A Multidisciplinary Approach to Complex Systems Design

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Discipline of Applied Mathematics

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To Eleanor, for ensuring this thesis did not consume me.
I may not have gone where I intended to go, but I think I have ended up where I intended to be.

Douglas Adams
Declaration

This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

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Date: June 18, 2007
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During my candidature two courses were influential: Introduction to Complex Systems taught by Yaneer Bar-Yam and Cognitive Science taught by Gerard O’Brien and Jon Opie. I am sure they would each recognise their influence in this document, and I thank them for challenging my theories and sharing some of their own.
Lastly and perhaps most importantly I would like to thank my coauthors, whose ideas have interwoven with my own to create a whole that is surely greater than the sum of its parts. The joint papers that have been published during my candidature include:


Even though [24, 139, 209, 271, 325] have not contributed directly to this thesis, my involvement in a wide range of complex systems modelling studies provided an essential grounding for my contributions to the theory of complex systems.
Abstract

The design and management of organised systems, comprised of dynamic interdependent collectives of autonomous agents, is the kind of problem that the discipline of complex systems is intended to address. Nevertheless, conventional model-based applications of complex systems may be of limited utility when the problem is also data-poor and soft. In this case, a quantitative model may be at best meaningless; at worst harmful. Systems approaches, such as soft systems methodologies, have been developed that provide some guidance in this domain. However, these alternatives do not utilise the exact techniques of complex systems, preferring to abandon mathematical representations altogether. It is the aim of this thesis to advance a “conceptual analysis” approach to complex systems design that exploits deep insights from the mathematics of complex systems, without building explicit models of the underlying system. It is argued that this approach can extend the domain of applicability of the discipline of complex systems into situations where quantitative data is unavailable, and human and social factors are significant.

Conceptual analysis of complex systems is inherently multidisciplinary, because it is broader than the foundations of any single conventional discipline. This is reflected in the structure of this thesis, which spans the philosophy, theory and application of complex systems. Part I on systems philosophy develops an understanding of representation, which sheds light on the utility and limitations of models. The history of the systems movement is then surveyed, systemism is distinguished from both individualism and holism, and ‘system’ is defined. Complex systems is contrasted with both early systems theory and contemporary systems approaches.

Part II on complex systems theory firstly relates the major theoretical concepts within a rigorous information theoretical framework. They include complexity, edge of chaos, self-organisation, emergence, adaptation, evolution and self referentiality. The central systems concept – emergence – is then examined in depth beyond its information theoretic interpretation, leading to a concise definition of emergent properties and emergence. A new framework for understanding emergence in terms of scope, resolution and state yields substantial novel insights. It is shown that emergence is coupled to scope, in contrast to the conventional explanation that relates levels of description.

Part III applies the preceding philosophical and theoretical framework to real-world problems in the defence and security arena. In the first example, the theory of multi-scale complexity reveals structural impediments to success for conventional force structures in asymmetric warfare, such as Operation Iraqi Freedom. The second example analyses the capability development process, which is responsible
for transforming the security needs of Government into equipment purchasing decisions. The analysis produces practical recommendations for improvements that address the underlying complexity of the problem. Reflections in the conclusion of this thesis focus on the interrelations between philosophy, theory and application. As the individual contributions of this thesis are woven into a single tapestry, they demonstrate the utility of a multidisciplinary approach to complex systems design.
Foreword

Mathematics is not a careful march down a well-cleared highway, but a journey into a strange wilderness, where the explorers often get lost. Rigour should be a signal to the historian that the maps have been made, and the real explorers have gone elsewhere.

William S. Anglin

Whilst this thesis and my background are notionally in applied mathematics, I think the multidisciplinary label is more appropriate. The interdisciplinary passport of complex systems has provided me with the freedom to cross disciplinary boundaries frequently enough that distinctions between philosophy, mathematics and science seem to be as much a matter of style as substance. One of the great drawbacks of the expansion of human knowledge is the proportional pressure on the individual to specialise in only one “language game”, when any messy real world problem requires contributions across many specialties to uncover effective solutions. Even real world problem solving, or “action research”, is itself a specialty! The compartmentalisation of knowledge into disjoint pigeon-holes by the Academic System has produced legions of subject matter experts, armed with vocal barrages of well-rehearsed critiques, ready to defend their turf against the occasional generalist and more frequently migrating interdisciplinarian (often a disillusioned physicist) that dares to “swim outside their lane”. A systemic cultural bias towards depth over breadth is just one of the barriers to multidisciplinary research.

To me, the great attraction of complex systems is the opportunity to learn in a direction lateral to the usual decomposition of scientific knowledge. This is still a process of specialisation, but the complex systems framework provides significantly more wriggle-space, as well as a fresh perspective on some of the most exciting challenges in science and engineering. I share with Gell-Man the belief that complex systems is capable of constructing bridges between the specialised representations of relatively isolated scientific disciplines. These links have the potential to improve communication and understanding, thereby strengthening the web of science. Complex systems can also help to interpret the relationships between the sciences, by accounting for emergence in a way that is neither reductionist nor holist – a topic which I address in this thesis.

Complex systems is a field that can present itself as an aspiring politician, enigmatic in its attempt to be all things to all people. Popular science books on complexity enjoy a higher profile than seminal papers in the field, and are often a researcher’s first exposure and primary impression of complex systems. The
success of the likes of Waldrop [319], Holland [153, 154], Lewin [204] and Casti [76] in enthusiastically informing the public about complexity is to be applauded. However, a brief survey of the foundational concepts: complexity, emergence, adaptation, self-organisation and co-evolution, reveals not just a lack of agreement regarding definitions, but often a reliance on definition by intuition or by example. Such definitions either assert that we know Complexity when we see it (except when we disagree), or provide a list of things and proclaim them to be Complex. Neither strategy involves any justification of the definition, and both are vacuous. Any reader who accepts these concepts is really only accepting the preconceptions they brought to the reading\(^1\), which implies that different readers will interpret the same concept in as many ways as there are different backgrounds. This is symptomatic of any field in its infancy, but clarity must be a priority for the research agenda of complex systems. This is not to say that complex systems requires a single foundation or perspective, but to emphasise that the danger of not having well-defined concepts is incoherence. The hyperbole surrounding complex systems buzzwords and catch phrases, none more prevalent and misleading than the “edge of chaos”, can only result in the misapplication of complex systems models out of context without understanding the assumptions of the original models. This aspect of complex systems is most manifest within the “complexity management” literature, where a number of gurus peddle management processes using complexity as a metaphor\(^2\).

At the other end of the spectrum, some traditionally hard – and often labelled reductionist – areas of science such as statistical mechanics are associating their research with complex systems. This is puzzling when, according to Bar-Yam [25, p. 91], a complex system can be defined as a system where the assumptions of thermodynamics do not hold. One could rather cynically suggest the involvement of theoretical physicists in complexity is motivated by the funding that fashionable interdisciplinary research attracts, rather than a genuine commitment to emergence and self-organisation, or agent based modelling. However, another way of viewing this development is that statistical mechanics is starting to ask questions beyond the properties of simple ergodic materials in equilibrium, moving from ‘thermostatics’ towards a genuine theory of thermodynamics. As more complex structures can be treated within a statistical mechanical framework, these tools will provide a new understanding of how systems can increase in organisation and persist far from equilibrium.

Between these two extremes, a remarkably diverse array of research is conducted under the auspices of complex systems, and this diversity is a source of great strength. I like to think of complex systems as almost orthogonal to and entangled with disciplinary science, which suggests that any attempt to demarcate simple versus complex systems is ill conceived. Instead, it is better to view complex systems as specialising in the study of organisation and relationships, in the global implications of structure at multiple scales. Some simple structures are already well treated within disciplinary science, in which case the only contribution of complex

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\(^1\)One is reminded of Sartre’s [274, p 17] critique of Marx: “I found everything perfectly clear, and I really understood absolutely nothing. To understand is to change, to go beyond oneself. This reading did not change me.”

\(^2\)See for example [86, 221, 273]. For more insightful discussions of management theory and complexity see the journal Emergence:Complexity and Organisation.
systems is to make connections with equivalent structures in other disciplines that may benefit from analogous techniques.

But the real work for complex systems is to extend our knowledge of how structures can change in organisation, and how increasingly complex structures can continue to be analysed even when traditional techniques fail. General insights into the nature of organisation, including appropriate mathematical techniques – which must always be supplemented with discipline-specific knowledge – can enable disciplinary science to progress beyond simple models and analytical techniques that fail to fully capture structures in space and time. When someone says that \( x \) is a complex system, I interpret this as a claim that conventional approaches to modelling the system have failed to capture an aspect of the system’s behaviour that is considered essential to the modeller. Consequently, when at least one significant conventional assumption is revised, this should count as a complex systems approach. And when a complex systems approach is generalised beyond the confines of its original discipline, this should count as a contribution to complex systems theory.

Throughout my thesis I have tried to balance application with inquiry. Application, in the spirit of the engineer, seeks to proceed with building more concrete instantiations of ideas in order to evaluate the ability of new theory to make a discernable difference to people’s lives. Inquiry, in the spirit of the philosopher, seeks to question how the framework the engineer builds to help solve problems may constrain thinking and create its own set of problems. Without a deep understanding of both perspectives, the increasingly specialised armchair of contemporary philosophy may appear to the engineer to have nothing to contribute to real-world problems. Meanwhile, science and engineering may appear to the philosopher as merely a new dogmatic techno-utopian cult\(^3\), a secularised mysticism that places Mother Nature in the vacuum left by the exorcism of God from philosophy beginning with Hume. Unfortunately, specialists at either end of the applied/inquiry spectrum commonly hold these misconceptions – perhaps to justify claims for the superiority of their own perspective. Of course, we all know that inquiry and application are opposite sides of the knowledge development coin; it is only because the System encourages specialisation that their relationship is viewed in predominantly competitive terms.

So this is the **Unique Selling Point** of my thesis: I take an end-to-end systems view of the development of knowledge, from philosophy to design via complex systems theory. Thus my approach is inherently multidisciplinary, because it develops knowledge about the whole that is distinct from the knowledge contained in each of the disciplinary parts. Whilst each part of my thesis could have been developed to a greater degree of sophistication by specialising in only that area, this would necessarily sever the connections between the philosophy and application of complex systems that are surfaced in a multidisciplinary treatment. My **Motivation** can be summarised as: to develop novel representations and theories that have an impact on how real world systems are designed and implemented.

**On Method**, where possible I have chosen to align the questions I ask with the “exact sciences”, and I expect substantial grounds to be given before directly

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\(^3\)I owe this turn of phrase to Darryn Reid.
contradicting working scientific hypotheses. This is a methodological decision: it is not based on metaphysical belief in the entities of the exact sciences, but on the belief that to be anti-scientific – by erecting barriers to scientific investigation – is almost always unhelpful. At the same time, science is not reflexive: it cannot be used to legitimate itself. Additionally, in my chosen application domain – defence science – the most important problems are messy, data poor and inherently soft. In order to discuss foundations and address real world problems, it will be necessary to operate outside the comfort zone of exact science, and be satisfied with qualitative or conceptual analysis. A commitment to multidisciplinarity also demands that the temptation to reduce all explanations to a single foundational perspective is staved off.

On Convention, I will depart from the scientific style of the impartial third person: ‘we conclude’, ‘this study opposes’, etc., for two reasons. On purely pragmatic grounds, distinguishing between my personal research and conclusions, and the research that ‘we’ have jointly undertaken – my collaborators and I – clarifies my contribution for the examiner. Also for clarity, instead of using ‘we’ to refer to ‘the readers and/or I’ eg. ‘we may ask’, I will write ‘one may ask’. The deeper reason behind this departure, is because the process of knowledge development is inherently personal – it depends essentially on personal judgement. This can be papered over and obscured by impersonal reporting, which only serves to promote a positivist interpretation of science.

In the interests of clear communication I have included precise plain English definitions of technical terms in the Glossary, the utility of which hopefully exceeds its dryness. When a new term is introduced that has a technical meaning, it is underlined, as are cross-references within the Glossary. Use of the Glossary is entirely optional, since the more important definitions are also developed in the body of the thesis.
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