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Project report

Science of complex systems for tackling challenges of the 21st century: a brief overview

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Abstract

The article provides a brief overview of the emerging 'Science of Complex Systems' and of some of the programmes sponsored by the European Commission and the DG for Information Society and Media. I explain what are the drivers for this emerging research area, what are its new concepts and what is its potential impact on science, society and business. The research landscape in Europe is described by focussing on programmes in the European Commission.

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The rise of complexity: when systems become highly entangled

The 21st century is confronting us with unprecedented challenges, very different in nature than those we have faced in the last century: globalisation, social instability, environmental problems, a rapid transition from a manufacturing to a knowledge economy, etc. Decisions makers – in policy as well as in business – can no longer act without considering the impact of their actions in a complex web of mutual interdependencies. What increasingly stands out about today's world is its immense complexities – its irregularity and apparent unpredictability, its dense webs of cause and effect that defy straightforward analysis.

We have started to realise that the technologies we create are playing an increasingly dominant role in our society and become at the same time more and more difficult to manage and evaluate. In particular, the rise of the Information Technologies (IT) facilitates and transforms human social relations and entangles technology, business, society, and us, as users, citizens, and customers. Tomorrow's technologies and businesses will have to be built on a deep understanding of the properties that arise in a context where technology and human social systems fuse to create 'techno-social communities'.

At the same time, science is dealing with unprecedented opportunities and challenges. We struggle to make sense out of a data deluge that progress of IT has enabled – and to master the torrents of data, for instance genomic data from micro array studies,[1] demographic real time data on our society,[2] detailed data on societal impact of natural catastrophes and of human society on nature,[3] or data on human behaviour from high-resolution measurements of brain activities.[4] These abundant data reveal intricate webs of interlinked complex processes *within and across* living, social and man-made systems that we need to better understand to draw the best possible benefit for society (public health, urban planning, sustainable development, etc.).

As a consequence, science in the 21st century will have to be different, it can no longer be clearly structured in traditional disciplines according to clearly distinct objects of study (physics, biology, chemistry, medical sciences), nor can it be neutral about the consequences of its own findings. Today science must respond to challenges of which its own successes are the root cause (stem cell research or impact of technologies on human and societal well-being). We will, therefore, require new alliances and joint efforts between all involved, between different scientific disciplines, engineering, business, and policy.

The science of complex systems emerged as an attempt to provide a conceptual framework for a novel integrated – holistic – approach to scientific discovery, decision-making in a highly entangled world of policy and business, and to the creation and adoption of new technologies. The novelty of and challenge for such a holistic approach are as much in developing new concepts to better understand highly connected systems as in the need to find new ways to organise research around big questions and challenges rather than established disciplines.

In the following, a brief overview will be given of the underlying concepts of the science of complex systems and of attempts to adapt the research landscape in Europe. We will emphasise the role of the European Commission in furthering holistic approaches by funding collaborative highly multi-disciplinary research projects and will describe briefly the role of a new generation of research institutes that effectively stimulate a novel open research agenda addressing the grand challenges of the 21st century. The references contain 'further reading'.

More is different

Nothing in traditional science, engineering, and management that seek to understand, to design, and to manage systems by 'divide and conquer' – by breaking components into smaller parts – has prepared us to explain let alone master the complexities of the systems that science, policy, technology, and business need to deal with today. The science of Complex Systems accepts and even embraces the frequent irreducibility of system behaviour and tries to develop a theoretical and conceptual framework that helps us better understand behaviour and functionality in highly entangled – interconnected – systems and the nature of transitions in behaviour and functionality that occur when a large number of system components organise – in absence of central control – into highly versatile organisational structures with augmented functional properties. The vision is to explore – based on such a conceptual framework – radically new ways of monitoring, modelling, managing, and designing the next generation of technological artefacts, as well as new business and social structures.

Broadly speaking, complex systems consist of a large number of heterogeneous *highly interacting* subsystems or components. Systems that qualify as complex systems in this sense are abundant – cells, cities, the Internet, ant colonies, financial markets, the global economy, etc. Such systems often show surprising characteristics that we cannot predict by focussing exclusively on the characteristics of the subsystems. The interactions between subsystems lead to new properties of the systems and thereby dominate the overall system behaviour. As P.W. Anderson (1972), a Nobel Prize winner in physics and an early promoter of complex systems research, succinctly put it: '*More is different*'.

Emergence, a key concept in the science of Complex Systems, is in essence the acknowledgment that systems as diverse a economies, cells, or ant colonies cannot be characterised by the behaviour of their individual components – humans, chemicals, ants – but only by the higher level organisations that grow out of them. For instance, this view attributes large fluctuations in stock markets to the mutual influences among stockbrokers – that tend to increase market trends – and *not* to variations of preferences of individual brokers. The highly versatile and adaptive behaviour of ant colonies that is in stark contrast to the limited capacities of individual ants is a consequence of the capacity of ants to organise collectively via simple (chemical) communication mechanisms. These two examples illustrate two concepts – positive feedback that is reinforcement of trends and swarm intelligence that is the capacity of agents to collectively achieve a higher level of intelligence. Other concepts include the notion of 'extreme events', that is rare events with a large impact on systems, like stock market crashes or earthquakes. The theory of 'extreme events' is now playing a major role in modelling of financial markets and for the risk insurance industry. Further down we will elaborate the concept of 'network'.

Two schools of thought on complexity

'*The engineer, and more generally the designer*,' as the economist and management theorist Herbert Simon wrote, '*is concerned with how things ought to be – how they ought to be in order to attain goals… Natural science has found a way to exclude the normative and concerns itself with solely how things are.*'

Traditionally, there has been a dichotomy between the natural sciences – based on measurements trying to establish facts about existing systems – and engineering and management – based on making things work and trying to design systems with added social value. This has led to different schools of thought on complexity having their own language and priorities: one looks into complexity as a phenomenon to be understood, while the other looks into complexity as an engineering problem to be tackled.

Today research can no longer be based on such a separation of science and engineering: we attempt to engineer nature – see, for instance, in synthetic biology that works on 'building blocks' of the living – and to establish facts about the artefacts that we create and no longer fully understand – for instance, when we attempt to measure the 'expanding universe' of the Internet[5] like science attempts since centuries to measure the universe. As a consequence, complex systems research thrives on interactions between science and engineering and a common trigger of complexity is the tight entanglement of natural systems – human, social, ecological – with artificial, man-made systems.

The increasing role of networks

A key concept common to many complex systems is that of a network. Various types of networks – communication networks, transport networks, global business networks, networks of friends, or the Internet – shape our daily life and the way we think and act. Technology itself is no longer a distinct set of artefacts but an intricate network of connected artefacts. For instance, electric power grids that form a critical part of a nation's infrastructure are very large and complex engineered networks logistically connecting power grids across large geographical distances.

Increasingly, the technologies and social institutions on which we depend for our daily life are explicitly engineered as networks. We use information networks to connect persons, businesses, and technologies in complex business and social networks that create added value. Sophisticated manufacturing logistics allows on demand supply chains, novel business models use the almost instantaneous access to millions of online customers via the Internet.

We only become aware of our dependence if failures occur in these networks: when cities are plunged into darkness because of a breakdown of the power grid like happened recently in New York, when national economies collapse because of a failure of the global highly interconnected financial system as happened in the South-Asian banking crisis, or when computer viruses spread with mind-boggling speed over information networks destroying or, even worse, exposing sensitive data.

Networks are indeed everywhere, but it is fair to say that our understanding of networks has not kept up with our dependence on them. How can we avoid that local failures in one part of such networks lead to a cascade of failures in the whole network? How are decisions made in systems that become more and more open, more and more interconnected, and less and less centralised? How do we design systems – technological or political – that act reliably in such highly dynamic networked environments?

A network is essentially anything that can be represented by a graph: a set of nodes connected by links representing some binary relationship. In social networks, the nodes are people, and the ties between them are friendship, political alliance or professional collaboration. In the case of the World Wide Web, the nodes are websites, and they are joined when there is a hyper-link from one to the other. But these social and technological networks are only part of a much bigger variety of networks in nature. For instance, a living cell is a fascinating network of molecular events that allow cells to multiply and therefore organisms to grow (metabolic pathways and gene expression networks).

One might argue that apart from an abstract notion of 'being connected' all these diverse networks have very little in common. Recently, however, inspired by empirical studies, researchers from the mathematical, biological, physical, and social sciences have made substantial progress uncovering commonalities across networks as diverse as the Internet, the food web, biological cells, ecosystems and networks of board members of companies. Intrinsic properties of networks studied include robustness of networks to disturbances, or the influence of the topology of the underlying networks in spread of epidemics or in the flow of information.

ICT systems mirroring social systems and social organisation shaped by IT

The Internet is the perhaps most telling example of a network that literally changed our lives while at the same time the Internet is itself dependent on and a reflection of human social organisations.

Today's widespread use of the Internet is fundamentally changing the way in which people exchange information and interact with each other. The spectacular emergence of the Internet has enabled unprecedented opportunities for novel types of collective action via blogs, wikis, and podcasts. Through the collective input of its users, the free online encyclopaedia *Wikipedia* has emerged as a competitor to *Britannica*. *Wikipedia* is growing day by day, becoming evermore accurate. Participants in online forums can collectively arrive at educated positions on political issues. Not without reason, *Time* magazine elected 'you,' that is, 'all of us,' as Person of the Year, 2006.

In business and society, IT enables large-scale service systems satisfying the diverse needs of a large number of users (for instance Google, EBay, Amazon, Flickr, MySpace etc.). Services are a rapidly growing part of the economy, yet have only recently started to be the sharp focus of research. Increasingly economies and organisations are seen as dynamic networks of services that can self-organise to produce value-chains or high-level services dynamically composed from lower-level services. Today, many small online businesses together weave large-scale service economies. What happens when there are (literally) millions of interacting services? What happens to organisations/human groupings where such services are offered? Such questions can be tackled with concepts from the science of complex systems.

Rather than pure market mechanisms such networks organise on the basis of links based on prior interaction, trust relations or other factors. Understanding and modelling such massive service economies can produce more efficient ICT tools to support them and improve their performance.[6] The underlying challenge is to bridge between human/social activities/goals and computational/technological processes. Formulating research at the border between technological systems and human systems requires a joint effort across many disciplines including computer science, economics, psychology and anthropology.

The complexity research landscape in Europe

We have seen recently a surge in funding by public research bodies as well as several private companies. Efforts in the 'Future and Emerging Technologies'[7] unit of the Directorate for Information Society of the European Commission were focussed on novel paradigms for system design, in particular for information technologies, later extended to multi-level modelling of complex living and social systems and recently to efforts to better use insights from complex systems science to guide policies. The e-business programme in the European Commission has set up an innovative initiative on 'digital business ecosystems'[8] and the directorate for Research has been funding research in science of networks and in complex living and social systems.

Research funded spans from new paradigms for measuring the Internet and studying the Internet using a game theoretic approach[9] to studies of the emergence of language in societies of communicating robots.[10] The robot societies studied and built in this project develop collectively higher capacities to accomplish a given task based on the concept of swarm intelligence that was mentioned earlier in the context of ant colonies. One project develops multi-level models linking micro – and macroeconomics;[11] another project focuses on complex systems methods to better understand evolution of urban environment and innovation cycles.[12]

The results from complex systems research have demonstrated the benefit of a multi-disciplinary perspective. But science more generally needs to embrace this multi-disciplinary approach and develop a more integrated – holistic –approach. Our traditional way to organise research is only slowly (and often grudgingly) reacting. Research institutions in science, engineering and management are still divided according to departments focussed on one discipline that have few links among each other. We still enlarge the gap between the engineering departments and the science departments, not mentioning the natural sciences and the humanities that are continuously drifting apart since the 20th century.

It is in this context that a number of small dedicated research institutes are starting to play an increasingly important role. These centres of excellence are driving forward a highly interdisciplinary research agenda in Europe: for instance ISI foundation in Turin,[13] Collegium Budapest,[14] European Centre of Living Technologies in Venice,[15] Centers for complex systems research funded by the regions of Lyon and Paris,[16] and recently UK centres financed by EPSCR in Warwick and Bristol. They have an open research agenda, no department boundaries and serve as a melting pot for different types and modalities of doing science. As such they are highly pertinent examples of the holistic approach to scientific discovery and technological breakthrough that we need to see more in the coming years.

Conclusion

Complex systems research may never become a single, encompassing theory-of-everything, or an independent discipline. It will thrive at the border between disciplines and by interacting with engineering (thus approaching the 'science of the artificial' that Herbert Simon (1996) was promoting). It will drive a holistic approach to science that is somehow reminiscent of the ideal scientist of the Renaissance period in Tuscany that created an incredible volume of science, art and wealth. From that period, Leonardo da Vinci was probably the last universal mind able to span multiple skills and disciplines as a scientist, artist and engineer. Complex systems research strives at a research agenda that is similar in spirit and – hopefully – as far-reaching in the insights it can bring.

Disclaimer

The views expressed in this article are those of the author and do not necessarily reflect the views of the European Commission.

Notes

1 These data are used for instance in the new discipline of synthetic biology that attempts to 'engineer the living'.
2 Data are gathered for instance from signals of cell phones that allow to track movements of large numbers in mass demonstrations in real time. While such data are anonymised there is still ethical issues associated with the use of such data. On the other hand, such data are for instance put to great use in detailed predictions how and how fast an epidemic will spread.
3 See for example the recent UK report of Sir N. Stern on economic impact of global climate change.
4 For instance, FMRI – functional magnetic resonance imaging – in the new field of neuro-economics.
5 'The Internet is the most complex artefact ever created by mankind. It grows and evolves in absence of any central control almost like a living organism'(Christos Papadimitrou).
6 Competent data about the traditional service economy are scarce and hard to acquire. It has been particularly difficult to track the 'e-economy' because the transactions are usually silent and often hidden. (Purchase transactions in e-commerce are typically protected by encryption today.) We will need improved data gathering (data discovery-data observatory and experimental data collection) to observe the behaviour of real services to permit modelling their behaviour as well as their interaction patterns.
7 See http://cordis.europa.eu/fp7/ict/programme/fet_en.html
8 http://www.digital-ecosystem.org/
9 EVERGROW see www.evergrow.org and DELIS www.delis.upb.de
10 ECAGENTS www.ecagents.istc.cnr.it
11 EURACE www.eurace.org
12 ISCOM see www.iscom.unimo.it
13 www.isi.it
14 www.colbud.hu
15 www.ecltech.org
16 ixxi.fr and isc-pif.csregistry.org

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