Foresight Intelligent Infrastructure Systems Project

Science Review Summary: Emergent Behaviour Paper

Component parts

Scientists and engineers are taking an increasing interest in "complex" systems. But they use the term in a very different way from its everyday definition. A car or a television is complicated because it has many components, but the components work together in a predictable way. The car's brake or the television's volume control usually do what we expect them to do. Complex systems are different because their behaviour cannot be predicted directly from the properties of their component parts.

This matters because complexity is found in many natural and engineered systems. The behaviour of the World Wide Web cannot be extrapolated from the behaviour of the computers and data links that make it up, much as the behaviour of a colony of ants cannot be calculated from one individual ant. Instead they show "emergent" behaviour that we cannot predict – at least not with our present knowledge.

Emergent behaviour has emerged as a significant factor in several areas examined by the UK Office of Science and Technology's Foresight directorate, ranging from computer crime to neuroscience.

Foresight asked Seth Bullock of the University of Leeds and Dave Cliff of Hewlett Packard to examine complex and emergent behaviour.

They found that the phenomenon poses both threats and opportunities for the UK.

Looking mainly at its implications for Information and Communications Technology (ICT), they pointed out that the data systems that underlie modern society are now too large to be understood by old-fashioned engineering approaches. This includes the internet and the Web. Even if you are not a regular surfer, you are dependent on the services which the Web supports, including banking, telecommunications and the distribution of food, power, water and other vital goods and services.

Complexity that works

It is hard for designers of complex systems to be confident that the systems they design will have behave predictably. In addition, it is not possible to have central control of a complex system – as traditional engineering prefers – because such control would slow it to a halt.

Once systems become too complicated for their behaviour to be predicted by "divide and rule" analysis, new ways of understanding them are needed which do not yet exist. But there are many examples in nature of complex systems from which we might learn. The human brain, an ant colony or a rain forest are all complex systems which work. They are adaptable under stress, they do not have central control and they have proved their durability over millennia.

The fact that a system is complex does not mean that it has to be mysterious. Emergent behaviour is not necessarily unpredictable. It may be possible to prevent future repetitions of events such as the power blackouts across large areas of North America, which arose from apparently minor incidents in complex grids of power stations, power lines, transformers and other equipment.

Such systems are unpredictable at the moment because their development is highly dependent upon the initial conditions from which they start out. Removing a few ants from a nest, or a particular computer from a network, may make no difference to its performance, or may alter it fundamentally. The ants may become unable to forage for food, or the computer system may slow down unexpectedly.

Underlying laws

But it is possible that the laws that underlie this apparently random behaviour will be found in the next few years. This might allow engineers to produce complex products which are as robust and adaptable as natural ecosystems and are as predictable as simple systems are today. This knowledge might also allow us to improve our management of evolved systems such as threatened natural environments.

Achieving this certainty about the behaviour of future complex systems will require a number of developments. One is a better set of tools for simulation modelling of complex systems. These could be used to simulate proposed ICT systems but could also tell us about the effects of proposed changes to complex social systems, such as the introduction of congestion charging in a city.

Today's statistical methods are also inadequate for assessing complex systems. They cope best with situations where small causes have small effects. They are poor at describing systems in which slight changes can mean big final effects.

The artificial complex systems that we see around us also interact with each other and we need to understand more about how this happens. In the future we will all depend on an increasing number of large ICT systems designed for different purposes. We will depend on these more and more for our livelihood. How will these systems interact, when they are both in their own way complex and prone to exhibiting unpredictable, emergent behaviour?

Better performance

Current ICT research may lead to systems which allow scarce resources to be used more effectively. Although the world's computer and communications capacity has grown immensely and will continue to do so, ICT systems are limited in size by their budgets. Better understanding of complexity might allow their performance to be optimised better. It could mean that they were more able to cope with viruses, worms, spam and other attacks. And it might become possible to alter them without the extensive rebuilding that is required to modify today's ICT systems. Trends in the capability to produce computing and communicating devices at a smaller and smaller scale are pointing the way to ICT systems which will consist of thousands of cheap devices linked together. They will almost certainly exhibit emergent behaviour which we need to understand better.

Bullock and Cliff call for academic research in the UK and elsewhere to address these problems by producing general theories to back up the limited empirical work which is going on today. Many consultancies and other companies have products with features derived from complexity research. But industrial customers want more reassurance that they are buying a system with predictable properties than current knowledge provides.

They also point out that complexity is not widely taught as a subject in UK schools and universities, either in ICT courses or more widely. This means that students are often naive about the problems of modelling complex systems. Many university courses provide students with the computing skills required to build a simulation, but not the experimental skills that are needed. This is a situation in which a little knowledge really can be a dangerous thing.

UK strengths

Researchers across the world are now looking at complexity and emergent behaviour from a number of directions. Some complexity researchers come from the world of information technology, artificial intelligence and robotics while others come from biology. Their research is inherently interdisciplinary.

Bullock and Cliff find that despite funding problems for interdisciplinary research, and the lack of a clearly defined discipline of complexity studies with its own courses, careers and university departments, the UK is well-placed to produce the new insights, discoveries and methods which the subject needs. This could be the key to significant, profitable innovation.

Bullock and Cliff's full paper, Complexity and Emergent Behaviour in Information and Communications Systems, is available online at www.foresight.gov.uk and can be ordered in hard copy there. This summary is by Martin Ince, martin@martinince.com.

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