept of path dependence, provides the means and vocabulary for thinking about and grappling with this problem.

4 Sensitivity to initial conditions

Some approaches within the FS toolkit attempt to overcome these problems by marrying together past and present developments with possible future disruptions by examining ‘weak signals’. Horizon scanning, for example, does just that. The UK government recently established a horizon-scanning unit designed to inform all aspects of government so as to ‘future proof’ government policy-making [34]. This illustrates how FS and its associated toolkit are now penetrating to the highest levels of decision-making, rendering it vital to consider the extent to which the philosophies and tools of FS currently enable a sophisticated grappling with the uncertainty arising from complexity.

The concept of 'weak signals' (also known as 'early warnings') was originated by Igor Ansoff [35]. Weak signals represent early indications that a particular trend or development trajectory is unfolding, the identification of which allows for consideration of actions to mitigate the negative effects of the associated anticipated future in the case it is negative, or to catalyse or consolidate its emergence in the case it is positive. Essentially, weak signals can be considered signs associated with early developments in relation to, for example, technologies, societal innovations, conflicts, cultural shifts etc. [36]. In fact, the aforementioned complexity-science concept of path dependence implies exactly this possibility to anticipate the future using weak signals. Since the past trajectory to the present goes on to influence the future, by identifying weak signals - trends that are building over time through the past to the present - it is possible to learn something about the future. However, another complexity-science concept, known as 'Sensitivity To Initial Conditions' (STIC) tempers this possibility and challenges us to consider whether weak signals are indeed a useful means for considering potential unfolding futures.

In a seminal paper, May [37] showed that a fully-determined process can unfold in a way that renders it indistinguishable from a random process, even though it is fully-determined. This implies that it is often impossible, at an early stage of their unfolding, to distinguish between the traces (weak signals) of an unfolding trend which will lead to important societal shifts on the one hand, and random signals which turn out to be of no significance on the other. This impossibility is known as 'deterministic chaos' [38]. Deterministic chaos is often explicated by reference to the 'butterfly effect' [39] that is perhaps one of complexity science's most widely-known metaphors. A butterfly flapping its wings on one side of the planet causes the outbreak of severe storms on the other side some time later. The tiny initial effect of the flapping is amplified by the non-linear dynamic system in question (the weather system) over time. This amplification is subject to deterministic chaos in the same way as are the simple equations in May [37].

This deterministic chaos comes about because infinitesimal initial differences in the starting coordinates of a focal system at the beginning of a causal process, though initially tiny in terms of their differences from each other, go on to cause very different outcomes once an unfolding causal chain is fully realised. This sensitivity implies that for the FS concept of weak signals to be valid it would have to be possible to measure the initial starting coordinates of a system (its coordinates in 'state space') with absolute accuracy in order to have any sort of inkling as to how a causal chain might resolve itself over the long term. In reality, such infinitely accurate initial measurement will never be possible.

As May goes on to state [37 p.466], the fact that a fully-determined process can possess dynamical trajectories that look like random noise 'has disturbing practical implications'. This is true, we argue, not least for FS and the tools employed by those engaged in it. That a fully-determined process can result in an infinite number of possible future trajectories based on tiny differences in initial conditions brings into question the usefulness of weak signals/early warnings as a concept for considering the future. Unless a trend we are observing is observed with infinite accuracy, it is very difficult to distinguish from random trends which prove unimportant and, even if we could do so, it would anyway have multiple possible trajectories, and which one is ultimately followed is subject to radical uncertainty. Most of the systems we are interested in considering the future of, such as the economy, the environment or the political systems of focal countries, are of such a nature that they are not, and can never be, measured with sufficient accuracy to overcome this problem.

However, complex systems are not only subject to STIC but, as will be discussed subsequently, are also characterised by feedback and attractor states. These concepts tend to imply less pessimism with regards to the identification of unfolding paths into the future based on current and recent 'signals'. They act to reinforce existing paths of development, meaning that many systems of interest to FS are complex in that they have multiple possible outcomes, but not chaotic in the way May [37] describes because the set of possible outcomes is not extremely large as it is under chaos [12, p.19]. Nevertheless, the usefulness of a concept such as weak signals in light of STIC still warrants consideration, little of which has so far occurred in the FS literature. The relative power of STIC to pull systems in multiple possible, radically uncertain directions, compared to the power of the opposing forces of path dependence and positive feedback which reinforce prevailing trends, is something we return to later in this paper as a key question for a complexity-orientated FS.

5 Emergence and the hierarchical layering of reality ('systemness')

Emergence is a further concept central to complexity science, and another with significant implications for FS. Emergence relates to the hierarchical layering and nestedness of systems. Systems are comprised of hierarchical layers, which both affect and are affected by each other. It is this dual function of each layer – both affecting and affected by the layers above and below – which leads to emergence.

For example, in a business setting, a firm is comprised of individual employees. In this particular setting, the individual employee represents the lowest level of hierarchy in the system. The individual employee may work for a particular team in a specific business unit within a broader enterprise, representing three more levels of hierarchy. Moreover, the enterprise is itself a single entity at a higher hierarchical level: that of the industry. The industry, in turn, is part of the national macro economy, which is in turn part of the global economy. Each level is comprised of multiple entities at the lower level which are subsumed by higher level entities at the level above. Higher hierarchical levels *emerge* from lower levels.

However, the behaviour of a higher level in the hierarchy is not reducible to that of the aggregated behaviour of subsumed lower levels and is not, therefore, amenable to understanding through disaggregation into component parts – component lower-level hierarchies and their constituents [40]. Indeed, a team in a business setting, as incorporated in the above example, is perhaps a very good example of this. The complexity theorist D. Helbing has used the concepts and techniques of complexity science to explore the outbreak of cooperation among individuals pursuing their own interests, which is a requirement for a team to function effectively [41]. A well-functioning team in which team members have well-developed, respectful and supportive relationships towards each other, is more than the sum of its individual parts. The work the team is capable of producing is far better than any individual team-member could produce in isolation, as is its productivity. Recall Adam Smith's description of a well-functioning pin factory with a sensible division of labour and the contrast between its productivity and that of an individual pin-maker who has to perform all tasks. This is the essence of emergence – an outcome at a hierarchically higher level that is not reducible to the aggregated outcome at a lower level.

A central implication of 'emergence' for the philosophy and toolkit of FS is the need to take account of both the micro and macro layers of reality, and also the way in which the two co-produce and co-influence each other. In a business setting for example, the actions/strategy of a particular business are constrained by the competition it faces within its particular industry, and also by other exogenous factors such as the state of the macro economy, the availability of skilled labour, or the regulations which apply to the particular industry. These all act to constrain the actions of the businesses within the industry. On the other hand however, a business is not a passive entity incapable of agency, and its destiny is, to some extent at least, within its own hands. So for example, a business might train employees in response to the shortage of skilled labour; or it may lobby government to change regulation that is having a negative effect upon it.

Note that by training employees, some of whom may leave to work for a competitor within the same industry, or by lobbying government to change legislation, which will also be constraining other businesses in the same industry, the business alters the higher-level hierarchical system (the industry) within which it resides. Skilled labour becomes less constrained and regulation becomes less constraining. However, should businesses then engage in actions that are viewed as counter to the general good of society, such as overly polluting the environment, or issuing credit to non-credit-worthy borrowers, the government may then re-impose additional regulation. While this is an action by an exogenous (to the firm and industry) body (the government), it has also partly been brought about by endogenous, micro-level actions (the societally-negative actions of firms within the industry). There is then, a constant interplay between micro- and macro-level outcomes and behaviours.

It is crucial when considering the future, then, to ensure that we take account of the co-production and co-influencing of micro and macro layers of reality. Byrne and Callaghan [12] refer to the assumption that all that matters is micro-level behaviour as a ‘micro-fallacy’. A micro-fallacy is an insufficient taking into account of the constraining and shaping effect of the macro-level system in which micro entities exist and operate. On the other hand, a failing of some methods for thinking about the future is to view micro-level entities, such as individual businesses, or perhaps individual members of society, as passive responders to macro-level, exogenous developments, or ‘shocks’. In line with Byrne and Callaghan’s [12] concept of a ‘micro-fallacy’ we may refer to this opposite extreme as a ‘macro-fallacy’[ii]. A macro-fallacy places insufficient emphasis on individual entities’ – not least, that of individuals or groups of people – agency and power to influence and shape the future.

The danger inherent in overly-focusing on one or the other of the micro or macro aspects in FS – and especially the danger from an over-focus on the macro-level environment – has been well illustrated by Wilkinson and Kupers [42-43]. They show that foresight exercises fell out of favour within Shell Corporation in the 1980s because they were perceived to place too much emphasis on the environmental context in which Shell operated, at the expense of consideration of the company itself, and its own potential actions and strategies. This illustrates the importance of taking account of both micro and macro layers of reality in FS. The interplay between agency and superstructure is the crucible within which the future is forged and the concept of emergence from complexity science challenges us to find a way to take account of the two simultaneously.

6 Attractor states

Complex systems can also be subject to what are known as ‘attractor states’. This is also a concept with important implications for FS. Attractor states, as the name implies, exhibit strong attraction, such that all paths of development that fall within the basin of the attractor end in the same place (i.e. have the same future outcome). The implications of this for FS are perhaps initially in apparent opposition to some of the implications of previously-considered concepts, such as sensitivity to initial conditions, which implies indeterminism and fundamental uncertainty about the future.

By contrast, if a focal system of interest is instead subject to an ‘attractor’, its current and past trajectory does not affect its future end-point or outcome; all trajectories, regardless of the historical direction of travel, result in the same outcome. On the one hand this ultimate form of determinism implies the possibility - at least under some circumstances (those in which an attractor is present) - for absolute certainty about the future, such that error-free prediction is possible. However, if we consider the concept of attractor states in combination with that of the irreversibility of time, the certainty we might benefit from in relation to attractor states is somewhat diluted. As described previously, time-irreversibility emphasises that we travel only forwards in time; therefore, we travel only one of the many possible paths into the future that could be travelled. This implies a difficulty with identifying those situations in which our system of interest is subject to an attractor and there is certainty as to outcome, and those situations in which it is not subject to an attractor and there is no certainty. In effect, in order to be certain of the presence of an attractor, it would be necessary to rewind time and travel several alternative paths into the future, and to note them all as ending in the same outcome. We cannot do so because of time-irreversibility.

This somewhat pessimistic view (for the usefulness of FS) is again tempered, however, by the possibility for retrospection. We may not be able to rewind time and travel an alternative path into the future to see if we anyway end up in exactly the same place, thereby confirming that our focal system of interest is indeed subject to an attractor; nevertheless, we can observe similarities between outcomes that have occurred in the past even when the antecedent conditions prior to those outcomes (i.e. the historical development of the focal system of interest) varied somewhat. The causes of the recent Great Recession, which began with the financial crash of 2007/8, bore some of the same hallmarks as those of the Great Depression of the 1930s that resulted from the financial crash of 1929 [44], as did the outcome in terms of the effect on the economy [45], albeit the damage was somewhat lessened by improved policy responses in the more recent case [45], this latter fact representing evidence that learning from the past can indeed lead to correct and useful anticipations of future outcomes. But the preceding paths of development - the antecedent conditions and historical development of the respective financial systems prior to each crash - were not *exactly* the same, even though the outcomes, and the causes, were similar. Essentially, the financial system, and the broader economy, ended up in a similar place despite somewhat different paths of development to that same end-point. Financial systems appear to be determined by inevitable and relatively frequent busts (as-well-as booms) regardless of their path of development over time, or the regulation (or lack of) created to prevent such outcomes, and regardless of the epoch. The financial system, and the broader economy of which it is part, is of obvious importance to those considering the future, and would appear to be a prime example, if there is one, of a system that seems drawn to the same outcome over-and-over again, as is characteristic of an attractor.

Where an attractor is present, assuming that this cycle is considered undesirable, the problem for those tasked with thinking about the future is one of how to disturb the system sufficiently such that it is pushed out of its current attractor, leading it to behave in a different, perhaps more desirable fashion in the future, under the auspices of an alternative attractor state. However, herein is perhaps where the real uncertainty of attractor states lies, regardless of the certainty associated with knowledge of the end-point of the cycle within the current attractor. First of all, a large disturbance would be required to override the attraction of the current attractor and, secondly, while this may move the system to an alternative attractor, there is no certainty as to what this alternative attractor will be, or whether it will indeed exhibit a more desirable path of development and outcome, as intended.

Attractor states have other important implications for FS. DeLanda [46] suggests that the presence of attractors emphasises the tension between choice and determinism in relation to the future, with any particular end state a system occupies ‘a combination of determinism and choice’ (p.35). Herein we see a further central challenge from complexity science for FS: the challenge to take adequate account of a lack of agency resulting from the determinism of attractor states on the one hand, and choice, or the ability to construct the future as we want it to be on the other. Complexity science can assist in cultivating a more nuanced understanding of agency - the choices we have in constructing the future - and the constraints upon this choice that results from determinism, such as that associated with attractor states. Our actions to construct the future are constrained by determinism, but we nevertheless do have agency and, therefore, the responsibility to make efforts to construct the future that we want. This is something that Shackle [18-22], the non-mainstream economist earlier cited as originating the idea of 'crucial decisions' that is so important in light of time-irreversibility, went to great lengths to emphasise [23]. That we have responsibility for constructing the future that we want - despite the determinism of attractor states which render it difficult to bring about an alternative, more desirable future outcome - implies that our consideration of the future should be as much about what we *want* it to be as what we *expect* it to be. There is arguably a bias in the application of techniques such as horizon scanning and scenario planning towards a consideration of what the future may do to us negatively as passive corks bobbing in a sea of chance driven by a range of factors beyond our control, rather than consideration of how we can construct the future as we want it to be [47].

7 Complex causation

Finally, complexity science challenges FS to incorporate a view of causation that goes beyond the 'conjunction' or 'successionist' [48-49] view that forms the basis of causation in much of economics and social science more broadly. A view of cause as something more than one event precipitating another through conjunction is important from a complexity science perspective for a number of reasons. Firstly, in relation to the positive feedback discussed above in connection with emergence. As Wilkinson et al. [1] discuss, emergence comes about because initially weak feedback loops build over time until the inherent tensions they give rise to generate sudden disjuncture, resulting in powerful emergent effects which disrupt existing trajectories, leading to new future paths. As the name implies, feedback loops are based on 'generative' [48] causes in which an effect feeds back on its own causes, providing the fuel for its further causation, and so on over time. Circular, generative causes are not simple precipitative, cause-and-effect relationships. This latter, simple form of cause is also known as 'efficient cause' [50, 47]. Simple, efficient cause-and-effect relationships are, in many respects, the least important form of cause when it comes to transformation over time. And it is transformation from one state of a system to another with which we are primarily concerned in FS.

An alternative form of cause, as highlighted long ago by Aristotle, is ‘final cause’ [50-52], which relates to human agency since it captures the motivation for a particular act. The motivations behind particular acts or behaviours is a highly important consideration for those seeking to consider possible unfolding futures. Efficient, precipitative cause-and-effect relationships contribute little to an explanation of, say, the emergence of new groups that seek to challenge the status-quo, such as Isis in the Middle-East, or the actions of bankers when engaging in sub-prime lending. Human motivations are a fundamental part of what shapes the future and requires a broader understanding of cause, which complexity science can assist in achieving [40, 52].

Complexity science also places emphasis on non-linearity, as stemming from interactions between causal factors. It is this non-linearity which results in causes that do not pan out in expected, straightforward ways, leading to ‘surprise’ futures – the very bread-and-butter of FS. Sensitivity to initial conditions comes about because of both positive feedback and causal interactions. It is non-linear interactions between causal factors that bring about the amplification that occurs through the feeding back between micro and macro levels of a focal system, leading to deterministic chaos and radical uncertainty.

Complexity science emphasises the importance of contingent causation and countervailing factors. Derbyshire and Wright [26] highlight Loasby [53] as emphasising the provisional and tentative nature of all human notions of cause as a direct result of countervailing and contingent factors. Loasby’s [53] important example is the effect of the chlorofluorocarbons that caused the hole in the ozone layer approximately twenty years ago. Chlorofluorocarbons were thought to be inert because they were tested for reactiveness in laboratories at ground level. What this did not take into account is that at altitude they are no longer inert. Altitude here is a countervailing factor which brings about a change in a causal relationship rendering it different under particular circumstances. The relationship between chlorofluorocarbons and ozone depletion is contingent upon altitude. Such contingency is a major factor in the emergence of surprise futures, as it was in this case.

Complexity science assists in cultivating a broader understanding of this by emphasising contingency, sensitivity to initial conditions, non-linear interactions, and a broader notion of causation based on transformation from one state to another. Aaltonen [54] notes that our best chance to influence the emergence of desirable, positive futures is to recognise that there are different types of systems and that different combination of causal assumptions – in essence, different types of causes – apply across these different systems. In one context a particular type of cause, such as human motivations, may be central. In another, cause may be more straightforward. Complexity science can assist in cultivating sensitivity to causal nuances.

8 The implications, challenges and benefits for Futures Studies from complexity science

The implications and challenges, as well as the benefits, derived from the preceding discussion of six complexity-science concepts, are highlighted in Table 1. Following Table 1 is a series of summarising questions which must be answered in order to realise the benefits of a complexity-orientated FS.

- Given the irreversibility of time, and the fact that we therefore only ever travel a single path into the future, and do not experience the outcome associated with alternative paths, how do we identify the type of complexity-science concept which is dominating the particular focal system of interest with which we are concerned? The implications for the future, and the implications for policy, are likely to differ somewhat if we consider the focal system to be subject to path dependence, sensitivity-to-initial-conditions, emergence or an attractor of one type or another. Particularly in relation to the social systems with which FS is mainly concerned, and in which measurement is far more difficult than it is in natural sciences, how do we identify which of these factors is at play and the best course of action in light of this?

- How do we simultaneously meet the seemingly contradictory needs to mitigate uncertainty by maintaining and increasing options, as required because of time-irreversibility, while also taking concerted action to construct the future as we want it to be, implying a commitment to a single option?

- How do we simultaneously take account of human agency and the ability and desire to construct the future as we wish it to be, alongside the lack of agency associated with the tendency for the future to go on looking like or repeating the past regardless of our many efforts at change, as implied by a complexity-science concept such as attractor states?

- How can we take account of the interaction and feedback between micro and macro layers of reality that leads to emergence? This is important because, as discussed above, FS tools can sometimes over-emphasise one-or-the-other of these two aspects, leading either to what has been identified in this paper as a 'micro-fallacy' or a 'macro-fallacy'.

- How do we acknowledge the indeterminism of multiple possible paths of development, implying a rejection of prediction, while acknowledging the need to consider the timing of possible disruptions to a current path of development, implying a need to engage in an at least weak form of prediction?

- How do we simultaneously take account of the relative power of sensitivity to initial conditions to pull systems in multiple possible and radically uncertain directions with the power of path dependence and attractor states to reinforce prevailing trends?

- To what extent is the concept of 'weak signals' useful for thinking about the future? Is the concept inherently deterministic because it places emphasis on pre-determined trends and deterministic paths of development? It may be more relevant where path dependence is present, or, alternatively, where a focal system of interest is subject to an attractor state. However, where there is a high degree of sensitivity-to-initial-conditions weak signals may be less useful. How do we avoid using weak signals in situations in which they could be highly misleading?

- How can the toolkit of FS incorporate a broader consideration of cause that is not based on simple, precipitative cause-and-effect relationships? How can alternative forms of cause, such as human motivation ('final cause'), play a more prominent role in our consideration of the future?

9 Summary

Complexity science is increasingly referenced in the FS field, both by scholars and those who seek to employ the various tools and approaches of FS for the practical purpose of considering the future. Many central tenets and concepts from complexity science, some of which have been discussed in this paper, have been widely-discussed and written about within the field. Yet, despite this, the exact implications of complexity science for

FS remain both somewhat opaque and disputed. This paper has addressed this issue by setting out a number of explicit implications, challenges and benefits for FS from complexity science. The purpose has been to challenge those who argue for a FS grounded in complexity science to make explicit its implications and challenges and how these can be overcome, so as to realise their aspiration of a complexity-orientated FS.

The paper has highlighted a number of significant benefits that would be accrued from realising this aspiration and creating a genuinely complexity-orientated FS. By bringing together concepts such as time-irreversibility, path dependence, sensitivity to initial conditions, emergence, attractor states and complex causation, complexity science provides the tools by which to consider how the future unfolds as both a continuation and break from the past. Furthermore, it provides the means, as well as the vocabulary, to think about how and when path disruption might occur due to emergent phenomena, and the means to think about how this emergence might be brought about. This is a vital contribution that complexity science can make to FS. Related benefits include a broader and more nuanced temporal perspective and a more nuanced understanding of causation, including countervailing and contingent causation.

On this latter benefit of a more sophisticated understanding of causation, one way in which it may be possible to reconcile the apparent contradictory requirements to take account of the past while ensuring we are not wedded to it in our consideration of the future is by focusing more on causes of different types. The future may differ from the past, but lessons can nevertheless be learned from the causes of past events. Causes of particular types can be repeated under particular contingent conditions, even if the future is not an absolute repetition or continuation of the past. A clear example of this, discussed in this paper, is the credit crunch of 2008 and the similarities between it and the crash leading to the Great Depression some seventy years earlier. While some aspects of the two were very different, what is perhaps more striking is the large number of similarities. Furthermore, causal lessons from the earlier crisis were learned and acted upon in the more recent crisis to prevent it from spiralling into a full-blown depression. This provides optimism that useful lessons from the past can be used to make better decisions in the future. It is, therefore, possible to draw lessons regarding causation from the past, even if it is not possible, in many circumstances, to straightforwardly extrapolate from the past to the future. Through a focus on causes and how these differ under different circumstances the past can beneficially inform our consideration of the future without dominating it.

That the uncertainties we face as a society are increasing over time is undoubted, as is their complexity. It is therefore beholden upon us to consider the means by which we can mould a FS capable of dealing with this increasing complexity and uncertainty. We cannot and should not simply take the tools and philosophy of our discipline for granted, but should constantly seek to consider the extent to which they are fit-for-purpose in light of the challenges we must face. We do not only have some agency with which to construct the future as we see fit, rather than being passive responders to a pre-determined future, but we also have the ability to construct and adapt the discipline of FS so as to better meet the complex challenges of the 21st century. Complexity science can hold the key to the creation of a FS with such capability, but much work remains to be done.

[i] While it is true that past 'facts' are constantly reinterpreted through the lens of the present, there are nevertheless indisputable past actions that were taken or not taken, with consequences. Germany did indeed invade Poland in 1939 with obvious consequences. Major banks were indeed rescued following the credit crunch in 2008, with obvious and on-going consequences for the finances of governments across Europe. There exist, then, past facts that no amount of reinterpretation can deny [14].

[ii] It is worth noting the distinction between 'restricted' and 'general' complexity that Byrne and Callaghan [12] outline by reference to Morin [55-56] since this distinction is important for FS as an explicitly social-science-based discipline. Byrne and Callaghan [12 p.39] similarly distinguish between 'simple' and 'complex' complexity, which are equivalent to Morin's [55-56] 'restricted' and 'general' complexity. From this social-science perspective on complexity, 'restricted' complexity represents an understanding of complexity based on simulation that employs simple, rule-based algorithms, such as genetic algorithms or agent-based modelling. This approach to complexity is particularly associated with the work of J. Holland [30] and, from a social science perspective, provides only a very simple or partial understanding of the origins of complexity in the social world. Byrne and Callaghan [12] and Morin [55-56] suggest such an understanding, and such tools, have their place in an understanding of complexity of use in the social realm, but it is somewhat restricted. The social science perspective on complexity, as described by Byrne and Callaghan [12] would tend to be much broader - hence the titles 'general' or 'complex' complexity - emphasising that causal factors between hierarchical system layers tend to run in all directions [12 p.45], and that complexity originates perhaps most of all from human reflexivity, power-relations and motivations.

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Tab 1 Summary of implications, challenges and benefits for Futures Studies from complexity science

Concept	Implications	Challenges	Benefits
Irreversibility of time	• Change of modalities that occurs as time unfolds • Mutual exclusivity of future paths • Closing down of options over time • Options foregone also have opportunity costs	• Overcoming the tension between, on the one hand, the need to maintain and broaden options but on the other hand, committing to a single, time-dependent option • Difficulty of knowing which complexity-science concept dominates in focal system of interest (since we only ever travel a single, irreversible path into the future)	• More nuanced temporal perspective • Emphasises importance of making good decisions • Brings the concept of 'crucial decisions' to the fore
Path dependence	• Two systems with identical present states may have very different past trajectories • The path taken to reach a present state goes on to influence the future • Intertwining of perspectives of past, present and future	• How can we take account of history without our consideration of the future being dominated by what has come before? • How to simultaneously take account of path dependence and the path disruption that results from emergence? • In the presence of path dependence, how is it that we have agency to construct the future as we want it to be?	• More nuanced temporal perspective • Emphasises future as emergent from present and past • Awareness that interpretation of the present, and how it has come to be through the past, affects interpretation of what might come to be in the future
Sensitivity-to-initial conditions	• Difficulty of distinguishing between randomness and non-randomness because of deterministic chaos • A fully-determined process can have multiple possible outcomes • Inability to measure with infinite accuracy means there will always be a degree of uncertainty	• Is the concept of 'weak signals' useful when considering the future or is it actually dangerous because of its emphasis on pre-determined trends? • How can those trends that subsequently turn out to be important be distinguished from those that do not (i.e. those which are just random)?	• Awareness of the potentially radical uncertainty associated with the future • Awareness that even simple relationships between just a few causal factors can bring about radical uncertainty
Emergence and systemness	• Interplay between micro and macro aspects of reality • What emerges at a higher hierarchical level is not reducible to the sum of the parts of lower hierarchical levels and, therefore, not amenable to traditional forms of 'analysis'	• How can we 'analyse' complex systems so as to consider the future in as holistic a fashion as possible, without resorting to reductionism or understanding by examining individual, focal parts of a system? • How can FS tools be adapted to avoid overly-focusing on either the micro or macro aspects of the focal system of interest, leading to a 'micro-fallacy' or 'macro-fallacy'?	• Emphasises need to account for both micro and macro aspects of reality • Awareness that aggregate-level effects from particular actions or behaviours can lead to uncertain, emergent outcomes not discernible from individual behaviour
Attractor states	• A focal system of interest may be governed by an attractor, implying a repetition of past patterns of development, leading to the same outcome (determinism) • The future can sometimes be guessed because of this tendency for unfolding patterns to repeat, implying a degree of usefulness for 'weak signals' and 'horizon scanning' as tools for considering the future	• To what extent do we have agency to change the future if an attractor is present? What is the relative balance of agency versus non-agency? • How do we disturb a focal system of interest sufficiently to knock it out of an attractor state it has become locked in? • How do we know what other attractor state it will move to and whether that state will be more desirable?	• Awareness that systems can be subject to determinism leading to certainty, not only indeterminism leading to uncertainty • Awareness of the future as a combination of determinism and choice, but the difficulty of bringing about alternative futures • Awareness of why the future often continues to look like the present and past despite considerable effort to change course
Complex causation	• All human knowledge is tentative, subject to revision and uncertain • Surprise futures sometimes occur because of countervailing factors and contingent conditions • Unexpected interactions between causal factors lead to surprise futures	• How can we incorporate a broader set of causes into our consideration of the future? How can FS tools be adapted to take a broader account of complex causation? • In particular, how can we place greater emphasis on human motivations as a cause? • How can we take account of 'generative' causes which lead to positive feedback, in turn eventually leading to path disruptions and shifts to alternative attractor states?	• Broader and more sophisticated understanding of cause • Move away from simplistic, 'efficient' cause-and-effect relationships in FS • Awareness of importance of generative causes • Awareness that different types of cause dominate in different types of system