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A simple past — a complex future: thoughts from the Heron Island symposium "Complexity, Criticality and Computation"

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Abstract

The big questions, once the sole province of philosophers and theologians, are coming under increasing scrutiny by scientists. In January 2023 a group of such scientists — a deliberate mix of the older generation and young future leaders — met on Australia's Heron Island to delve into such questions as the fundamental relationship between physical and biological sciences, the emergence and principles of consciousness and its relation to artificial intelligence, the rise and fall of civilizations, and even the future of man itself. It rapidly became obvious that we are at the beginning of a journey with regard to such questions. Here I report on the first few faltering steps, and how they may hopefully help lead future scientists to a path that will steer us away from potential global catastrophes.

Introduction

An old scientists' joke describes the reaction of a physicist when asked for a mathematical description of a cow. "Let us begin," says the physicist "by assuming that the cow is spherical."[1]

The joke encapsulates an essential truth — that science has largely been at a loss when it comes to describing complex systems that are more than just the sum of their parts. Our main weapon for understanding such systems, and natural laws in general, has been reductionism: a process where a complex system (from an atom to a galaxy) is simplified, often by breaking it down literally or metaphorically into its component parts, whose individual properties or interactions in pair-wise fashion are then studied and used to predict the behaviour of the system as a whole.

The reductionist and other simplifying approaches have been hugely successful over the past few centuries in helping us to understand how nature operates. But it has always been apparent that most complex systems are more than just the sum of their parts. Complexity arises from internal feedback loops and multi-component, multi-scale interactions within and between systems that range from atoms to galaxies, from amoebæ to elephants, from natural ecosystems to human societies and human institutions at all scales. In all of these cases, the outcome of complexity is *emergent behaviour* that cannot be predicted from the properties and pair-wise interactions of the component parts alone, whether these parts be subatomic particles or biological organisms.

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[1] My Bristol University colleague Sir Michael Berry has, however, performed a contour integration over a real horse (Berry 2010).

But, during the last half-century or so, increasingly powerful computational approaches and fresh insights into the mathematics of networks have made it possible to study complex systems as an integrated whole. So a new field of "complexity science" has emerged,[2] with a host of applications that include town planning, ecosystem management, communication technologies, and the behaviour of human societies.

The new science is particularly important when it comes to understanding and coping with interconnected global threats such as pandemics, climate change loss of biodiversity, and food security. It has also encouraged a re-examination of some of the biggest questions in science, including the nature of science itself.

A group of scientists at Sydney University, led by Professor Mikhail Prokopenko FRSN, are in the vanguard of research into modelling and understanding complex systems. Mikhail, Ian Wilkinson and the Centre for Complex Systems organized a meeting on Australia's Heron Island to examine where science has got to and where it is going.[3]

The Meeting

Heron Island is situated at the southern tip of Australia's Great Barrier Reef, and is so small that it could fit comfortably into Sydney's Farm Cove and not protrude beyond the Opera House. It is home to one of the world's most complex ecosystems — a system that scientists from the University of Queensland have been studying for decades in an effort to understand how it all fits together. The research institute on the island was thus a particularly apt choice of venue for a meeting devoted to understanding progress on how complex systems of all types fit together and function as integrated entities.

The island itself was formed through a complex process where sediment drawn from a reef was swept by shallow waves to a focal point determined by interactions between the waves and the contours of the reef flat. The resulting coral cay, perched on a corner of the reef, is reached from the coastal town of Gladstone by a two-and-a-half hour ferry journey, crossing a channel that was traversed by Captain Cook in 1770. A helicopter journey is now also possible, and sometimes preferred for a return to the mainland by those who have suffered from the waves on the way over.

On arrival, the sandy path from the jetty divides after just a few metres. The fork on the left takes arriving passengers to an expensive resort, dream world for honeymooners and the holidaying older generation. The fork on the right leads through a dense tangle of *Pisonia grandis* (the Giant Pisonia, or Bird-Killer Tree) to the more functional University of Queensland research station, which was home for the week to dreams of a very different sort — nothing less than the role of complexity in determining the past, present and future of human society, mankind and the universe.

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[2] The late Lord Robert May DistFRSN, a pioneer in the field with his seminal papers "Will a large complex system be stable?" (1972) and "Simple mathematical models with very complex dynamics" (1976), expressed a doubt that there is such a thing as "the science of complexity." (Rear cover comment on Len Fisher *The Perfect Swarm* (2009).) But the common principles that scientists are continuing to discover across a range of disciplines, as exemplified by the talks on Heron Island, now more than justify the term.

[3] See the web site https://www.sydney.edu.au/science/our-research/research-centres/centre-for-complex-systems/c3-symposia.html

The group of scientists that met at the research station was also more than the sum of its parts. Chosen by invitation to represent present leaders in the field and the up-and-coming younger generation, the idea was to mix the two in a friendly and stimulating environment where interaction and feedback within and between the generations was not only encouraged, but almost inevitable.

This was not the first time that such a group had been brought together at this venue. The first such complexity conference, brainchild of Ian Wilkinson, Louise Young, and Fabian Held, and based on a course devised by Terry Bossomaier of Charles Sturt University, had been held there eleven years previously under the umbrella Sydney University's Complex System Institute, and had proved to be a great success. A series of biennial "Complexity, Criticality and Computation" conferences, driven by the enthusiasm and dedication of Mikhail, followed at various venues. Now it was time to return to Heron Island, and to an eclectic mix of subjects that included pandemics, the nervous system, consciousness, the changing nature of science, and the origins and future of life, human societies, and the universe itself.

Mikhail's goal was to build the meeting around three big questions:

1. Is biology beyond physics: are there universal principles across both physical and biological phenomena?
2. What are the principles underlying the emergence of consciousness, language and intelligence, and can these principles be applied to develop powerful AI?
3. Are there fundamental physical constraints guiding the rise and fall of civilisations?

These questions to be considered in the context of a set of practical issues:

- Critical phenomena, singularities & entropy
- Brain and mind
- Survival of the fittest
- Pandemic/crisis modelling
- Why do civilisations fall?

An eclectic mix indeed. To the accompaniment of some 30,000 mutton birds (*Puffinus tenuirostris*), screeching day and night in their burrows, the participants set forth on an exhilarating ride of new, and sometimes revolutionary ideas. Here I share the ride, and outline some of the main ideas that emerged across a range of fields too broad for most minds to encompass, but providing cross-disciplinary fertilization upon which the new and rapidly emerging science of complexity — possibly the most important scientific discipline of the century — will be built.

The Ideas

Let me begin with two caveats. The first is that it is impossible in a short article to cover all of the topics that were presented. What I offer here is a personal selection of those that I believe readers of the *Journal & Proceedings* will find most interesting and/or will feel to be among the most important.

The second caveat is that, even with this selection, it is still impossible to go into much depth and detail about the chosen ideas. Many of them have deep roots that require equally deep consideration, and some require specialist knowledge of the field concerned. What I have thus attempted to do is to offer a taster of what the ideas are *about*, with major references for those who wish to follow them up. The ideas are often a stimulus, rather than a final solution. Be prepared for the ride of your life, and make sure that your seat belts are fastened.

I have divided the ideas into four broad categories: *Beginnings and Endings*; *The Brain*; *Change*; and *Practicalities*.

Beginnings and Endings

Author, broadcaster and all-round scientific savant, **Paul Davies**, launched proceedings with a dizzying array of fundamental questions (Davies 2004; Lineweaver *et al.* 2013) that went back to the very beginning of the universe and took us through to its end. What are the laws of physics and where do they come from? Is Newtonian dualism (of force and matter, implicit in the equation force = mass × acceleration) correct? Have the laws of physics always been the same, or may they have been different in the past and may they change in the future? Is there an arrow of time, and does complexity increase along it? How does this relate to the Second Law of Thermodynamics and the postulated increase in *dis*order with time, leading ultimately (as Lord Kelvin suggested in 1852) to the "heat death" of the universe?

Founding member of the Santa Fe Institute, **Stuart Kauffman**, offered potential answers to these questions in a fascinating talk based on a trilogy of staggeringly original, very recent papers (Cortês *et al.* 2022; Kauffman 2022, 2023) (the most recent had not even appeared in print at the time of the Heron Island symposium, where arguments were presented to a scientific audience for the very first time). In these three papers, Kauffman argued that:

- In a universe that contains life, physical laws do not and cannot provide a complete explanation for everything that occurs. As Stuart claims "We cannot explain the evolution of the biosphere using physicals alone. No law entails that ever-creative evolution."
- A Fourth Law of Thermodynamics is thus required whereby, at constant energy input, the biosphere will construct itself into an ever more localized sub-region of its ever-expanding phase space
- We are facing a third major transition in science beyond the Pythagorean dream that "All is number" and beyond the subsequent number-based Newtonian physics, to a phase where the emergent creativity of an evolving biosphere is also taken into account.

Central to these arguments is the notion that the ergodic hypothesis (which postulates that all accessible microstates of a system have an equal probability of being occupied over a long period of time) fails for biological systems, where the vast majority of potential biological states (organisms) are never realized. Since the Second Law of Thermodynamics relies on the truth of the ergodic hypothesis, it may therefore be open to challenge once biological systems enter the picture.

The ergodic hypothesis may equivalently be stated in terms of a physical concept called *phase space*, where each possible combination of defining variables (e.g. position and momentum) for all the components corresponds to one unique point. The ergodic hypothesis means that the system spends equal amounts of time in equal volumes of phase space.

Phase space entered the picture in a different way when **Geraint Lewis** pointed out (Barnes & Lewis 2021) that the beginnings of the universe must have been at a single very rare point in phase space. If things had been just slightly different, he argued, the periodic table would now consist of just two elements — iron and nickel. “But,” says Lewis, “we won the multiverse lottery, with selection over a myriad of universes that has allowed us to live in a complex universe that has made complexity from order, and filled the periodic table with elements.”

Archaeologist **Roland Fletcher** brought us back to earth with a thump when he pointed out that the rise and fall of civilizations most likely depended on issues of complexity. It’s not a new idea. As I have mentioned in an earlier article for the *Journal & Proceedings* (Fisher 2018), the historian Joseph Tainter has proposed the fall of the Roman Empire was due to “the fact that the empire had reached a level of complexity that rendered it susceptible to small perturbations.” But Fletcher, an expert in the evolution of the Angkor and Khmer civilization, has made the argument a lot more concrete, and has identified three great transformations in human civilization over the centuries:

- Agriculture and sedentism
- Managed human labour and agrarian urbanism
- Machine production and industrial urbanism.

Fletcher’s original observation has been that each of these transitions occurred at successive order-of-magnitude increases in the number and density of people aggregated within centres of population (Fletcher 2020). On this model, he argues, we may expect the next transition (away from the age of metals and metal-based products) some time within the next two centuries.

The Brain

The big ideas involving ergodicity and phase space were brought down to earth by **Valentina Baccetti** with her talk on changes of state in the human brain. Baccetti described recent studies which showed that the statistics of ergodicity could be used to accurately model these transitions in a neuromorphic system (e.g. the brain) close to its critical point. Put in less abstract terms (Caravelli *et al.* 2021), a circuit containing simple elements and based on memristors can give rise to intricate emergent behaviours that mimic the behaviour of real networks such as the neural network of the brain.

The brain very likely operates near criticality (i.e. in a state where a small fluctuation can drive a major change) according to Sydney University modeller, **Mac Shine**, who is studying the complex topological organization of the brain. It appears that the emergent dynamics of the inherent circuitry of the brain might shape complex, adaptive behaviours (John *et al.* 2022), which require robustness, flexibility and unity. These three signatures are well-aligned with the structural and functional interactions between the thalamocortical system and the cerebellum, basal ganglia and superior colliculus, respectively.

One of the most exciting big ideas was to bring to actuality the concept of using *reservoir computing* to model and mimic the behaviour of the human brain. The basic, very abstract idea[4] “lies in leveraging a fixed non-linear system, of higher dimension than the input, onto which an input signal is mapped. After this, it is only necessary to use a simple readout layer to harvest the

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[4] See https://martinuzzifrancesco.github.io/posts/a-brief-introduction-to-reservoir-computing/

state of the reservoir and to train it to the desired output."

This very abstract idea was brought into concrete reality by **Caravelli & Kuncic**, who constructed a working reservoir computer from a stack of short lengths of silver wire, each coated with a very thin layer of insulting polymer (not unlike conducting neurons coated with myelin sheaths). On the application of an electrical signal, the wires produced dendritic growths that penetrated the polymer coating and eventually made electrical contact with neighbouring wires, first through quantum tunnelling, and eventually through direct contact. This reversible process permits the assembly to "learn" in response to feedback (Hochstetter *et al.* 2021). **Michael Small** offered a rigorous analysis of this process, and introduced a key idea of the shortest description length being the computationally most efficient (Thorne *et al.* 2022).

What about the efficiency of the brain itself? **Daniel Polani** argues that its evolution may be driven significantly by the conflicting needs to process information efficiently while maintaining effectiveness in the use of that information. In this "perception-action loop," information that is extracted from the environment comes in many cases with extraneous information that is not need for the task in hand. An efficient organism will use this "piggyback information" to help with other tasks where it may be relevant.

Polani argues that "the effectiveness of the action-perception channel is a proxy for the organism sitting in a good sensorimotor niche, and when it doesn't, driving it to move there. This can provide a good direction for behaviour whenever no obvious overriding drives control the behaviour" — a process that he calls "empowerment" (Volpi & Polani 2020).

Change

The Santa Fe Institute's **Michael Lachmann** argues that evolutionary theory has much broader application than just biology, offering nuclear decay, the growth of snowflakes and the evolution of planets as examples. "Since the explanatory power of evolutionary theory lies in explaining the formation of function/functionality/purpose," he argues "this means that these are generated in many other areas. Thus in thermodynamics/statistical mechanics there is a process of conversion of free energy into functional information, related to the conversion of order into complexity that Paul Davies discussed."

But Michael argues that we can go further. "If we give up considering evolution as happening just at the level of individuals, and instead [focus on] on lineages of information, it will apply much better to how biology works, [and] will also apply much better to other systems, such as the free market, culture, etc. These lineages of information can also be information about how to be a good group, so it includes the regular view of levels of selection" (Sharma *et al.* 2022).

I cannot here go into the ramifications of the many informal discussions about consciousness and the nature of mind, but must make mention of **Michael Harré**'s work in marrying game theory and artificial intelligence into the beginnings of a new theory of mind (Harré 2022). An important step.

Practicalities

The improvement in our understanding of complex systems has come largely from increasingly powerful computational methods and the use of big data.

Progress in computation has largely consisted, not just in speed, but in finding really novel, efficient ways to understand and predict the behaviour of complex systems using computational methods. This has often involved the analysis of big data sets, although this is not without its dangers. Seeking for patterns in data is the basis of Baconian science, and it is perilously easy to forget that correlation does not imply causation. My ecologist daughter once pointed this out when she "demonstrated" that sheep farmers were migrating from New South Wales to Victoria and turning into letterboxes. According to Government reports, the two numbers were identical.

Fortunately, our theoretical understanding of complex systems is progressing, and it thus becomes possible to use the correlations from big data as a basis for hypothesis, rather than jumping the gun and taking them as the direct basis for conclusions. **Eduardo Altmann** made a related point with regard to some well known statistically-based "laws," such as Zipf's law for word frequencies, or even the frequency of scale-free networks. Many such "laws" (of which there is now a plethora) are in fact influenced by unexpected correlations in the observations, and need careful statistical testing and understanding (Altmann & Gerlach 2015).

Metaphorical thinking can be quite useful if handled carefully, as **Mikhail** showed with his overview of thermodynamic models of complex systems and the efficiency of self-organization, with examples ranging from the thermodynamics of collective motion near criticality (Nigmatullin & Prokopenko 2012) to the growth of Greater Sydney (Crosato *et al.* 2018). The main point of Mikhail's talk was to suggest that *self-organization* is ubiquitous because it brings "thermodynamic efficiency," providing a gain in predictability per amount of additional work at some sweet spot (e.g. the critical behaviours of swarms, etc.), as opposed to the lower efficiency demonstrated by extremes of *randomness* (low predictability gain and low additional work) or *perfect order* (high predictability gain but high additional work).

Big data can also be used to understand and handle details of pandemic spreading (and in fact spreading and chains of many types) as **Carl Suster** and **Rebecca Rockett** (Rockett *et al.* 2020) showed with their work on genomic surveillance and the role of genomic differences in the occurrence and severity of COVID-19, **Sheryl Chang** through her work on population heterogeneity and interdependencies in pandemic spreading (Chang *et al.* 2022), and **Sara del Valle**'s highlighting of the importance of social interactions in supply chains, also in the context of pandemic models (Beesley *et al.* 2023). In a different context, **Arunima Malik** showed how climate change is already affecting food supply chains in a differential manner across the various sectors in a world already full of socio-demographic inequalities (Malik *et al.* 2022).

The pandemic, with all of its negatives, at least offered a chance to test, and to demonstrate the success of, agent-based computer models, which simulate the behaviour and interactions of multiple individuals. **Tim Germann**, a pioneer in the use of such models during the influenza pandemic of 2006 (Germann *et al.* 2006), emphasized their successful application (unfortunately often disregarded by politicians) during the COVID pandemic.

One aspect of science that non-scientists have become aware of during the COVID-19 pandemic has been the effective replication (R) number.[5] A very important insight from **Joel Miller** was the importance of individual action when this number is close to one (Althouse *et al.* 2020).

The biggest question of all: does man have a future?

Most readers of this article will be aware of the Fermi paradox. Proposed by Enrico Fermi during a lunch-time conversation at the Los Alamos laboratories sometime shortly after WWII (Jones 1985), it asks of extraterrestrial life forms "Where are they?" As argued in detail by Michael Hart in 1975, interstellar travel should be feasible for a technologically advanced civilization, and the resultant migration should fill a galaxy within a few million years — a very short time compared with the known age of the Milky Way. Given that the conditions for the formation of life seem to be relatively common among the increasingly discovered number of planets, why have we had no contact with any of these civilizations?

A terrifying potential answer, proposed by Robin Hanson in 1998, is *The Great Filter*. Put simply, a civilization must undergo a series of steps/transformations in order to reach a stage where interstellar travel and colonization of distant planets become possible. Since such colonization seems not to have happened, at least one of those steps must be very improbable, so that civilizations become locked down, or even exterminated, prior to that stage. Hanson suggests that pessimistic scenarios like nuclear war, ecological disasters or (prescient for 1998) the takeover of machine intelligence may form part of this process. (I would add personally that overcoming the constraints to cooperation exposed by game theory may be the biggest problem of all[6] (Fisher 2008).)

Perhaps, as argued by astronomy writer Doug Adler (2020) "the Great Filter might be a consequence of technology itself. Perhaps advanced civilizations usually eradicate themselves via some sort of technology run amok … Humanity is already more than capable of destroying itself via global thermonuclear war. And sadly, it's possible that such extinction is virtually inevitable throughout the cosmos" — a scenario that was neatly encapsulated by Isaac Asimov in his remarkable 1958 short story "Silly Asses."

The Great Filter and The Nature of Consciousness were two of the biggest questions that preoccupied our after-dinner discussions on Heron Island. Many of the talks that I have listed under "practicalities" may in fact be reinterpreted as modelling Great Filter events (thanks to Mikhail Prokopenko for this suggestion), and attempting to understand such events and their consequences better. If the Great Filter hypothesis is anywhere near correct, as it certainly threatens to be on the only planet where we know for certain that life exists, the big ideas that Mikahil proposed at the beginning — Is biology beyond physics?; Consciousness and the emergence of AI.

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[5] The effective reproductive number (R) is the average number of secondary cases per infectious case in a population made up of both susceptible and non-susceptible hosts. [Ed.]

[6] See Diamond (2011) for his explanation of the disappearance of trees on Easter Island and the disappearance of European settlers on Greenland. [Ed.]

How do civilizations rise and fall? — assume an even greater importance. The answers are crucial to our future, and perhaps to our very survival. A major objective of the Heron Island meeting was to help pass the torch for illuminating these answers on to the next generation of researchers. We can only hope that, as with the last generation that has laid the foundations, the next generation will build a structure that keeps us safe in the face of such problems as climate fragility, future pandemics, the threat of nuclear war, and the conglomeration of social problems driven by the relentless pursuit of individual self-interest at the expense of cooperation and integrated action. The omens may not be promising but, on the evidence of Heron Island, the talent is certainly there (see also a perspective by PhD student Christina Jamerlin[7]).

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