Preface

Our world is a large, integrated system of systems. These systems, whether they are ecological, social, or financial, are complex and constantly adapt to their environment. Many of them are essential for our very existence. Being so complex, and because of the intensive interactions among the system components, they cannot be fully understood by isolating their components or applying simple cause and effect reasoning. These systems, however, can be examined by looking for patterns within their behaviour. Intelligent complex adaptive systems (ICAS) research uses systemic inquiry to build multi-disciplinary representations of reality to study such complex systems.

Because the use of ICAS is prevalent across a number of disciplines, papers describing ICAS theory and applications are scattered through different journals and conference proceedings. It is, therefore, important to have a book that broadly covers the state-of-art in this highly evolving area. There has been a strong interest among researchers regarding the publication of this book. Forty-nine submissions were received. All papers went through rigid peer review by at least three reviewers and only 23 were accepted for publication, an acceptance rate of just under 50%. Because of size constraints, these papers are published two volumes. This book focuses on the theoretical side of ICAS while its sister book *Applications of Intelligent Complex Adaptive Systems* emphasises the techniques and applications. These two volumes cover a broad spectrum of ICAS research from discussion of general theory and foundations to more practical studies of ICAS in various artificial and natural systems. It is important to highlight that a significant portion of contributions come from the social sciences. This will, we believe, provide readers of these books with extremely valuable diverse views of ICAS, and also clearly demonstrates the wide applicability of ICAS theories.

Intelligent Complex Adaptive Systems

The study of ICAS draws richly from foundations in several disciplines, perhaps explaining in part why ICAS research is so active and productive. These diverse fields that contributed to the formation of ICAS included the genetic algorithm (Holland, 1975) and cellular automata (Gardner, 1970, von Neumann, 1966) in computer sciences, evolution and predator-prey models (Lotka, 1925) in biology, and game theory (von Neumann & Morgenstern, 1944) in economics.

Researchers of ICAS are interested in various questions, but these can be summarised as to how to describe complex systems, and how to describe the interactions within these systems that give rise to patterns. Thus, although researchers from different backgrounds may have very different approaches to the study of ICAS, it is the unique properties of ICAS systems, such as nonlinearity, emergence, adaptivity and modularity that form the centre of inquiries. Many of these properties will be thoroughly explored in these two volumes. It is the complexity of ICAS systems which means that although a variety of techniques which have been employed to study ICAS, computer simulations have become important and widely used. These simulations involve several important computing techniques that may interest readers of these books.

- Evolutionary computation (EC) is a highly active field of research inspired by natural evolution. Essentially, EC models the dynamics of a population of distinctive entities such as chromosomes in genetic algorithms or programs in genetic programming. Thus, while EC has been used as a simplified model to study ICAS, it is also an ICAS itself having wide applicability for solving scientific and engineering problems.
- Cellular automata (CA), and related techniques such as Boolean networks, are common techniques in ICAS. The behaviour of entities that respond to the environment is defined as rules or other forms. Each

entity can interact with adjacent ones. The topology of adjacency can be defined in various ways depending on the focus of the research. CA and related techniques have been widely used to study important properties of ICAS such as emergence.

- Multi-agent systems (MAS) are systems composed of several autonomous agents. These agents may use a belief-desire-intention model or other mechanisms to guide their behaviour, respond to the environment, or communicate and interact with other agents. The concept of MAS model can be directly applied to study a number of ICAS systems. More often, a computer simulation of MAS is used to understand corresponding ICAS.

ICAS research has applications across numerous disciplines. As we are surrounded by complex systems, and indeed are ourselves a complex system, applications are everywhere. In this preface, we have no intention of providing a compete list of applications of ICAS, although some of the chapters do survey ICAS applications in a particular field, but we do wish to highlight the following subjects that are covered by this book and its sister volume.

Because human society is a complex system, comprising a large number of autonomous individuals and entities that are connected by various layers of networks, it has been the one of the major fields of applications of ICAS research. As explained in a number of excellent chapters, significant research has been conducted into how disease, information, belief, language, and innovation propagate and diffuse in society.

Economics and finance are also the focuses of applied ICAS research. The economic and financial interactions among the entities of modern society, either at individual or institutional level, are vital to its existence. ICAS has been used to study these interactions and to understand the dynamics that underpin them.

Management can also been understood and further explored with ICAS concepts and methodologies that provide both a novel perspective and an exciting new set of tools. Besides applications to general management, these two books also have chapters dedicated to specific management applications such as military transformation.

And finally, ICAS has been widely used in science and engineering. Complex systems exist almost everywhere in the natural world, from the complex dynamics of the weather to important ecological systems. ICAS plays an important role in understanding these systems. Furthermore, it is well known that the robustness and reliability of an ICAS system is partially due to the fact that there is usually no centralised control system. This idea has been explored in solving engineering problems.

Audience

Researchers working in the field of ICAS and related fields such as machine learning, artificial intelligence, multi-agent systems, economy, finance, management, international relations, and other social sciences should find this book an indispensable state-of-art reference. Because of its comprehensive coverage, the book can also be used as complementary readings at the postgraduate level.

Organisation

The diversity of backgrounds within ICAS research provides the deep well of intellectual resources, which has allowed ICAS research to continue thriving. This diversity of backgrounds leads to a blurring of boundaries when categorising ICAS studies, a feature that should be seen as one of the unique characteristics of this field of research and one that need not be regarded as a problem. In organising a book, however, divisions are necessary. Thus, our organisation of this book into four sections on general theories, importance concepts, and perspectives in computing and the social sciences is only meant to provide the audience with a simple reference to make the book more accessible. The interdisciplinary nature of ICAS means that many articles might fit into multiple sections.

Two chapters in the general theories section seek the core of complex adaptive systems (CAS) and provide an alternative top-down method called “method of systems potential” rather than conventional “agent-based modelling” to study CAS. The first chapter by Wallis seeks to identify the core of CAS theory. To achieve this, it introduces innovative methods for measuring and advancing the validity of a theory by understanding the structure of theory. Two studies of CAS theory are presented. These show how the outer belt of loosely connected concepts support the evolution of a theory while, in contrast, the robust core of a theory, consisting of co-causal propositions, supports validity and testability. The tools presented in this chapter may be used to support the purposeful evolution of theory by improving the validity of ICAS theory.

In the second chapter by Pushnoi et al. emergent properties of CAS are explored by means of “agent-based modelling” (ABM) and compared to results from method of systems potential (MSP) modelling. MSP describes CAS as a holistic system whereas ABM-methodology considers CAS as set of interacting agents. The authors argue that MSP is a top-down approach, which supplements the bottom-up modelling by ABM. Both ABM and MSP exhibit similar macroscopic properties such as punctuated equilibrium, sudden jumps in macro-indices, cyclical dynamics, superposition of deterministic and stochastic patterns in dynamics, fractal properties of structure and dynamics, and SOC-phenomenon. ABM demonstrates these properties via simulations of the different models whereas MSP derives these phenomena analytically.

In the second section of this book on important concepts, two chapters seek to understand modularity, hierarchy, complexity, and emergence in the context of ICAS. Cornforth et al. provide an in-depth discussion of modularity, ubiquitous in CAS. Modules are clusters of components that interact with their environment as a single unit and, when they occur at different levels, form a hierarchy. Modularity occurs widely in natural and artificial systems, in the latter where it is used to simplify design, provide fault tolerance and solve difficult problems by decomposition. Modular and hierarchic structures simplify analysis of complex systems by reducing long-range connections, thus constraining groups of components to act as a single component. Network theory, widely used to understand modularity and hierarchy, can make predictions about certain properties of systems such as the effects of critical phase changes in connectivity.

In the study by Standish, investigation of important concepts in CAS is continued. The term *complexity* is used informally both as a quality and as a quantity. As a quality, complexity relates to our ability to understand a system or object—we understand simple systems, but not complex ones. On another level, *complexity* is used as a quantity when we talk about something being more complicated than another. This chapter explores the formalisation of both meanings of complexity during the latter half of the twentieth century.

The third section of this book features four chapters on the use of modern computing techniques to study the emergence of creativity, emergent specialisation, information bottleneck to central processing in adaptive systems and the role of barriers to information flows in the robustness of complex systems.

Creativity has been a difficult concept to define and its exact relationship with intelligence remains to be explained. In the first of the four chapters on computing techniques, Thórisson presents a theory of natural creativity and its relation to certain features of intelligence and cognitive faculties. To test the theory, the author employs simulated worlds of varying complexity that are inhabited by creatures with a genetically evolving mental model. Plan-making strategies are compared between creatures in each world. This shows that creative behaviours are governed by the world's structural coherence and complexity. The theoretical framework presented in this chapter may serve as a foundation and tool to improve our understanding of natural creativity and to help develop creative artificially intelligent systems.

Nilsson contributes the second study on computing perspectives, considering sensory information bottlenecks in adaptive systems. Such bottlenecks are an inevitable consequence when a complex system adapts by increasing its information input. Input and output bottlenecks are due to geometrical limits that arise because the area available for connections from an external surface always exceeds the area available for connections to an internal surface. Processing of the additional information faces an internal bottleneck. As more elements increase the size of a processor, its interface surface increases more slowly than its volume. Such bottlenecks had to be overcome before complex life forms could evolve. Based on mapping studies, it is generally agreed that sensory inputs to the brain are organized as convergent-divergent networks. However, no one has previously explained how such networks can conserve the location and magnitude of any particular stimulus. The solution to a convergent-divergent network that overcomes bottleneck problems turns out to be surprisingly simple and yet restricted.

In the current information age, a high premium is placed on the widespread availability of information, and access to as much information as possible is often cited as a key to making effective decisions. While it would be foolish to deny the central role that information flow has in effective decision making processes, in the chapter by Richardson, the equally important role of barriers to information flows in the robustness of complex systems are explored. The analysis demonstrates that, for simple Boolean networks, a complex system's ability to filter out certain information flows is essential if the system is not to be beholden to every external signal. The reduction of information is as important as the availability of information.

Specialisation is observable in many complex adaptive systems and is thought to be a fundamental mechanism for achieving optimal efficiency. In the final chapter on computing perspectives, Nitschke et al. present a survey of collective behaviour systems designed using biologically inspired principles in which specialization emerges as a result of system dynamics, and where emergent specialization is used as a problem solver or means to increase task performance. The authors argue for developing design methodologies and principles that facilitate emergent specialization in collective behaviour systems.

In this book's final section, three chapters provide insight into emergence in multi-agent systems in the social sciences, and the application of ICAS theories in international relations and economic systems. Dessalles et al. provide a survey of concept of emergence from both a conceptual and a formal perspective, and discuss the notions of downward/backward causation and weak/strong emergence. They pay particular attention to the formal definitions introduced by Müller and Bonabeau, which are operative in multi-agent frameworks and are derived from both cognitive and social points of view.

In the second social sciences chapter, Alker provides a study on ontological reflections on peace and war. Responding to a question by Hiroharu Seki about Hiroshima ontologies, the author reviews thinking about the ontological primitives appropriate for event-data making, accessing high-performance knowledge bases, and modelling ICAS used by researchers on war and peace. It cautions against "Cliocide," defined as of the "silencing" or symbolic killing of collective historical-political or historical-disciplinary identities and identifying practices by historical or discipline deficient "scientific" coding practices. He proposes that more intelligent multi-agent models in the "complex, adaptive systems" tradition of the Santa Fe Institute should include the socially shared memories of nations and international societies, including their identity-redefining traumas and their relational/migrational/ecological histories of community-building success and failure. Historicity in an ontologically distinctive sense of the "time ordered self-understandings of a continuing human society" is still a challenge for the computationally oriented literature on war and peace.

In the final chapter of this book, Potts et al. discuss a classic allocation problem. The substitution relation between two primary carriers of complex rules—agents and institutions—is a function of the relative costs of embedding rules in these carriers, all subject to the constraint of maintaining overall system complexity. This generic model is called the allocation of complexity, which they propose as a bridge between neoclassical and complexity economics.

Conclusion

This book and its sister volume bring together prominent ICAS researchers from around the globe who provide us with a valuable diverse set of views on ICAS. Their work covers a wide spectrum of cutting-edge ICAS research, from theory to applications in various fields such as computing and social sciences, and provides both comprehensive surveys on some topics and in-depth discussions on others. This offers us a glimpse of the rapidly progressing and extremely active field that is ICAS research. More importantly, because of the interdisciplinary background of the contributors, these books should facilitate communications between researchers from these different fields and thus help to further enhance ICAS research. Thus, we hope that these books may help to raise the profile of the contribution that complex adaptive systems can make toward better understanding of the various critical systems around us. In doing so, this work should encourage both further research into this area and also the practical implementation of the results derived from this area.

References

Gardner, M. (1970). Mathematical games: The fantastic combinations of John Conway's new solitaire game "life." *Scientific American, 223*(October 1970), 120-123.

Holland, J. H. (1975). *Adaptation in natural and artificial systems.* Ann Arbor, MI: University of Michigan Press.

Lotka, A. J. (1925). *The elements of physical biology.* Baltimore, MD: Williams & Williams Co.

Von Neumann, J. (1966). Theory of self-reproducing automata. In A. W. Burks (ed.), *Lectures on the theory and organization of complicated automata*. Champaign, IL: University of Illinois Press.

Von Neumann, J. & Morgenstern, O. (1944). *Theory of games and economic behaviour.* Princeton, NJ: Princeton University Press.

Ying Shan, Ang Yang

Canberra, Australia

June 2007