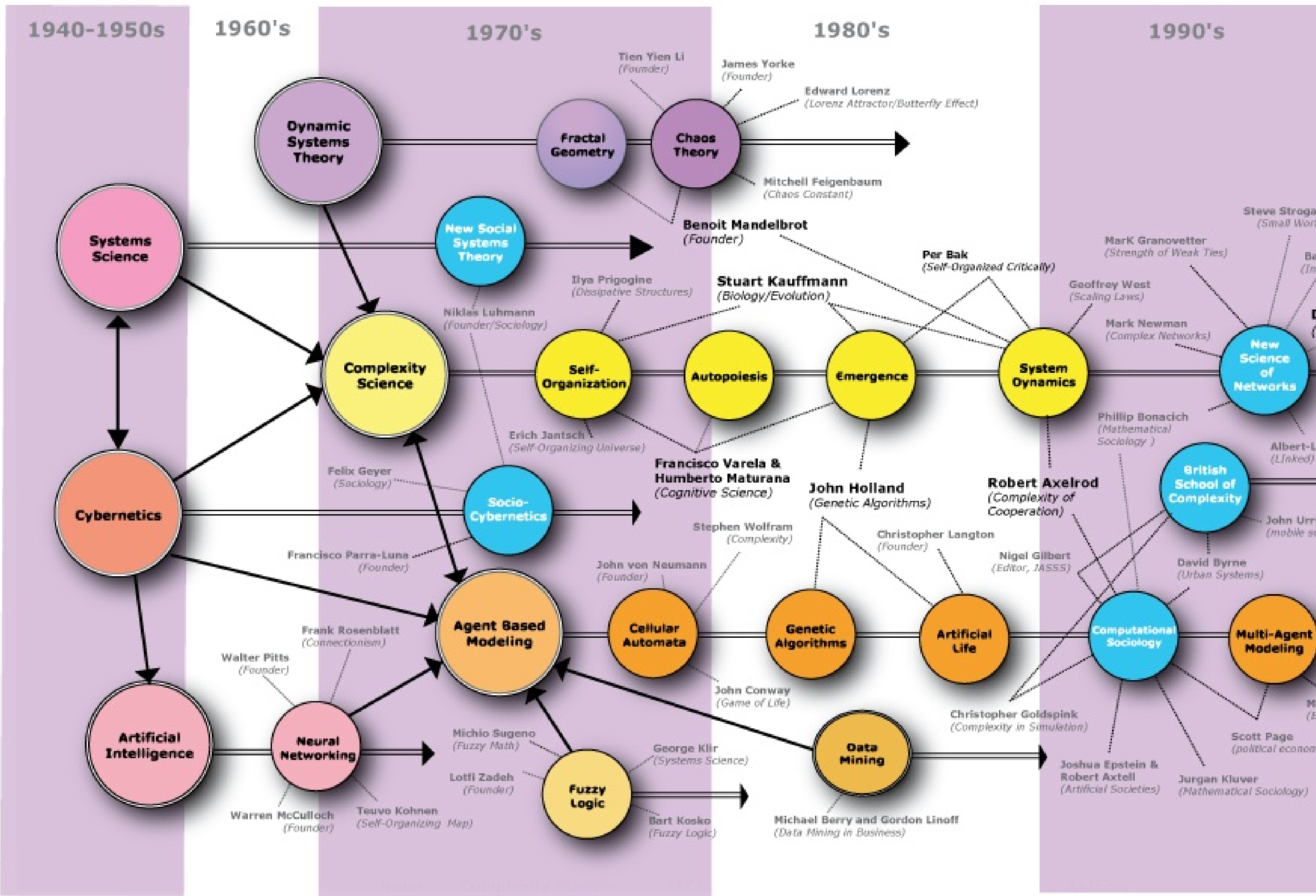
What is complexity science?

Complexity science is a broad and multi-disciplinary subject. In a wide range of systems that are the subject of study in biology, in the social sciences and in industrial applications, computational modelling is undertaken to study the behaviour of these sytems; Mathematical developments and modelling approaches from physics can be used to better understand these systems; And expertise in domains from software engineering to systems biology can be used both to inspire new approaches and apply new results.



The concerns that complexity science addresses has developed from investigations from a varied intellectual ancestry. Some of it has developed from work in cybernetics in the 1940s, to work on general systems theory in the 50s, chaos and catastrophe theory in dynamical systems in the 1960s and 70s, to work on complex systems spearheaded in the 80s by groups like the

Santa Fe Institute
. Some of this work focussed on abstract mathematical systems and simple physical systems, e.g. sand piles, but more recently, interest has increased in complex adaptive systems, such as social systems, biological systems, and technological systems where the parts actively change the way they interact. The increased use of computer simulation and interest in biological questions created research in artificial life and the simulation of adaptive behaviour in the 1990s.

Now, in the 00s, complexity science takes in parts of all this rich background of work. An important part of the current emphasis of complexity science is its application to practical technological systems; industry needs to know how to design, manage, build and control systems as they increase in size and connectivity. They want to be able to build systems that are scalable, robust, and adaptive by using properties such as self-organisation, self-adaptation, and self-repair that biological systems utilise. Thus the contemporary applications of complexity science are complemented by a rich background of theoretic work, and continue to address deep scientific questions about nature.Complexity science is a subject of study that is in the perfect position of bringing together deep scientific questions with application-driven goals across many interesting domains.

Complexity science touches on almost all aspects of modern technology and science creating lots of exciting new opportunities in training, careers and research. One thing to be careful of: 'complexity' doesn't just mean 'complicated'. Complexity is not just determined by the number of parts a system has, for example. Engineered systems, such as a microprocessor or the space shuttle, might have a very large number of parts with very intricate design. But complexity science is interested in dynamical properties like self-organisation, adaptation, and emergence. Often engineered systems are designed to minimise these tricky dynamical properties – they can make the system difficult to design, predict and control. However, if desirable emergent behaviours can be harnessed and exploited they can help us to move beyond the limits of traditionally-engineered systems that are merely complicated.

Why is complexity science important now?

The rapid increase in interest in complexity science is being driven predominantly by new challenges and demands in technology. Various industries are becoming increasingly aware that traditional approaches to design and engineering are failing to keep up with the increasing scale of today's systems .

"The management and design problems facing modern ICT [information and communication technologies] practitioners are critically concerned with ensuring reliability, usability, robustness, efficiency, effectiveness, security, and evolvability in the interconnected ICT systems upon which societies and economies increasingly rely. As our world becomes an ever more interconnected place, so-called “systems” ideas and perspectives become increasingly important. A central issue is the emergent behaviour of complex systems." - UK government's *Foresight report on ICT and complexity* . (Read a non-technical summary .)

Systems from telecommunications, to information storage and retrieval, to economic trading, are rapidly increasing in scale. Also, processes and transactions that used to be implemented manually are becoming automatic, and many systems are being connected together. These increases in scale and connectivity make managing the complex dynamics of such systems difficult. Traditional approaches to engineering try to remove complex dynamical behaviours and emergent phenomena that are difficult to control and manage - but they often happen anyway, producing errors and undesired behaviour that can bring the system crashing down . New approaches to design, engineer, manage and control complex systems are urgently needed. This produces a demand from industry to both drive new research at universities and seek new graduates trained to understand and deal with complexity. This creates an urgent need for a change in training:

"Open challenges that must be faced by the complex systems community include overcoming institutional and cultural obstacles to interdisciplinary and industrial involvement in complexity research. In the UK in particular, most computer science undergraduate degree programmes currently have a manifest lack of formal training in complexity ideas and techniques: especially simulation modelling methods, experiment design, and statistical data analysis." - *ibid.*

This need for new training in complexity science has now resulted in the development of new courses in complexity and related subjects, (see Courses).

Another driver in the recent upsurge of interest in complexity science is the availability of computing resources with sufficient power to model large scale complex systems and investigate new ways of approaching their design. Without this, using only formal mathematical methods and traditional design approaches, the design of large scale systems was forced to avoid complex dynamical behaviours because they were too difficult to predict. Computational modelling allows new approaches that were not previously testable.

The third main driver is systems biology (or "the new biology" , as it is sometimes known). With the advent of high-throughput devices (e.g. genome sequencing and microarray data) the biological sciences are for the first time able to gather information about whole systems and begin to ask questions not just about one detail at a time, but about the complex interaction of the components together. There has been an enormous change in the way cellular and molecular biology, in particular, is being researched, and large amounts of funding from the biological research council is being directed to these new approaches (see *Bioscience for society: a ten-year vision, BBSRC (2003)* and *UK Biosciences: The next ten years, BBSRC (2004)*).

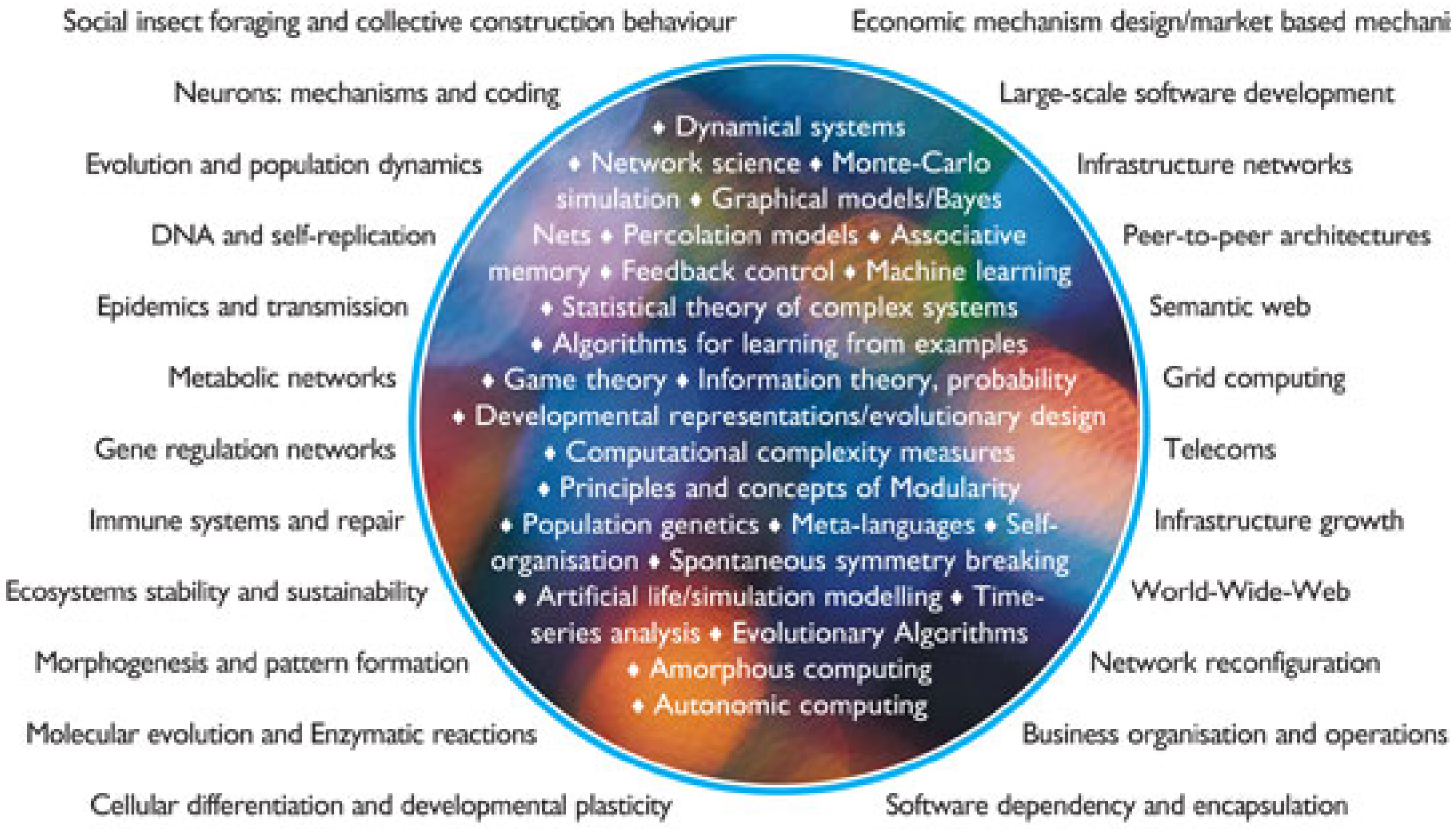
Complexity Science interfaces with systems biology in two different ways:

1. As systems biologists gain new information about how biological systems work, and how they cope with and exploit emergent systems level phenomena, we gain new insight and inspiration for tackling complexity in engineered and technological systems.
2. As we tackle complexity in technological systems and gain understanding of new approaches to modelling and controlling complexity in engineered systems, we can provide new insight that can help biologists understand complexity in natural systems.

Where is complexity science headed?

One of the most exciting aspects of complexity science is its interdisciplinary nature, and the interface with the life sciences is paramount here. Biology (from ecology, to organismic biology, to neurology, to cellular biology, and molecular biology) is filled with marvellous examples of complex adaptive systems that not only cope with emergent dynamical behaviours but have adapted to control and exploit them in every way imaginable. A lot of research in complexity science is looking for ways to model, understand and extract the useful properties of biological systems. This is both with a view to better understanding of the biological systems systems biology and for inspiration for new approaches to solving technological and engineering challenges.

In the figure below, the left side lists some biological complex systems, and the right side list some example systems from ICT (information and communication technology) that need new approaches to handling complexity. The topics in the centre are examples of subjects that help connect the biological inspiration on the left with the challenges on the right.



What opportunities are there in complexity science?

Training and employment

The activities of the research councils (below) and initiatives from the universities are beginning to produce the channels necessary to train the next generation of engineers and scientists that will have to face the complexity challenges of the future (see Courses). Graduates trained in systems thinking and techniques for handling and exploiting the properties of complex systems are desperately needed (see Careers).

Research funding

In response to the complexity challenges that industry is facing, the UK research councils have funded an amazing number of new activities in complexity science.

The main research council for these activities is the Engineering and Physical Sciences Research Council (EPSRC). Some of the activities that they have funded include:

- Investment of £12 million in Novel Computation: coping with complexity.

- Development with industry for a 5-year, £9 million centre in large scale complex IT systems. The research centre will address issues of complexity with the IT and communications industry and there will be an associated Engineering Doctorate programme to train researchers to doctoral level.
- Commissioning of specialised postgraduate training in complexity science, through a capacity building call for proposals: two centres, £4 million each.
- Postgraduate studentships in complexity science, funded through capacity building call, will be starting in 2007.
- £600,000 for short courses in complexity science to run during 2006.
- Aims to have an established £6 million research portfolio in complexity science, funded through responsive mode and strategic activities.

For more information see the EPSRC website.

Another important research council for complexity funding in the UK is the Biotechnology and Biological Sciences Research Council (BBSRC). The BBSRC is funding activities in systems biology and these provide an important complement to the research funded by EPSRC. The main activity here is the establishment of Centres for Integrative & Systems Biology (CISB):

"The aim of the Centres for Integrative & Systems Biology (CISB) initiative is to establish a number of Centres for Integrative Systems Biology in partnership with relevant universities. These centres are to possess the vision, breadth of intellectual leadership and research resources to integrate traditionally separate disciplines such as biology, chemistry, computer science, engineering, mathematics and physics in a programme of international quality research in quantitative and predictive systems biology". Taken from the BBSRC website.

These aims are a vital part of the 10-year strategic vision of the BBSRC (see *Bioscience for society: a ten-year vision, BBSRC (2003)* and *UK Biosciences: The next ten years, BBSRC (2004)*). Funding from the BBSRC includes:

- 3 Centres for Integrative Systems Biology at an indexed cost of £19.25M, including £3M from the EPSRC.
- Training and capacity building in Systems Biology is identified as one of the BBSRC's Targeted Studentship Priorities.
- 'Exploiting Systems Biology' identified as one of the priorities in BBSRC's Technology Strategy
- BBSRC involvement in Systems Biology in Microorganisms (SysMO) at a cost of £3M

over 4 years.

- Establishment by EBS Committee of networks for Mathematics in Systems Biology at a cost of £400K over 3 years

For more information see the BBSRC website, specifically link1 and link2 .

Activities like these funded by EPSRC and BBSRC support courses across the UK.

There are a growing number of books and websites that introduce and explain complexity science.

Key Websites and Recommended Introductory Reading

- The Principia Cybernetica is a self-proclaimed organic cybernetic forum for understanding system science and complexity. It provides a very complete overview of the theoretical aspects of complexity science as well as definitions of many of the buzz words often used by complexity scientists.
- The Santa Fe Institute has conducted complexity research since 1984 and continues to provide a centre to unite complexity researchers from across the world.

- *At Home in the Universe: The Search for the Laws of Self-Organization and Complexity*, Stuart Kauffman.

- *Turtles, Termites, and Traffic Jams: Explorations in Massively Parallel Microworlds*, Mitchel Resnick.

- *Signs of Life: How Complexity Pervades Biology*, Ricard Sole.
- *Complexity: The Emerging Science at the Edge of Order and Chaos*, Mitchell Waldrop.

Other Web Resources

- ONCE-CS stands for the Open Network of Centres of Excellence in Complex Systems. It provides a portal to complexity science research across Europe. It is funded by the European Commission by the FET unit (Future and Emerging technology).
- Exystence stands for the the Complex Systems Network of Excellence. It is the sister site of ONCE-CS. Again it funded by the European Commission to develop collaboration among European researchers interested in Complex Systems, from fundamental concepts to applications, and involving academia, business and industry.
- Complexity society is a UK focal sight that aims to promote the theory of complexity in education, government, the health service and business.
- The Centre for Complexity Research promotes interdisciplinary collaboration and hosted a recent conference in the complexity sciences at Liverpool University.

- The Complexity Digest is an international and interactive forum of complexity constituting a useful amalgamation of current research papers on modern complexity issues.

- The New England Complex Systems Institute is an umbrella organization that encompasses many of the leading companies and universities involved in complexity research.

- Ben Gonshaw's site provides some interesting material about complexity in the context of digital media and game design.
- Evolution, Complexity and COgnition group site includes links to related sites.

General Reading

- *Harnessing Complexity: Organizational Implications of a Scientific Frontier*, Robert Axelrod and Michael Cohen.

- *The Web of Life: A New Scientific Understanding of Living Systems*, Fritjof Capra.
- *Frontiers of Complexity: The Search for Order in a Chaotic World*, Peter Coveney.
- *The Computational Beauty of Nature: Computer Explorations of Fractals, Chaos, Complex Systems, and Adaptation*, Gary William Flake.
- *Deep Simplicity: Bringing Order to Chaos and Complexity*, John Gribbin.
- *Emergence: From Chaos to Order*, John Holland.
- *Emergence: The Connected Lives of Ants, Brains, Cities, and Software*, Steven Johnson.

- *Out of Control: The New Biology of Machines, Social Systems and the Economic World*, Kevin Kelly.

- *Complexity: Life at the Edge of Chaos*, Roger Lewin.
- *Exploring Complexity: An Introduction*, Gregoire Nicolis.

Computer Science and Complexity

- Towards 2020 Science , Microsoft Corporation. report

SocialSciences

- *Cities and Complexity: Understanding Cities withCellular Automata, Agent-Based Models, and Fractals* , Michael Batty.
- *Complexity Theory and the Social Sciences*, David Byrne.

Dynamical Systems and Network Theory

- *Linked: How Everything Is Connected to Everything Else and What It Means*, Albert-Laszlo Barabasi.

- *Chaos: Making a New Science*, James Gleick.
- *The Structure and Dynamics of Networks, Mark Newman, Albert-Laszlo Barabasi*, Duncan J. Watts.

- *Nonlinear Dynamics and Chaos: With Applications to Physics, Biology, Chemistry and Engineering* , Steven Strogatz
- *Sync: How Order Emerges from Chaos in the Universe, Nature, and Daily Life*, Steven Strogatz.
- *Small Worlds: The Dynamics of Networks Between Order and Randomness*, Duncan J. Watts.
- *A New Kind of Science*, Stephen Wolfram.

http://www.complexity.ecs.soton.ac.uk/index.php