Success stories in the science of complex systems

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1. Introduction

The complex systems society exists to coordinate and serve a self-selecting community of scientists and practitioners and to promote their activities to society at large. Frequently our community is challenged, quite legitimately, that the idea of complexity is ill-defined and has achieved little. In this special issue of the Liquid Journal of Complex Systems we will address both issues. We will try to show that there are some distinctive elements of complex systems science and that within this science there are some notable success stories.

What constitutes a success? Certainly the idea of success is relative to individuals or communities and one person's success may be another person's failure. However there are some criteria that are widely accepted as reflecting success. For example, in the field of medicine the discovery of penicillin is widely considered to be a success, as are the experiments of the Wright brothers with flying machines that open up the new engineering science of aeronautics. In its own terms the Manhattan Project was a huge success, although some may question its long term contribution to humanity. The invention of financial instruments that eradicated risk was considered by many to be a big success until, with hindsight, it can be seen to be a catastrophic failure. So we are aware that not all readers will consider all the examples given here to be successes. But we hope that one or two of the examples will convince them that this enterprise that we call complex systems science is producing something useful.

What constitutes complexity? Depending on one's point of view, the 'science of complex systems' the science of complex systems began in the middle of the last century and became recognisable in its modern form in its last two decades. Even so there is no agreement on what it means to speak of 'complex systems' and it is correctly pointed out by their practitioners that most established sciences study systems that are undeniably 'complex', e.g. oceanography, chemistry, biology, psychology, economics, sociology, linguistics. These sciences illustrate the silos of knowledge determined by the *objects* studied, *e.g.* oceans, molecules, living organisms, people, societies, and languages. These are research in depth and can be considered *vertical sciences*. In contrast some areas of science are *horizontal* and apply to many objects, *e.g.* philosophy, epistemology, mathematics, computation and statistics.
The horizontal-vertical metaphor is useful but not perfect. Arguably, some areas of study are objects in their own right and both vertical and horizontal. This is exemplified by mathematics which in its 'pure' form is the in-depth study of mathematical objects, and its 'applied' form is used to describe and investigate objects of other domains. In mathematics it has been found that some structure and properties apply to apparently different objects across the domains, *e.g.* the calculus seems to provide a way of representing the dynamics of many kinds of systems across domains such as biology, finance and warfare. Perhaps more obviously, the theory of statistics is useful across the physical, biological, social and engineering sciences. Philosophy attempts to understand the universe across the domains, while epistemology is explicitly the comparative study of knowledge.

DIAGRAM: Figure 1

As shown in Figure 1 there are some areas of science that do not fit neatly into the conventional division of knowledge that emerged in the nineteenth and twentieth centuries. For example climate change involves many environmental subsystems such as oceans, the atmosphere, and the heavenly bodies, where each of these involves many scientific specialisms. Arguably climate change involves human beings and their many systems including cities, financial systems, agriculture and wars.

Complex systems science is *horizontal*. Often the objects of study are complex because they involve many interacting subdisciplines, but also the *methods* used to study such systems are distinctive – an example being the theory and practice of computer simulation.

2. Complexity: the redundant paradigm?

The antonym of ‘complex’ is ‘simple’ but it is rare to hear of a science of simple systems. Does this mean that *all* systems studied in science are complex, and that the term ‘complex’ is redundant? Certainly the word ‘complex’ intimidates some and alienates others. The sceptical and anti-intellectual British have the expression that someone is “too clever by half” meaning that a person makes an immodest show of their knowledge and, usually, that they are not as clever as they think they are. Are complex systems scientists too clever by half, making a pretentious show of understanding which is not borne out by the achievements? Is this whole concept of ‘complexity’ a self-serving sham? Is complexity a redundant paradigm?

In this context Julian Hunt, a distinguished environmental scientist, has suggested that it may be better to speak of ‘global systems’ dynamics for the science of the interacting social and technical systems of global phenomena such as climate change. Useful though it is, this term does not seem to capture the generality of complex systems science.

In the Anglophone world people seem to be happy to talk out ‘complexity science’ while in parts of the Francophone world the term ‘complex systems science’ is preferred. The reason seem to be the need to distinguish the complex systems community from those who study computational complexity. Certainly computational complexity is very important in the science of complex systems and algorithms give one way characterising complexity. We will use the term complex systems.

In trying to give clarity to the term ‘complex’ people sometimes give the example of mechanical clock which can be ‘complicated’ but do not exhibit the property of being *adaptive*. In a changing environment a clock will not reconfigure itself to become, say, a barometer or an ammeter. In contrast many systems do exactly this and have the property that they can change their structure and dynamics. Apart from the obvious example of biological evolution, examples include market innovation and spontaneous social change such as the Arab Spring.

Laplace wrote in his 1814 *Essai philosophique sur les probabilités*, that ‘We may regard the present state of the universe as the effect of its past and the cause of its future. An intellect which at any given moment knew all of the forces that animate nature and the mutual positions of the beings that compose it, if this intellect were vast enough to submit the data to analysis, could condense into a single formula the movement of the greatest bodies of the universe and that of the lightest atom; for such an intellect nothing could be uncertain and the future just like the past would be present before its eyes'.

This view suggests that the universe is like a very complicated clock which, given its mechanics and the right data, would be entirely predictable in all its details. He was wrong. The first depends on data being finite and all measurement having a finite limit to its precision.

In the nineteen sixties the weather scientist Lorenz formulated the set of equations that now bear his name and investigated their properties using a computer. In one experiment he began a computer run from a state generated by a previous run but, to his surprise, the two runs had divergent trajectories. The reason was that the internal representation of the machine in the first run had more precision that the printout of the state that formed the initial conditions of the second run. In other words, a very small change in initial conditions can result in a very different states evolving through time. Sensitivity to initial conditions and boundedness are essential ingredient of chaos theory.

The discovery of chaos and the subsequent development of the theory of dynamical systems could be considered to constitute a success story in complex systems science since they have completely changes our understanding of what it might mean to *predict* the future states of systems. Now it is understood that for some systems there is a 'prediction horizon'. To be more precise, there are systems for which 'point predictions' that the system will be in a particular state at a particular time are meaningless. For such systems the best one can do is predict the probability of future states of the system. Sometimes the challenge is even more difficult than this since the range of possible futures is not known.

The traditional sciences have been very successful in representing the dynamics of system by formulae, often representing aggregate properties such as temperature, pressure and volume of gases. Although such systems contain large number of particles at lower levels of aggregation, those particles all appear to be the same and behave in the same way. In contrast the individuals in social systems are all different and usually their behaviour cannot be aggregated in any simple way.

One of the ideas in complex systems science is that behaviour emerges from the interaction of relatively autonomous agents. Generally every agent does not interact directly with every other. Instead there are networks of interaction. The behaviour of any individual agent usually depends on the behaviour of connected agents so that the network topology constrains the dynamics of the system.

The dynamics of networks involves various different kinds of change. Many networks carry flows such as electricity, vehicles, information, money and influence. These flows have their own dynamics across the network which may be smooth or turbulent, and may represent phase change illustrated by the formation of traffic jam shock waves when fast low density flow changes to slow high density flow. Another kind of dynamics involves the creation or destruction of links in the network illustrated by cascades of failed links in electricity supply networks or the links that people intentionally make with others on social networking sites such FaceBook. Apart from the dynamics of links, networks can undergo change in the nodes, as illustrated by opinion dynamics. In many cases the opinions people hold depend on the opinions held by others in their networks and in some cases individuals can change their opinions from one state to another and behave differently. Thus changes in opinion may percolate through a system, enabled and constrained by the by its network connectivity.

The numbers of ways even small numbers of agents can be connected and interact can be large. Even if one had perfect knowledge of the interactions and the mechanisms of the link and node dynamics, there are no known formulae for calculating their future states given their current states.

The science of complex systems addresses systems of systems of systems that may include subsystems corresponding to traditional vertical domains. For example the foot-and-mouth disease that ravaged cattle farming in the UK involved biological subsystems, the agricultural subsystems, food subsystems, the tourism subsystems, transportation subsystems, economic subsystems, and political subsystems. Specialists in none of the individual scientific domains of biology, agriculture, economics, tourism could by themselves model the phenomenon, illustrating the essential integrating nature complex systems science that makes it distinctive from traditional science.

Network dynamics are clearly important and the problem of predicting future states of systems is compounds by there often being many networks with coupled dynamics. For example, the trips that people make to work involve their family network, their employment network, and various transportation networks with related land use networks. Sometimes it seems that everything is connected to everything else.

How then can one know anything about the space of possible futures? One way that complex systems science addresses this is by computer simulation using agent based models. In other words the agents in a system and the interactions between agents are modelled, and computer programs calculate the transition from the state of the system at one tick of the clock to its state at the next. To run a simulation it is necessary to establish the initial conditions from which it will run. But if the system is sensitive to initial conditions, as almost all systems are, slightly different initial conditions could give very different outcomes. For this reason simulations are often run many times starting from many different states and by sampling in this way, in this way a picture can be formed of the huge space of future states.

Social systems are different to physical system in that formulating theories of social systems can change their behaviour so that, even if it the theory had been correct when formulated, it ceases to be correct. For example, the spread of contagious diseases is a network phenomenon. Suppose that a simulation shows that in absence of policy interventions that a city will suffer widespread infection. If this prediction is published many people may decide not to go to that city, including possible those unknowingly infected, and the infection may fail to materialise after all.

Related to this is the close relationship between social science and policy. Policy and its implementation is the deliberate attempt to change the behaviour of systems. Large scale computer simulations are becoming widely used to formulate and test policy leading to has been called *policy informatics* by Christopher Barrett, a leader in this field.

Policy informatics involves: modelling a social and infrastructure system, often using mathematical constructs; implementation of the model as computer program; data on the particular system being modelled; and policy makers who say what should be changed and how it should be changed, using the output of computer simulations to guide their decisionmaking.

For practical reasons, policy-driven science has to be parsimonious in what is included in the model and what is left out. A policy-driven study of transportation in the USA is unlikely to include the colour of people's cloths in its model while, in another context such as security this could be an essential input. Thus policy shows that we do not have a ‘theory of everything’ whose application involve inputting data relevant to the particular policy questions – rather than this policy informatics involves building models in response to policy questions. Perhaps on day these models will be synthesised into an integrated theory, but today these models are one-offs forming a patchwork science of more or less coupled models.

The science of complex systems is computer-enabled. Before the advent of powerful modern computers the kinds of simulations that characterise modern would have been impossible. Apart from the ability to perform fantastic numbers of computations, computers enable the construction of large databases which, increasingly, contain data enabled information and computer technologies. Traditional methods of collecting data on social systems were typically expensive and yielded very sparse samples of social data. By comparison, electronic records of our financial transactions and telephone usage provide unprecedented torrents of data supporting new scientific methods.

3. Criteria for success

What are the criteria for something to be a success story in complex systems science?

A practical reason for identifying success stories is that he can be shown to funders as an argument to keep supporting the science. This is clearly open to abuse with the unscrupulous or misguided pulling the wool over the eyes of funders and policy makers. As different communities compete for scarce resources it is inevitable that there will be hyperbole if not downright dishonesty. Of course in the long run the community loses credibility by such shenanigans.

We identify two major criteria for success. The first is that a piece of scientific work makes a major contribution to the field, answering an old question or setting a new promising direction of inquiry. The second is that a piece of scientific work makes an impact on society, capturing the public imagination or solving a significant problem. Often the two come together but sometimes scientific work can have high short term social impact but low long term scientific impact as ideas and discoveries are oversold or do not deliver what was expected. In this the liquid for of publication may be very valuable. A paper may begin its life in turbulent state making very interesting speculations, and as it matures it may find justification for them. However after time doubts and problems make emerge, and if these are absorbed the paper becomes a richer story as the reader can observe the evolution of its ideas. Also working in this way may stimulate other to find solutions to the openly expressed problems, enabling further scientific progress.
Complex systems science can be traced back two centuries and in that time many ideas have emerged which have become entangled and woven together into this new science. In this section we will suggest criteria for success associated with the various ideas and approached of complex systems science.

3.1 Representing dynamics by equations: dynamical systems and chaos

The processes of many systems can be characterised by numbers and their dynamics can be expressed as equations in multidimensional Cartesian spaces that can combine geometry, time and system properties such as temperature, prices, flows, and so on. The theory of dynamical systems shows that systems represented in this way may have chaotic attractors with system behaviour apparently well behaved until the system trajectory moves to another attractor. Thus small changes can have big effects, and this is interesting for managing and controlling such systems. Here the challenge is to know when a system trajectory is likely to shift attractors, and to know how to nudge the trajectory in order maintain the current state or move to dramatically new states, possibly releasing large amounts of energy or resource in the process. Any example or major theoretical development in this area could be a success story.

There are many other ideas in this area, *e.g.* dissipated structures, far from equilibrium, history of systems, path-dependence, increasing returns, and so on. Again, well documented illustration of these ideas, and any theoretical developments are success story candidates.

3.2 Time, prediction and science as the reconstruction of dynamics from data

A *point prediction* can be defined to be the assertion that a system will be in a particular state at a given point in time. This depends on how the state of the system is represented and the properties assumed of time. An *interval prediction* can be defined to be an assertion that a system will be in a particular state at a given interval in time. Probabilities can be added to these definitions so that, for example, a prediction might be a probabilistic assertion that a system will be in one a set of states in given set of time intervals. Other kinds of prediction are possible, .*e.g.* that the states in a system trajectory will be ordered in a given way, illustrated by Shakespeare's seven ages of man.

Traditionally prediction and testing predictions against data has been the test of a science, where necessary creating the data artificially in laboratories. The problem with this approach is that some systems have much longer timescales than the lifespan of human beings and there are some systems that are too large for laboratory experiments, *e.g.* those systems studies by geologists and those studied by climatologists. Furthermore, it is well known that social systems may change their behaviour in response to predictions, either making them self-falsifying or self-reinforcing. For example the prediction that terrorists will kill many people at an event may lead to that event being cancelled, while predictions in the context of policy can become self-fulfilling prophesies. Despite these problems, predictions and forecasts can be very valuable and, at worst, small and large predictions structure the future in ways that allow life to go on.

Predictions require some kind of theory of the dynamics of systems, and science is characterised by its attempt to reconstruct the dynamics of systems from data. At its simplest the term 'dynamics' means the way system states change through time, requiring time to be adequately defined to place the prediction in the future, and system state to be adequately defined to enable it to be recognised.

Any examples that can illuminate or illustrate this discuss of 'prediction' could be considered a success story. Well design experiments may show how to manage high degrees of uncertainty, and well instrumented and reported policy experiences could give deep insights.

3.3 Agency, autonomy and intelligence

In complex systems science it is recognised that some parts of systems have 'agency', with some degree of autonomy in their behaviour. The obvious example is the individual person in a social system. Human agents can be very different from each other and human agents can decide what they will do. Human agents have intelligence in that they can build up pictures of their environment and take actions that are relatively advantageous. Robots provide another example of agency, as do processes in distributed computer systems.

Agent based models have become a widely used way of modelling systems and their dynamics. Ideally the description of the agents and behaviours are based on data, and this can lead to simulated trajectories that can be construed as predictions. For some systems these are the only known ways of predicting their possible futures.

Examples of agent based models used in practice could be considered success stories, especially when they have demonstrable added value.

3.4 Networks, connectivity, interdependence and social intelligence

One of the fundamental tenets of complex systems science is that for many systems dynamic behaviour emerges from interactions. In other words the system dynamics reflect network phenomena. Although agents may be autonomous they are influenced by other agents, either directly by agents in the neighbourhood, or indirectly as effects percolate through the system. Thus agents are interdependent, influencing and being influenced by each other with the possibility of agents acting collectively with an emergent social intelligence.

Within networks there are feedback mechanisms, with negative feedback tending to return systems to previous states, positive feedback tending to move them into new states, and interacting positive and negative feedback loops that may keep systems within stable attractors.

The ‘six degree of freedom’ story is a success story in network science snce it shows that the world is much more highly connected than one might have imagined, and that news, gossip, and influence are likely to percolate rapidly through systems.

There has been a huge amount of work with network but there is clearly a need for something more. The pictures of large networks have successful illustrated the high levels of connectivity in the world. However there is an outstanding need for new analytic theory on the dynamics of networks, and the need for new theory on networks of networks. Progress here would certainly be a success story.

3.5 Evolution and Coevolution

Evolution is a powerful principle within complex systems science. To understand the dynamics of a system it is necessary to make the system and its environment as well defined as possible. Evolutionary principles say that if the environment changes the system will adapt to better fit its changed state. Reproduction in biological systems provides a heterogeneous pool of more or less well adapted individuals with constantly changing characteristics through combination and mutation. This variety allows natural selection to favour those best fitted as the environment changes. This can be illustrated by the evolution of the motor cars in environments where fuel is more or less expensive and changing social environments more disposed toward green travel.

The neat separation between system and environment is not always possible, and even when it is a system may induce coevolutionary changes on its environment. Examples include pollution of the physical environment, the creation of dust bowls through inappropriate farming, and the interaction between fashion houses and their market environment.

Co-evolution between a system and its environment can be viewed as the dynamics of a larger system that includes (parts of) the environment, so that the system is redefined with its own internal co-evolutionary dynamics. This redefines the environment leaving open the possibility of new co-evolutionary dynamics between it and the redefined system, and a regress on this until the system is a system of systems of systems that includes everything, except perhaps outer space.

Empirical examples of coevolutions based on good data with new analytic insights into coevolution could be a success story, as could be examples of how coevolution has been successfully or unsuccessfully managed in particular cases.

3.6 Multilevel systems with bottom-up, top-down and middle-out dynamics

Many systems of systems of systems have identifiable levels from microlevels through meso-levels to macro-levels, with dynamics at many levels of aggregation. Some process esare clearly bottom-up, some are clearly top-down, some are middle-out and there are coevolutions between levels in multilevel systems. For most systems there is no formalism for representing their multilevel dynamics and this is a major challenge in complex systems science. Anything that contribute to the almost non-existent theory of multilevel system could be an important success story.

3.7 Search and exploration of the space of possibilities

By any standards, Google is one of the great successes of the modern world. Google's success is based on its discovery of a new search algorithm and its ability to search huge amounts of data on web pages and return useful information. The ideas of searching spaces of possibilities was developed in the field of Artificial Intelligence, which some would see an important part of the science of complex systems. Certainly the search paradigm is relevant in systems for which there are formulae to predict their future states.

Any progress in the area of search could be a success story for complex systems science, including the huge amount of effort going in to data mining. We are still waiting for the success story about the 'ultimate Google' suggested by (??) where one asks a question in ordinary language and the system can understand the semantics of the question, devise a search strategy, find the relevant information, and synthesise it into a coherent answer.

3.8 Self-organisation, emergence & creation of new order

Many complex systems such as the internet or social groups do not have centralised top-down control, and it is increasing realised that this may not be appropriate for some social and technical systems. More to say

3.9 The language of complex systems

Whereas Galileo said that "mathematics is the language of the universe"[check quotation], and many complex systems scientists believe that mathematics and computation are essential for complex systems science, it is striking that almost all policy and the management of all systems from the family to the United National is articulated in natural language such as English.

Complex systems science has an unresolved problem. People in positions of authority and power ant to use its insights but they will never understand its technicalities. There is no indication that this will change. Generally scientists do not put themselves forward for election, and those devote their lives to politics generally do not have the time or inclination to learn technical things.

At a recent meeting on complex systems a member of the audience asked "isn't it all just common sense". An answer was given that, ideally it is common sense. However, whereas one can build a dog kennel using common sense you cannot build a skyscraper using common sense alone.

Bridging the gap between those who use exclusively natural language to control and manage complex systems, and the technical science of complex systems that might help would be very important success story in this science.

4. Success stories

Several success stories were collected within the complex systems research community, during the period 2009-11.

These success stories are actually published in the Liquid Journal of Complex Systems, allowing authors to receive some feedback from the community and improve their articles, from the liquid turbulent to the liquid flowing states, until a liquid published state where success stories will be printed and distributed in a hard copy of the journal.

Their origin is from specific work developed within some research lab (the case of ‘Large-Scale On-Line Game’, developed at the Section for Science of Complex Systems, Medical University of Vienna) or company (the case of ‘Scheduling Systems’, developed at Magenta Corporation and Knowledge Genesis), but most of them are the result of European funded research projects, such as ‘SYNLET - Novel Routes in Cancer Therapy’, ‘EMBIO - Complex Biomolecular Systems’, ‘GABA - Brain Activity, from Cognition to Disease’, ‘GENNETEC - GENetic NETworks’, ‘E2–C2 - Extreme Events’, and ‘BRACCIA - Nonlinear Dynamics of Anaesthesia’.

The success stories were classified according to the criteria previously detailed in section 3, as follows.

4.1 Major criteria of success: contribution to the field and impact on society

The two major criteria for success considered were that research proposes a major contribution to the field, or it makes an impact on society, contributing for solving a significant problem. Ideally these two criteria come together. However, this is not always the case, as it is made clear by the table below.

Success story	Scientific work makes a major contribution to the field	Scientific work makes an impact on society
Large-Scale On-Line Game	Yes: the scientific work concerns systemic properties of human groups, providing two new empirical social laws and strong quantitative evidence for classical social balance assumptions: the weak ties hypothesis and triadic closure.	Not yet. Results might be applied in the future for understanding social dynamics.
Scheduling Systems	No.	Yes: improvement of the scheduling in large systems such as taxis in London and crude oil sea-going tankers around the

Success story	Scientific work makes a major contribution to the field	Scientific work makes an impact on society
		world. Impact: performance of these transportation networks.
Novel Routes in Cancer Therapy	Yes: identification of novel targets for overcoming chemoresistant neuroblastoma, as well as the first neuroblastoma candidate therapy targets grounded on the concept of synthetic lethality. The workflow of merging Omics data, the concept of synthetic lethality, and a computational network analysis procedure, provide from now on a good framework for identifying novel cancer targets in general.	Not yet. Results will take around ten years to be evaluated. Potentially a strong impact in health care.
Complex Biomolecular System	Yes: approaches and algorithms for quantitative estimation of complexity of general multidimensional dynamic systems were collected, and specifically concerning self-organising biomolecular systems. These approaches can now be applied to a large variety of complex systems in any branch of natural and social sciences.	Not yet. Results might improve research on any multidimensional dynamic systems in natural and social sciences.
Brain Activity, from Cognition to Disease	Yes: description of the phenomenon of neuronal synchronization at a wide range of spatial scales as a major orchestrator of brain integration processes, including: computing functional connectivity between brain activities; a novel analytic methodology to measure abnormal synchronization allowing to understand how normal aging and pathological senescence differentially affect Neural coupling strength; topology of interconnected modular organizations in the brain; connectivity dynamics in such networks; shape identification in the brain visual system.	There is no quantification of results yet. Results are expected to be relevant in the early diagnosis of Alzheimer's disease and the anticipation of epileptic seizures.
Genetic Networks	Framework allowing to simultaneously describe a given complex object at multiple scales: algorithms for sampling and counting systems with multiple	Not yet. Very promising set of applications concern discovery or completion of genetic networks from incomplete data.

Success story	Scientific work makes a major contribution to the field	Scientific work makes an impact on society
	scales, such as RNA sequences; modelling systems with multiple objectives and an underlying network of regulatory interactions	
Extreme Events	Interaction between the natural and human sciences; study of longtime memory processes	Not yet. Statistics of extremes in non-stationary cases in order to assess the impact of rare environmental events on well defined socio-economic fields; possible applications: climate data, probabilistic and dynamic geophysical models, coupled climate, and economic models
Nonlinear Dynamics of Anaesthesia	New methods for assessment of depth of anaesthesia, including analyses of directions of coupling, and possible interactions between cardiovascular and neural (cortical) oscillations; complex interactions between brain waves and cardio-respiratory oscillations that occur during anaesthesia	Yes. Marked changes occur in the inter-oscillator interactions during anesthesia; further results are expected from applying the new methods of analysis

Table 1: Major criteria of success

4.2 Mesures of success associated with the complex systems science approaches

The criteria proposed on section 3.2 were used to measure success specifically concerning complex systems science ideas and approaches.

Success stories / Criteria	Large-Scale On-Line Game	Schedu-ling Systems	Novel Routes in Cancer Therapy	Complex Biomole-cular System	Brain Activity, from Cognition to Disease	Genetic Networks	Extreme Events	Nonlinear Dynamics of Anaes-thesia
Representing dynamics by equations: dynamical								X

systems and chaos								X
Time, prediction and science as the reconstruction of dynamics from data	X						X	X
Agency, autonomy and intelligence	X	X						
Networks, connectivity, interdependence and social intelligence	X	X	X		X	X		
Evolution and Coevolution	X						X	
Multilevel systems with bottom-up, top-down and middle-out dynamics				X	X	X	X	
Search and exploration of the space of possibilities								
Self-organisation, emergence & creation of new order	X	X		X				
The language of complex systems								