Computing and complexity—networks, nature and virtual worlds

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Complexity has had a profound influence on the evolution of computing and information processing. It arises both in the nature of computers themselves, and in the nature of the applications for which computers are used.

Complexity arises in many aspects of computing. For instance, it has profoundly affected the design of software, hardware, and communications networks. It also occurs in dealing with many kinds of problems, such as: cascading faults, emergent properties, robustness and reliability, and critical behaviour.

In applications of computers, complexity arises in the need to handle enormous volumes of information and to solve ever larger and more intricate problems (e.g. multi-objective optimisation). Combinatorial explosions in large datasets create problems of high complexity and pose a major challenge for computer science.

Several key ideas from complexity theory have dominated the struggle to cope with the inherent complexity of computing and information. The most prominent of these ideas is *encapsulation*, which is the most common way of dealing with complexity and involves grouping related items together into distinct units (modules). Encapsulation first arose in programming as a way of organizing code into manageable units (e.g. macros, functions, subroutines, and procedures). Subsequently, it has led to object-oriented design of systems, databases and processing.

Another fundamental idea from complexity theory is a *network*. A program is a network of processes (or objects). A supercomputer is usually a network of processors (e.g. clusters or grids). The Internet is a network of interlinked computer networks. Distributed data warehouses are organized networks of information objects.

As the complexity of computers and computational problems has increased, traditional ideas and approaches have often proved inadequate to cope. Computer science has therefore sought inspiration from nature, which has evolved numerous ways of coping with extreme complexity. The result is that modern computing often resembles biology. Many productive analogies have been drawn between living things and computing systems. Examples include gene expression and switching networks, disease outbreaks and computer viruses, social networks and telecommunication networks, stock markets and software agents, and intercellular signalling and multi-processing arrays.

The idea of "natural computation"—treating natural processes as forms of computation—has proved to be an extremely fruitful idea, both in computing and in theoretical biology. In biology, for instance, this new paradigm has led to a host of insights about biological systems, especially through the increasing use of simulation and "virtual experiments", giving rise to new fields of research, such as Artificial Life. In bioinformatics, for instance, the idea of encapsulation is seen in such ideas as controller genes and motifs; and the idea of networks finds expression in the idea of genetic regulatory networks. In sociology, societies can be viewed as networks of interacting agents.

On the other hand, nature has evolved ways of dealing with many complex phenomena and of solving many kinds of complex problems. Investigating these "solutions" had proved to be a fruitful source of insights about the nature of complexity, and about ways of managing complex systems. This has led to a host of new ideas in computing, as evidenced by the names of new fields of research, such as *cellular automata*, *data mining*, *evolutionary computing*, *neural networks*, and *swarm intelligence*.

The rise of natural computation as an alternative to numerical analysis has led to new research paradigms and new methods of interpretation. For instance, simulation replaces formulae in modelling, scenarios replace forecasting, evolutionary computing replaces optimization and sensitivity studies replace mathematical analysis.

Perhaps the ultimate expression of natural computing is the idea of virtual reality. A practical motivation arises from the difficulty of dealing with many real systems directly. It is safer, and less expensive, for instance, for trainee pilots to learn in a simulator rather than risk crashing a real aircraft. Simulation has come into its own in coming to terms with complex systems. The increasing power of computers makes it possible to investigate complex matters that could not be addressed previously. As modern clusters approach the size of organic systems, the potential has motivated proposals for grand challenges, such as modelling the human brain in detail.