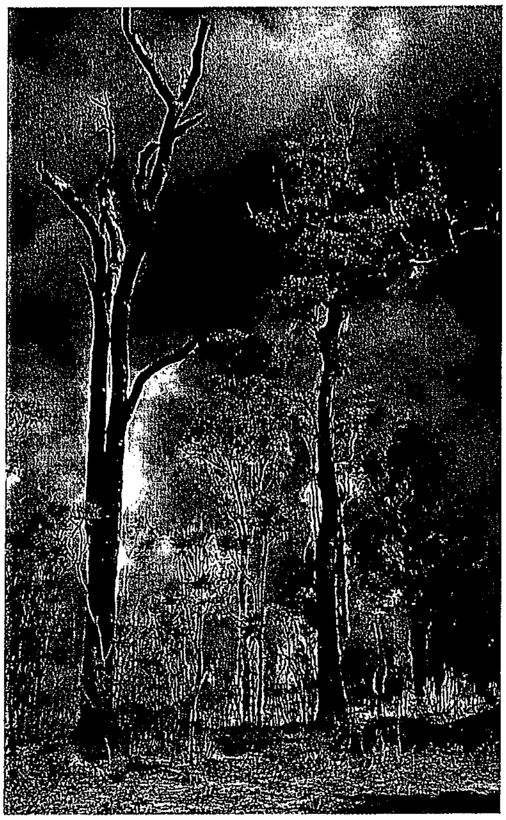
The Science of Complex Systems

John Finnigan explains how scientists are probing the complex interactions that influence the behaviour of bushfires, cyclones, the stock market and even electricity prices.



Better understanding of complex systems is enabling bushfire researchers to model fire fronts and their speed of advance.

In northern Queensland, CSIRO marine scientists are learning how information networks based on trust and reliability are built and evolve between fishermen on the Great Barrier Reef, and are using the dynamic behaviour of these "belief networks" to help design marine protected areas.

In Sydney, engineers are designing a "self-aware" skin for a future spacecraft that can sense when and where it has been damaged by a meteorite and repair itself.

A Melbourne-based specialist in turbulent airflow is working with a Brisbane entomologist to reproduce the ability of insects to track vanishingly faint pheromone trails by simulating the evolution of the insects' motor responses.

In Canberra, a theoretical ecologist is using the rules of the children's game Rock-Paper-Scissors to demonstrate why exotic species can sometimes take over landscapes almost overnight after years of living in balance with native flora and fauna.

In Melbourne a consortium of economists and computer scientists are simulating the behaviour of Australia's privatised electricity market to understand the 1000-fold price oscillations that occur from one 15-minute period to the next.

These wildly different topics are all aspects of a single CSIRO research program. The link between them is that they are all complex systems.

Self-organisation and Emergence

Two properties set a complex system apart from one that is merely very, very complicated: self-organisation and emergence.

Emergence is the appearance of features that are not implicit in the parts of the system. For example, cyclones, tornadoes or weather systems are emergent features of the motion of air particles on the spinning Earth, while recessions and booms are emergent features of national economies.

Complicated artefacts like motor cars or power plants also have emergent features in this sense, so a further property is needed to distinguish complex systems. This is self-organisation, by which we mean that there is no external controller or planner engineering the appearance of these emergent features. They appear spontaneously.

Probably the most pervasive example of self organisation is biological evolution. The 3.5 billion year journey from simple blue-green algae to the variety of life today as a result of aeons of blind reproduction, mutation and natural selection has required no outside agency to guide it. After writing *On the Origin of Species*, Charles Darwin, a religious man who knew how disturbing his ideas would be to those who believed the Bible literally, lamented: "What a devil's chaplain I would make". Evidently, self-organisation and emergence are not new ideas!

What has led to the explosive growth of interest in complex system science in the past decade is the realisation that general laws and rules governing these processes can be discovered, and that these apply equally to the weather, society and life itself.

Local Interaction

A key feature of real systems that has proved to be essential in the appearance of rich emergent features is local interaction. In other words, elements of a system only interact with their neighbours.

If we are studying a disease like AIDS or flu in a population, it makes sense to consider transmission between members of a social group; that is, the people who actually get close enough to be touched or sneezed upon or have sex together. Surprisingly, however, standard models of disease spread make no such assumption and deal instead with well-mixed populations where everyone can potentially contact everyone else.

The differences between the theoretical behaviour of epidemics in the two situations can be profound. When only local interactions between members of social groups are considered, diseases that would die out according to the well-mixed model persist indefinitely at a low level and can spawn new outbreaks when conditions are favourable.

Similar problems bedevil economic theories. The neoclassical economist's model of the market involves players who have perfect knowledge of what everyone else in the market is doing (as well as assuming that all players behave perfectly rationally, which is another story). New, more realistic market simulations, where players have only limited knowledge of the behaviour of prices and bids, reproduce real markets much better and yield market performance that is very different from the optimum efficiency of resource allocation that economic fundamentalists assert as an act of faith.

The emergent features of financial markets are the coherent changes in prices that result spontaneously from the individual buying and selling of the players in the market. Like the emergence of weather systems from the local interactions of air particles or of epidemics from contact between individuals, the scale of market booms and busts is orders of magnitude larger than the local trades that combine to cause them.

Local interaction is so obviously a feature of real systems that it is fair to ask why it has taken so long for its critical nature to be recognised. The reason is that mathematical solutions for such systems are fiendishly difficult to find. Theoreticians have concentrated instead on approaches where average properties are assumed to stand for all the diverse assembly of players.

Cellular Automata

Two of the critical ideas that were eventually to undermine this complacent picture were planted as long ago as the 1960s by the brilliant Hungarian mathematician, John von Neumann. As well as being influential in the design of the first practical digital computers, von Neumann invented cellular automata.

Imagine a giant chess board with only white squares. Now colour a random selection of squares black. Next, stipulate a set of rules that govern whether any square will turn black or white according to the colour of its neighbouring squares. Finally start the clock ticking and at every time step apply the rules. What you will find, for some choices of rules, is a constantly changing pattern of black and white squares, with complex extended motifs that span many squares appearing repeatedly and moving across the board.

One example of what I have described is the computer-based "Game of Life". This is a two-dimensional cellular automaton because it is played on a two-dimensional surface, but cellular automata of any number of dimensions can be designed and simulated on a computer. It is in specifying the rules that cause a square to change colour according to the colour of its neighbours, and in specifying which squares are to be counted as part of the neighbourhood, that we are able to model a huge range of real-world situations as cellular automata.

A situation where cellular automata have found ready application is bushfire modelling. A black square represents a part of the landscape that is already burning while the rules encapsulate empirical knowledge of how the fire spreads. For example, the probability of igniting a neighbouring square will increase if several contiguous squares are already burning because temperatures will be higher, fuel in nearby squares will be heated by radiation and there is a greater possibility of burning embers being lifted aloft in buoyant air currents and blowing sideways. What bushfire researchers are interested in is reproducing the self-organising shapes of fire fronts and their speed of advance, which in intense fires is controlled (in ways that are only poorly understood) by the way that flame fronts distort the airflow, by the strength of the ambient wind and by the fuel load and its flammability.

Networks

A powerful concept that extends the simple neighbourhood structure of cellular automata and brings us much closer to natural systems is the network. Almost all systems can be represented as networks where the elements of the system form the nodes, and nodes are considered to be linked if there are interactions between them.

Many physical systems like power and water grids are clearly networks but other less obvious examples are also easily cast into this form. Ecological food webs, for example, are networks where the nodes are organisms and a link between two nodes represents one eating or being eaten by the other. Social groupings – from families to companies to whole societies – can also intuitively be seen to be networks. What flows across the links of these networks can be materials, energy or information, including emotions like love and trust.

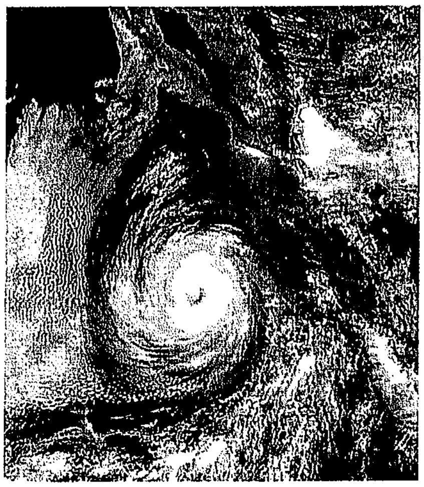
The advantage of viewing systems as networks is that much of their behaviour is determined by the pattern or topology of the network linkages rather than what passes across the links. At first this seems a surprising idea but research, especially over the past 5 years, has shown it to be true. Scientists can deduce a great deal about how a system will behave by observing its network topology. In many cases, particularly in social networks, it is much easier to determine the network topology than to discover in detail what is happening across the links, let alone to model it mathematically.

The first steps in studying the properties of networks (or graphs, as mathematicians term them) were taken in the 18th century, but results were confined to the simple case of regular lattices, where each node has a fixed number of links to adjacent nodes (as in a fishing net).

A major advance occurred in the 1960s with the study of random graphs by the Hungarians Erdos and Renyi. In these networks, nodes are connected at random to other nodes, resulting in a tangled pattern of connections. For many years random graphs were assumed to be good representations of real networks like social systems or food webs, but that view has been turned on its head in the past decade or so. Now it is realised that the network structure of most systems observed in nature lies midway between, being more disordered than regular lattices but more structured than random graphs.

A topology that is observed over and over again in systems that grow by accretion – like living organisms, social groups or even artefacts like the world wide web – is the so-called scale-free network, where some nodes have many links, many nodes have very few links and others lie in between so there is no clear average number of links per node. The dynamics of such structures are very resilient to random removal of links or nodes as there is little likelihood that any particular link is critical. However, these scale-free networks may break into a set of disconnected segments if the most connected nodes are targeted.

Protein–protein interactions in cells occur on a scale-free network, making the cell robust to accidental damage to its proteins either by environmental toxins or DNA transcription mistakes. On the other hand, modern society depends on the interdependent infrastructures of power, water, telecommunication, finance and government, which may also have a scale-free structure that is vulnerable to accidental damage to critical nodes by natural disasters or targeted attack by terrorists.



Cyclones are emergent features of the motion of individual air particles.

Interestingly, network theory tells us that the drive to make systems like power grids and company organisations as lean and efficient as possible often produces a network structure that leaves them vulnerable to catastrophic failure in the event of minor unforeseen mishaps. In such systems, managers may have the illusion that they are in control but the results of management intervention are often unpleasantly counterintuitive and surprising. In fact, these systems are self-organising and no one is in control. We see the consequences of this all around us from the environmental and social side-effects of well-intentioned environmental controls to the booms and recessions in our economies.

One area that is being profoundly affected by these new ideas is the modelling of societal and economic behaviour. By stipulating rules of individual behaviour and patterns of connections between individuals and their environment, researchers are modelling whole societies. *A priori* assumptions of the way large groups behave become superfluous; instead this behaviour emerges as the simulations proceed. The resulting computer models are reshaping our understanding of social and economic processes as well as phenomena like societal resilience and collapse.

For example, researchers at the US Department of Energy in Chicago have combined with the University of Chicago's School of Oriental Studies to simulate the trajectory of ancient Mesopotamian society from the individual household to the city state, and are comparing it with the 3000-year historical and archaeological record.

In another time and place, CSIRO researchers are modelling the social and biophysical behaviour of selected Australian farming communities to understand the combination of ecological, economic and social forces that have produced phenomena like dryland salinity. An immediate practical outcome of such research is design rules for robust social organisations.

A less serious application of these "agent-based" models is in entertainment. The massive battle scenes in recent epics like *The Lord of the Rings* were created by endowing individual simulated fighters – elves, orcs and men – with characteristic behaviours and then letting them interact in a virtual landscape.

Australian research in complex system science started with a few individual pioneers in universities. The CSIRO Centre for Complex System Science, a virtual operation spanning most of CSIRO, commenced operations in 2002. It was quickly followed by two Australian Research Council-funded Centres of Excellence. Other Australian universities have followed a growing world trend by setting up complex system science departments around their existing interests, and last year 12 of these linked up with the CSIRO Centre and two overseas universities in an ARC-funded Research Linkage network. Other government research laboratories, notably the Defence Science and Technology Organisation, also now have significant resources devoted to this field, which is undoubtedly one of the most rapidly growing fields of science worldwide.

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