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Society as a complex system: how can we make the best decisions for our future?

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Abstract

The papers in this volume examine, through the lens of complexity science, some of the major problems that society now faces. Here I review the insights that have emerged, and ask how those insights might be used to help us make better decisions for our economic, social and environmental futures.

Introduction: What is a Complex System?

As spelled out by several authors (e.g. Finnigan, Prokopenko) in this volume, a complex system is an assemblage of components that interact with each other in a non-linear way, so that the *emergent* properties of the system as a whole are different from the summed properties of the individual components. Most ecosystems, economies and societies fit into this category. Those that are discussed in this volume are generally viewed as networks, consisting of *hubs* (biological organisms, people, groups of people, organizations, etc.) connected by *links* through which they interact. Most of the networks are *adaptive*, where hubs or links can change in response to their previous communication history. Links may get stronger or weaker; they may break, and new ones may form; new hubs may enter; interactions may reinforce or undermine.

Computer modelling has become the major tool for helping to understand these processes and their consequences. Economist and complexity thinker W. Brian Arthur, writing in *43 Visions for Complexity* (2017) points out that "in no small way [our understanding of] complexity has come out of the arrival of computers. Before computers, if we wanted to understand systems, we had to treat them as linear, in stasis or equilibrium, predictable, and expressible in equations. Now, with the help of computers, we can look at systems that are nonlinear, not in equilibrium, not predictable, and expressible in algorithms … We are thus finding new insights into real-world systems."

Henrik Jensen, (2017) in the same volume, says: "A saxophone and a tree don't have very much in common. But a jazz band and a forest might very well have … as soon as one realizes that the world is made of interconnected processes … one immediately realizes why complexity science is the most fundamental of the sciences … ".

Real World Complex Systems

An understanding of complexity is fundamental to our understanding of the world, and new insights are certainly needed if we are to make the best decisions in an environment of complexity and uncertainty. As the Hon. David Hurley, Governor of New South Wales, points out in his opening address to the forum, the problems involved are "wicked problems"; that is, "social or cultural *problems* that are difficult or impossible to solve for as many as four reasons: incomplete or contradictory knowledge, the number of people and opinions involved, the large economic burden, and the interconnected nature of these *problems* with other *problems*" (Kolko 2012).

Hurley specifies some of the actual problems: "What will life and society look like in 30, 40 years? Who will be the stakeholders? Time is running out, we haven't got a central authority, this is a self-organizing system, and the people who are trying to solve the problems are often the ones who are creating them."

Wicked problems may not be able to be solved but, as John Camillus pointed out in an article in the *Harvard Business Review* (2008), at least some of them may be able to be tamed. To do so, however, requires a radical shift in the way that we understand and respond to such problems. The contributors to this volume discuss some important examples, with ramifications that extend well beyond the Australian context.

John Finnigan points out that complex systems have two important characteristics that distinguish them from systems that are merely very, very complicated. One is *emergence*. The second is *self-organization*, where the system will tend spontaneously towards some level of organization. Such systems have their own internal dynamics and attractors. So, for example, villages, towns and cities are "attractors in this space of people with a food surplus trying to organize themselves in an efficient way."

For most of the last 10,000 years, says Finnigan, a major attractor has been the "Malthusian trap", where population has stayed constant or changed relatively slowly. Following the Industrial Revolution, mankind has burst out of this trap into a state that Finnigan labels as "open access order," with faster population growth, "faster political and economic development … faster growing economies … more decentralised governments and more of the country's GDP going to support governments and impersonal relationships."

What are the safe boundaries in this era of rapid change? The biophysical boundaries in key areas such as biodiversity, climate change, and ocean acidification were analysed in a seminal paper from members and associates of the Stockholm Resilience Alliance (Rockström et al. 2009) entitled "A safe operating space for humanity". But these are not the only boundaries to be considered. As Raworth (2012) argued several years later, a safe *and just* [my italics] space for humanity requires the recognition of social boundaries as well.

Finnigan argues that these two sets of boundaries are, in some sense, incommensurate, and draws the stark conclusion that *a safe and just operating space for humanity is not an attractor for the human/earth system, at least with the settings that we have at the moment*.

What can we do about this situation? At the moment, not a lot. As Finnigan points out, "it's not easy to reach into a complex system and say that's the lever I need to pull. More often than not, it will have the wrong result. To take one example, sustainable development goals could be self-defeating if the underlying drivers are strongly coupled, so that the pursuit of these goals means that we are making something else much worse." Understanding such interactions must be a major goal of modelling, but there is a long way to go.

Unfortunately, as Brian Spies points out, there isn't much time, especially when it comes to the issue of climate change. Spies reviews the huge amount of evidence available, especially through the reports of the Intergovernmental Panel on Climate Change, and makes the point that the wording of the conclusion on anthropogenic contributions changed from "very likely" in 2007 to "extremely likely" in the 2014 report. The evidence, and the conclusions, can hardly be questioned at a scientific level. Its effect on policy, though, is a very different matter.

Policy, as Spies points out, is largely a matter of psychology, and people's choice of whether or not to "believe" in anthropogenically-driven climate change largely depends, not on the scientific evidence, but on their world view. As Garnaut (2008) pointed out, this makes climate change the hardest policy problem in living memory — one, moreover, where taking small actions to give the appearance of action is the most inappropriate, but most common, response.

Yet, with politicians unwilling or unable to grasp the nettle, that is precisely what is happening. Vested interests, from the oil and mining industries to the Heartland Institute, continue to promote the fallacy that the topic of climate change is controversial and uncertain. Policies for mitigation, such as the economist-supported emissions trading scheme, receive minimal or no support.

The alternative to mitigation is adaptation (Fisher 2015) — recognizing that change is inevitable, and preparing for it. Here it seems that, in the Australian context at least, things are happening, especially at local and State Government level. Local councils are cooperating to develop measures to cope with more frequent storm surges, and planning regulations are being put in place to allow for a possible 1m rise in sea levels.

One promising trend is that big financial institutions are beginning to sit up and take notice. Mark Carney, Governor of the Bank of England, has talked about climate change threatening financial reserves and long-term prosperity, while the Business Council of Australia has prepared a report on pathways to net zero emissions. The Australian financial systems regulator has also recently cautioned firms in the sector about ignoring the risks associated with climate change (ABC News 2017).

But, as Spies points out, there is still no roadmap (in Australia or in most other countries) to look for the longer-term.

Stephen Simpson, head of the Charles Perkins Centre at the University of Sydney, takes a different tack. A major programme at the Centre is the study of obesity. Simpson refers to a British-based foresight map demonstrating all of the factors that lead to an individual having a propensity to become obese (Foresight Obesity System Map 2007). The map has become known in the field as the spaghetti map, and it has in some senses paralysed the field because it is too complicated.

Simpson's answer is to "look for the really simple things … that can have the biggest impact." This seems to be in line with the concept of "influencers" of opinion in complex networks, although this concept has been challenged (Watts 2007). The topic is complex in itself, but certainly there is room to look for simple solutions before bringing the full panoply of methods to bear on the system as a whole. Hopefully, the obesity "epidemic" might prove to be such a case.

John Williams discusses the concrete case of the Murray–Darling basin, and whether it is possible to bring the three big issues — the environment, productivity, and social well-being of its inhabitants — into some level of outcome inside a boundary of a safe operating space.

The problem seems simple — how much water can one take from the system for agricultural and other purposes? But one cannot take more out than is going in, and the rainfall that is the source varies enormously from year to year. Dams can help to even out the situation, but "Dams do not make more water. Rainfall does [this includes snow melt]." There is also the problem of groundwater, and the movement of salt, to factor in.

The river system itself is "a system of connected flood plains, billabongs and anabranches. … So the river system itself [fits the definition of] a complex system, but it's nested inside a complex, highly variable climate system." Furthermore, the climate system is so variable that the ongoing effects of climate change are going to be difficult to detect in the short term.

But the problem can be simplified. Measurements and calculations in the early 1990s showed that no more than 11,600 gigalitres per annum could sensibly be taken, whereas something like 14,000 gigalitres per annum was actually being taken. So in 1994 a cap of 11,600 gL/y was set. But how could this be made to happen in reality?

But "to bring about an environmental reform" Williams rightly points out "you need to find a way to manage the actual social and economic impacts." One way of doing this with the river system is to "buy back" water from willing sellers *via* a tender process, although the impact on towns in the Basin has led to a considerable push-back against this process. Another is to use infrastructure enhancement and subsidies through the private sector to help minimise water use. The details of how this is happening, and the ongoing political complications that it involves, are given in the paper. They provide an excellent example of the communication, persuasion, and tough decisions that are needed to turn scientific understanding into concrete action in our complex socio-economic-ecological world.

Paul Griffiths, a philosopher at the Charles Perkins Centre, expands on the issue of communication, and especially of communicating biological complexity. He makes the important, experimentally verified point that "If we are going to communicate biological complexity, then … audience effects, namely the filter that the audience imposes on the information [through preconceptions and limited knowledge/background] may completely drown out the scientific signal."

Mikhail Prokopenko, who leads the Centre for Complex Systems at the University of Sydney, addresses the practicalities of modelling complex systems. Prokopenko follows Finnigan in emphasising the distinction between complication and complexity, and further emphasised that a key idea in self-organized complex systems is that of conceptualising data into information.

Prokopenko's talk focuses on the modelling and dynamics of cascades and avalanches, with the initial example being that of the triggering of a snow avalanche, with which he drew the parallel of a technological avalanche in the failure of a power grid. A side comment here is that the technological avalanche could be controlled through a design that allowed parts to be isolated — a suggestion similar to that which has been made for the global banking system (Haldane & May 2011).

Social dynamics are factored in *via* the example of people using the infrastructure network — technology, cars, roads — for vacations, and the spreading of epidemics. "The problem," says Prokopenko "is that [when social dynamics enter the equation] there are more and more hidden variables [and] the nature of the interactions is less defined so that it is harder to influence … There is also a self-referencing effect [where] the social behaviour that we are trying to engineer starts to feed back on to the rules of interaction."

Analysis of social dynamics is facilitated by the small-world model (Watts & Strogatz 1998) and the sorts of information transfer that occur within it. *Active information* "provides a clear distinction between the chaotic part of the network and the [predictable] ordered dynamics." *Transfer entropy* "is focused on changes in the system [and] the dynamics of that information as seen from its neighbours (see Prokopenko, this volume, for details). "To guide self-organisation," says Prokopenko "you have to look at [these] information dynamics [and] understand the cascades of information."

Fazal Rizvi focuses on the question of migration, and the fact that "people are dispersed but are remaining connected to a number of different places, often simultaneously and in an ongoing fashion [so that] networks are becoming really important."

Rizvi reports on a survey by ACOLA (The Australian Council of Learned Academies), which asked what contribution Asian Australians (some 16% of the population) were making to the Australian economy. The contribution of the diaspora was seen to be largely positive, but there is still some way to go before we understand "how the wealth of networks contributes to the wealth of nations."

Finally, Joan Leach, director of the Australian National Centre for the Public Awareness of Science, addresses the question of communicating the science of complexity to politicians and the public, beginning with Derek de Solla Price's notion that science itself is now a complex enterprise, and correspondingly more difficult to comprehend.

Another difficulty is that, with many segmented channels of information (and misinformation), audiences have also become segmented, and can choose the source or sources that reinforce their beliefs and prejudices. A third problem is that scientific literacy in the wider community is very low. This means (Fisher 1999) that scientific communication is often a two-step process, first, introducing the concepts, and then, showing how they apply to the problem. By the time that we have reached the second step, though, we have usually lost our audience.

Making the Best Decisions

What practical steps must we take to give ourselves the best chance of making the right decisions for our future in the face of the questions raised by the various contributors to this volume? The obvious recourse is to use computer modelling to help understand and predict the future behaviour of a system, and progress is being made in this direction (Prokopenko, this volume). It may also be possible to combine aspects of classical decision theory with agent-based modelling, and serious efforts are now being made in this direction (Elsawah 2015).

But we also need simpler, pragmatic approaches, and one of the roles of modelling must eventually be to check out the efficacy of these approaches. Three primary candidates are:

i) Simplifying the decision process.

ii) Using different criteria to allow for complexity in making the decision.

iii) Changing the system to improve control, resilience and predictability.

i) Cutting the Gordian Knot

"Make it simple. Make it quick."

Advice of title-winning English soccer coach Arthur Rowe.

One simple approach to solving complex problems was reputedly used by Alexander the Great when he visited the ancient city of Gordium, which stood on the site of the modern-day Turkish town of Yassihüyük, in 333 B.C.E. According to legend, the quasi-mythical King Midas had, some five centuries earlier, tied an ox-cart to a pole by means of an intricate knot that no one had been able to unravel in the intervening centuries. Alexander at first tried to untie the knot and then, when he could not even find an end, solved the problem in a rather more direct manner by slicing the knot in half with his sword.

Gerd Gigerenzer and his colleagues at the Center for Adaptive Behavior and Cognition in Berlin have shown that Alexander's direct, no-nonsense, simplifying approach can sometimes stand us in good stead when it comes to making decisions in complex situations. Rather than trying to allow for the complexities, they suggest, it can often be useful to adopt simple pragmatic rules that work in the majority of cases (Gigerenzer & Brighton 2009).

The beginning point is that our minds are simply unable to digest and process all of the information that might be necessary to reach a perfectly rational decision in the majority of circumstances. *Homo sapiens* ("thinking man") we may be, but Sherlock Holmes's we are not.

Gigerenzer and Gaissmaier (2011) argue that our normal brains have developed (presumably through a combination of emotional and rational experience) to use a range of simple practical heuristics as short-cuts to decision-making. Experiments by his group and others have shown that we can deliberately use such short-cuts ("fast and frugal heuristics") to make better decisions in complex situations. This approach seems to be especially applicable to making political decisions, where data are often inadequate and time can be short (hence the *dictum* "no more than can be written on one side of an A4 sheet").

Four of the major approaches suggested by Gigerenzer are:

Recognition: If faced with a pair of alternatives, choose the one that is most recognizable (this approach can easily be extended to a choice between multiple alternatives). In one study, for example (Ortmann et al. 2008), people with no prior knowledge of the stock market were able to construct portfolios that out-performed professionally managed funds, simply by investing in firms whose names they recognized.

Tallying: Look for cues that might help to make a choice between options, and go with the option that has the greatest number of cues (or the greatest excess of positive over negative cues if both sorts are available).

When hiking or skiing in avalanche areas, for example, there are seven major cues (including whether there has been an avalanche in the past 48 hours and whether there is surface water from sudden warming) that indicate potential for an avalanche. Studies have shown that, where more than three of these cues are present, the situation should be considered dangerous. If this simple tallying strategy had always been used, 92% of historical accidents could have been avoided (McCammon & Hageli 2007).

An interesting exercise in tallying is a comparison between Magnetic Resonance Imaging (MRI) and simple bedside rules for the early detection of strokes (Kattah et al. 2007). The simple bedside eye examination consists of three tests, and raises an alarm if the patient fails any one of these tests. This simple tallying rule correctly detected 100% of patients who had had a stroke (with just one false positive out of 25 patients), and outperformed the complex MRI diffusion-weighted imaging, which detected only 88%.

Take the Best: When faced with a choice between two options, look for cues and work through them in the order of your expectation that they will lead to the best choice. Make the choice on the basis of the first cue that distinguishes between the alternatives.

Satisficing: Search through alternatives and choose the first one that exceeds the aspiration level. This technique has a rigorous mathematical basis (Todd & Miller 1999) that defines the odds of making the right choice — so long as the guesser can make a reasonable estimate of how many alternatives there might be without having to look at them all individually.

All of these simplifying approaches fit with the suggestion of Stephen Simpson (this volume) to "look for the simplest things that can have the biggest impact." But there is an important *caveat*. It is well-established (Scheffer 2009a; Fisher 2011) that *all complex systems carry within their very structure the seeds of sudden change*. Warning signs may be available (Scheffer 2009b), but the timescales for responsiveness of human political and administrative institutions are often slower than the timescale of the change itself (Biggs et al. 2009). This means that simple heuristic responses are not sufficient of themselves; *what is needed is a drastic improvement in the level of flexibility of human institutions so that decisions can not only be made quickly, but also changed quickly in response to circumstances*.

ii) Using Different Criteria to Allow for Complexity in Making the Decision

"Everything should be made as simple as possible, but no simpler"
Albert Einstein (attrib.)

The simple heuristic criteria listed above (and many others that are described in the references quoted) can often be useful in making personal decisions. For the reasons outlined above, they are not quite so satisfying when it comes to making important decisions about big social, economic and environmental questions. Is there some other approach that we could use; one that avoids the Procrustean nature of heuristic decision-making, but which also overcomes the difficulty of assessing "utility," as required by classic decision theory?

Steering a course between such a Scylla and Charybdis of decision-making in complex situations is by no means easy. Three major possibilities for alternative criteria have been explored by Polasky et al. (2011) in a seminal article on future environmental management. These lines of attack are i) The Thresholds Approach; ii) Scenario Planning; and iii) Resilience Thinking.

The Thresholds Approach

Complex adaptive systems usually possess multiple basins of attraction (Finnigan, this volume), which (to mix a metaphor) act as islands of stability — sometimes veritable continents. The thresholds approach ignores these relatively stable or slowly changing environments, and focuses instead on potential transitions between them (*cf* Prokopenko, this volume).

These transitions, which are labelled as *critical transitions* or *regime shifts*, arise because the subtle balance between stabilizing negative feedback processes and runaway processes such as positive feedback have reached a point where the runaway processes take over, sometimes in dramatic fashion. Flood plains, and even whole rivers, may dry up (Williams, this volume). Natural populations may suddenly mushroom, or just as suddenly collapse and even disappear entirely (May 1976, 1977). Technical innovations, from the discovery of fire to the development of the personal computer, can transform our lives in a very short space of time. Banking systems may crash, revolutions may break out, whole societies, ecosystems and economies may suddenly burgeon or just as suddenly collapse. All of these are examples of critical transitions within complex systems, emerging directly from the nature of the system itself (Scheffer 2009a; Fisher 2011).

The thresholds approach offers a screen to rule out actions which modelling and other approaches shows offer a high risk of crossing a threshold. At the least, it allows us to rank actions according to the likelihood of such risk. Computer modelling of such risk goes back to the Club of Rome report *The Limits to Growth* (Meadows et al. 1972), whose predictions still largely held good thirty years later, despite the relatively primitive nature of the original model (Turner 2008).

A particularly important application of the thresholds approach lies in the calculation of boundaries for various variables that affect our planetary ecosystem. One pioneering study, published in the prestigious scientific journal *Nature* under the title "A Safe Operating Space for Humanity," (Rockström et al. 2009) provided conservative calculations for nine variables based on contemporary knowledge, and concluded that three (climate change, the nitrogen cycle, and biodiversity) were already close to or (in the case of biodiversity) well beyond the safe limit.

That's the science. The politics, as many despairing environmentalists and other concerned people will know, is quite a different matter. It is a truism that politicians do not understand how science works, but it is an equal truism that most scientists neither understand nor respect the constraints under which politicians operate. These are practical communication issues that need crucially to be resolved (Fisher 2012; Leach, this volume) before *any* sensible approach to decision-making in the world's complex socio-economic-ecological environment can be undertaken.

Scenario Planning

Scenario planning is science fiction for the real world. It conceptualizes the future by inventing plausible stories, supported by data and modelling, about how situations might evolve under different conditions if particular human decisions are made and acted on. By examining this range of potential futures, decision-makers can assess the robustness of alternative policies, and also hedge against "worst-case" scenarios.

Two contrasting cases (see Polasky et al. 2011) illustrate the potential value of this approach to decision-making in complex situations. In the early 1970s, with oil prices low and predicted to remain so, Shell nevertheless considered scenarios where a consortium of oil-producing countries limited production to drive oil prices upwards. As a result, the company changed its strategy for refining and shipping oil. It was then able to adapt more rapidly than its competitors when the scenario became reality in the mid-1970s, and rapidly rose to become the second-largest oil company in the world.

By contrast, IBM failed to use scenario planning in the 1980s when predicting the market for personal computers, and withdrew from a market that became more than a hundred times larger than its forecasts.

The weaknesses of scenario planning lie in the difficulty of choosing among a large number of possible scenarios and in assessing the likelihood that alternative scenarios (with different degrees of seriousness) will actually arise. Even so, as the above examples illustrate (see also Simpson, this volume), it can be useful as one of a portfolio of decision-making processes, and has the additional advantage that the stories that it tells can readily be understood by non-technical decision-makers. Perhaps this is why it finds such favour with government committees concerned with disaster planning.

Resilience Thinking

One of the key indicators for the nearness of a critical transition in a complex social, economic or ecological system is a decrease in resilience — that is, a decreasing ability of the system to recover from small perturbations (Scheffer 2009b).

Resilience thinking (Fisher 2016) focuses on promoting awareness of such warning signals, and also on the conservation of key processes so that the system is able to adapt most readily to sudden change if and when it arises.

The obvious problem here is that a very wide range of problems and options needs to be considered to make such planning possible. True interdisciplinarity is the key here — not just scientific interdisciplinarity, but social, economic and even political interdisciplinarity.

A second, major problem is that the time scale of most of the warning signs is unfortunately as short if not shorter than the current time-scale of many decision-making processes in society (Biggs et al. 2009), although careful analysis (Dakos et al. 2015) has shown that reliable prediction may nevertheless be possible under the right circumstances.

The difficult, confronting conclusion is that successful planning for our complex future will almost surely require a totally different approach to managing our affairs, and will need new, rapidly adaptive ways of decision-making, such as using the rapid response time of the Internet as a part of the information-collating and decision-making processes (Galaz et al. 2010). Developing such an approach may require a measure of understanding and good will that is currently beyond us, but the decision criteria above (especially if used in combination) at least suggest that there is light at the end of the tunnel, even if there is a train coming the other way.

iii) Changing the System

"A centipede was happy — quite!
Until a toad in fun
Said, "Pray, which leg moves after which?"
This raised her doubts to such a pitch,
She fell exhausted in the ditch
Not knowing how to run."

Katherine Craster "Pinafore Poems" (1871)

The plain fact is that complex systems, from our bodies to our social-economic-ecological environment, run reasonably well on their own self-generated rules for most of the time. We may not understand *how* they work, but there is a case for arguing that our attempts to understand and change them can only too easily make things more difficult (Finnigan, this volume).

It is a case that has some support in the fields of economics, ecology and society. Planned economies have a dismal record. Attempts to alter ecological systems for our own benefit have sometimes proved disastrous, as when the Hawaiian cane toad was introduced into Australia in an attempt to control the destructive cane beetle, only to prove itself to be the much more destructive agent itself. Attempts to set up planned utopian societies have almost inevitably ended in failure.

If we can't easily foresee the consequences of our actions in complex situations, should we not simply leave the situation alone and watch what develops? The argument, cast in mathematical form by Wolfram (1984), has a beguiling appeal, especially if it appears that any action we take has an equal chance of improving the situation or making it worse, and that there is nothing else that we can do.

But often there is something else that we can do, in principle at least. We can change the system.

Predicting change and evolution in even the simplest of networks is fraught with difficulty. The simplest network consists of just two hubs connected by one or more links. Even here prediction and decision-making is not a simple process. If the two hubs represent the partners in a relationship, and one partner responds badly to something that the other has said, there may be a positive feedback process where an argument rapidly develops, or a negative feedback process where the first person apologizes and calms the situation down. The "decision" of whether to use the first or second strategy can depend on other links between the partners, such as previous history. If we make the network bigger, to include (say) the first partner's mother, the relationship with the mother may influence the way that things develop.

When it comes to the many extended networks in which we are all involved, multiple links can influence our decisions and behavior. Our actions in a two-way partnership, for example, may be influenced by the actions of a bank manager at a distant hub, whose decisions about a mortgage application may cause anxiety in a relationship and increase the possibility of arguments.

All of this is blindingly obvious, as is the fact that with increasing complexity the evolution of a complex adaptive network becomes increasingly difficult to predict. What is less obvious is that we can, in principle, control at least some aspects of the resilience and stability of the network by deliberately altering the nature and strength of the links, and removing or adding appropriate hubs.

We are only at the beginning of understanding how this may be done. It is, however, worth making several key points:

1) As pointed out by ecologist Robert May and banking strategist Andrew Haldane in a seminal paper (2011), modular configurations can in principle prevent contagion (from the outbreak of a disease to the collapse of a bank or an economy) from infecting a whole network (be it an ecological network, a social network or a banking network). "By

limiting the potential for cascades," they say "modularity protects the systemic resilience of both natural and constructed networks."

"Modularity" in this context means breaking the system into blocks (sub-networks), with only limited links between the blocks. The problem here is to get economists, ecologists and others to understand the properties of networks, and in particular that those which are most efficient in the short term (sometimes through being non-modular) may carry within their very structure the seeds of long-term instability.

2) Modularity seems like a sound principle, but one must be aware that it is only applicable to certain types of network. It is difficult to visualize, for example, how the concept may be applied to the nested networks that are common in economics, ecology and society.

Nested networks also pose another problem. Paradoxically, the strongest contributors to the stability and persistence of the network as a whole are also those that are most vulnerable to extinction (Saavedra et al. 2011). This stricture applies equally to ecological networks and networks of business firms. Before we start messing around with such networks, we need to know more about why this paradoxical effect occurs.

3) Finally, our understanding of how signals and other effects are propagated through networks (especially those that contain a human element) is by no means complete (Barabási 2003). Why do some YouTube videos, for example, "go viral", while others attract virtually no attention? How do the activities and habits of individuals affect the behavior of the network as a whole? Do people who appear as hubs with many connections really act as "opinion-formers" (the answer seems to be "no" (Watts 2007))? Why and how do some types of information and influence appear to travel through social networks in "bursts" (Karsai et al. 2011)?

These questions were posed just a few years ago and, as the papers from this forum show, we are only just beginning to understand how these processes work. We can only hope that some answers will emerge in time to be useful in solving the serious problems such as climate change (Spies, this volume) and food security (Simpson, this volume) that confront us as we attempt to make the best decisions in an increasingly complex world.

Envoi

There are many important topics that it has not been possible to include in this brief overview. One, implicit in many of the papers from this forum, is the role of game theory, which analyses the paradoxes and problems that come in when a strategy of cooperation would lead to the best outcome for all concerned, but where each party is tempted to try for a better outcome for itself, only to become trapped by its own greed in an inferior situation, like a lobster caught in a pot (von Neumann & Morgenstern 1944; Fisher 2008).

The other major topic that I have not mentioned explicitly is the nature and perception of risk, which enters into many of the decisions that we must make in the face of complexity. This whole article could have been written from that perspective, and may even have been better for it. But it would have become much more mathematical, and others (e.g. Dekkers 2011) have tackled the subject much better than I could have. So I wasn't willing to take the risk.

References

ABC News (2017) Climate change could threaten entire financial system, APRA warns, 17 February. http://www.abc.net.au/news/2017-02-17/climate-change-could-threaten-entire-financial-system-apra/8281436

Arthur, W. B. (2017) Complexity is practical in its insights, in *43 Visions for Complexity*, World Scientific Publishing, Singapore, 3–4.

Barabási, A.L. (2003) *Linked,* Penguin, NewYork, NY, USA.

Barabási, A.L. (2010) *Bursts,* Penguin, New York, NY, USA.

Biggs, R., Carpenter, S.R. & Broc., W.A. (2009) Turning back from the brink: Detecting an impending regime shift in time to avert it, *Proceedings of the National Academy of Sciences of the USA*, 106, 826–831.

Camillus, J.C. (2008) Strategy as a wicked problem, *Harvard Business Review*, May, 1–9.

Dakos, V., Carpenter, S.R., van Nes, E.H. & Scheffer, M. (2015) Resilience indicators: prospects and limitations for early warnings of regime shifts, *Philosophical Transactions of the Royal Society B*, 370, 20130263.

Dekkers, S. (2011) *Drift into Failure: From Hunting Broken Components to Understanding Complex Systems*, Ashgate e-book, http://opac.vimaru.edu.vn/edata/EBook/NH2014/CSDL_CS2014_2/HH0050.pdf

Elsawah, S. *et al* (2015) A methodology for eliciting, representing, and analysing stakeholder knowledge for decision making on complex socio-ecological systems: From cognitive maps to agent-based models, *Journal of Environmental Management*, 151, 500–516.

Fisher, L. (1999) Physics takes the biscuit, *Nature*, 397, 469.

Fisher, L. (2008) *Rock, Paper, Scissors: Game Theory in Everyday Life*, Basic Books, New York, NY, USA, 39–45.

Fisher, L. (2011) *Crashes, Crises and Calamities: How We Can Use Science to Read the Early-Warning Signs*, Basic Books, New York, NY, USA, 53– 91.

Fisher, L. (2012) Shaping Policy: Science and Politics Need More Empathy. *Nature*, 481, 29.

Fisher, L. (2015) More than 70 ways to show resilience, *Nature,* 518, 35.

Fisher, L., Florin, M.-V., & Nursimulu, A. (2016) Governance of slow-developing risks in socio-ecological systems, *Society for Chaos Theory in Psychology & Life Sciences Newsletter* 24(1).

Foresight Obesity System Map (2007) https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/296290/obesity-map-full-hi-res.pdf

Galaz, V. *et al* (2010) Can web crawlers revolutionize ecological monitoring?, *Frontiers in Ecological Environment,* 8, 99–104.

Garnaut, R. (2008) *The Garnaut Climate Change Review*, Cambridge University Press, Cambridge, U.K. http://www.garnautreview.org.au/pdf/Garnaut_prelims.pdf

Gigerenzer, G., Todd, P.M. & the ABC Research Group (1999) *Simple Heuristics That Make Us Smart*, Oxford University Press, Oxford, UK.

Gigerenzer, G. & Brighton, H. (2009) Homo Heuristicus: Why Biased Minds Make Better Inferences, *Topics in Cognitive Science*, 1, 107–143.

Gigerenzer, G. & Gaissmaier, W. (2011) Heuristic Decision Making, *Annual Review of Psychology*, 62, 451–482.

Haldane, A.G. & May, R.M. (2011) Systemic risk in banking ecosystems, *Nature*, 469, 351–355.

Jensen, H.J (2017) It is an illusion to think that things exist, in *43 Visions for Complexity*, World Scientific Publishing, Singapore, 21–22.

Karsai, M. *et al* (2011) Small but slow world: How network topology and burstiness slow down spreading, *Physical Reviews*, *E*83. (http://pre.aps.org/abstract/PRE/v83/i2/e025102)

Kattah, J.C., Talkad, A.V., Wang, D.Z., Hsieh, Y.H. & Newman-Toker, D.E. (2009) HINTS to diagnose stroke in the acute vestibular syndrome. Three-step bedside oculomotor examination more sensitive than early MRI diffusion-weighted imaging, *Stroke*, 40, 3504–3510.

Kolko, J. (2012) *Wicked Problems: Problems Worth Solving* (www.wickedproblems.com)

May, R.M. (1976) Simple mathematical models with very complicated dynamics, *Nature*, 261, 459–467.

May, R.M. (1977) Thresholds and breakpoints in ecosystems with a multiplicity of stable states, *Nature*, 269, 471–477.

McCammon, I.H. & Hageli, P. (2007) An evaluation of rule-based decision tools for travel in avalanche terrain, *Cold Reg. Sci. Tech.*, 47, 193–206.

Meadows, D.H., Meadows, D.L., Randers, J. & Behrens, W.H. III (1972) *The Limits to Growth*, Universe Books, New York, NY, USA.

Ortmann, A., Gigerenzer, G., Borges, B. & Goldstein, D.G. (2008) The recognition heuristic: a fast and frugal way to investment choice? In Plott, C.R. & Smith, V.L. *Handbook of Experimental Economics Results*: Vol. 1 (*Handbooks in Economics No. 28*), North Holland, Amsterdam, Holland, 993–1003.

Polasky, S., Carpenter, S.R., Folke, C. & Keeler, B. (2011) Decision-making under great uncertainty: environmental management in an era of global change, *Trends in Ecology and Evolution*, 26, 398–404.

Raworth, K. (2012) A safe and just space for humanity, *Oxfam discussion* paper, https://www.oxfam.org/sites/www.oxfam.org/files/dp-a-safe-and-just-space-for-humanity-130212-en.pdf

Rockström, J. *et al* (2009) A Safe Operating Space for Humanity *Nature* 461, 472–475.

Saavedra, S., Stouffer, D.B., Uzzi, B. & Bascompte, J. (2011) Strong contributors to network persistence are most vulnerable to extinction, *Nature*, 478, 233–236.

Scheffer, M. (2009a) *Critical Transitions in Nature and Society*, Princeton University Press, Princeton, NJ, USA.

Scheffer, M. *et al* (2009b) Early-Warning Signs for Critical Transitions, *Nature*, 461, 53–59.

Todd, P.M. & Miller, G.F. (1999) From Pride and Prejudice to Persuasion: Satisficing in Mate Search, in Gigerenzer, G., Todd, P.M. & the ABC Research Group (1999) *Simple Heuristics That Make Us Smart*, Oxford University Press, Oxford, UK.

Turner, G.M. (2008) A Comparison of *The Limits to Growth*" with Thirty Years of Reality, *Global Environmental Change*, 18, 397–411 (www.csiro.au/files/files/plje.pdf).

von Neumann, J. & Morgenstern, O. (1944) *Theory of Games and Economic Behavior*, Princeton University Press, Princeton, NJ, USA

Watts, D.J. (2007) "Challenging the Influentials Hypothesis" *Measuring Word of Mouth*, 3, 201–211.

Watts, D. & Strogatz, S.H. (1998) Collective dynamics of 'small-world' networks, *Nature*, 393, 440–442.

Wolfram, S. (1984) Computation theory of cellular automata, *Communications in Mathematical Physics*, 96, 15–57.