Chapter 2
Complexity Sciences

Overview. Complexity sciences, in plain English, are the *sciences of interconnectedness*.

The aim of complexity sciences is to understand the many different facets of phenomena. Complexity sciences employs a variety of different methodological approaches to describe and to analyse multifaceted phenomena like health, the economy or environmental systems.

- Basically, a system consists of a number of parts that are connected to each other. Systems differ depending on the nature of their connectedness. Simple systems have one-to-one relationships and their behaviour is precisely predictable. Complicated systems have one-to-many relationships with mostly predictable behaviours
- This book deals with *complex adaptive systems* with many-to-many relationships. Their many-to-many relationships make their behaviour emergent, hence their outcomes are unpredictable. Complex adaptive systems have a special characteristic, the members of the system can *learn* from feedback and experiences. The relationships in complex adaptive systems change constantly allowing the system to evolve over time in light of changing demands. However, a system's overall behaviour, despite its adaptation to changing circumstances, remains relatively stable within boundaries, but occasionally, its behaviour may change abruptly and dramatically for no apparent reason

One can compare the behaviour of complex adaptive systems to that of a family; most of the time a family stays together despite ups and downs, but occasionally a family can abruptly break apart to the surprise of its members and its surroundings.

- Another important characteristic of complex adaptive systems is its nonlinear behaviour to change, i.e. the magnitude of change in one member of the system shows a disproportional change in that of others. As experience shows, small changes in the behaviour of a system member often show dramatic changes in

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the behaviour of the whole system, whereas a major change in the behaviour of that member typically results in little or no change

Studying complex adaptive systems aims to understand the relationships and the dynamics between the members of the systems. This understanding allows for better responses when the system as a whole is challenged by constraints and/or unfamiliar challenges.

A special characteristic of *social systems* is their "goal-delivering" nature. In organisational terms these are codified by their purpose, goals and values statements.

Points for Reflection

- What do you understand by the terms “complex/complexity”?
- What do the terms “complex health system”, “complex disease”, and “complex patient” mean to?
- How do you explain the nature of this “complexity”?
- How do you suggest to best manage this “complexity”?

Systems thinking is a discipline of seeing whole.

– Peter Senge

Everyone has experienced the complexities of the health system, irrespective of their particular role along the continuum of being a patient, working in grass roots care delivery to having overarching policy and financing responsibilities. We are all part of many different systems within the entire health system. We all have observed and experienced the at times surprising behaviours inside our "immediate working system" and the system as a whole. Most of us would have forwarded hunches why a particular system outcome may have occurred. Some of us may well have been involved in analysing "system failures", but did we do so from an understanding of the interconnected behaviours of complex adaptive systems?

Some preliminary considerations:

- "Complexity sciences" still is an emerging field of scientific endeavour (Addendum 1) and entails a number of different methodological approaches like system dynamics, agent-based modelling, or network analysis
- The *colloquial* meaning of complex/complexity needs to be distinguished from its *scientific* meaning. The colloquial meaning of complex/complexity as "difficult to understand" or "complicated" must be distinguished from the scientific meaning of "*the property arising from the interconnected behaviour of agents*"
- "Complexity sciences" defines a worldview that no longer sees the world as mechanistic, linear, and predictable. Rather it sees the world as interconnected. The interactions between elements being nonlinear make the behaviour of complex systems unpredictable (Fig. 2.1)
- Paul Cilliers outlined the philosophical foundations of complexity sciences, parts of which are quoted in more detail in Addendum 2
- The "complexity science framework", like any other scientific framework, provides a mental mind model ABOUT the world, i.e. *The truth of a theory is in your mind, not in your eyes*—Albert Einstein [1]
- Mental models (or worldviews) necessarily have to reduce the real complexity of any phenomenon being described [2, 3]. Useful models, as Box [3] stated,[1] are those that *describe the observed causal relationships* in the real world[2] [4]
- "Complexity" in its scientific understanding refers to "*the nature of the problem* ***not*** [emphasis added] *the degree of difficulty*" [5]. The systems theorist David Krakauer illustrates this aspect in relation to Ebola and is quoted in detail in Addendum 3
- "Complexity" exists at every scale, be it at the laboratory or the whole of society level
- The way we look at "things" determines what we see and how we understand. Understanding "things" at the **small scale** results in *greater certainty BUT loss*

[1] *Essentially, all models are wrong, but some are useful.* Box, George E. P.; Norman R. Draper (1987). Empirical Model-Building and Response Surfaces [3, p. 424].

[2] However, there are also many unobserved causal relationships (latent variables).

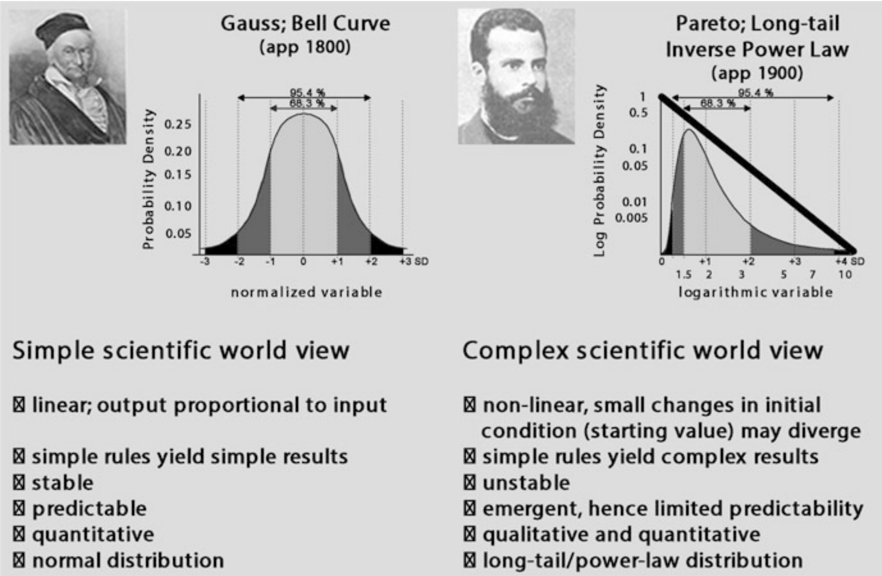


Fig. 2.1 Comparison of the characteristics of the simple scientific and complex scientific world views

of context, whereas understanding "things" at the **large scale** results in *greater uncertainty AND loss of detail* (Fig. 2.2)

2.1 Complex Systems Are . . .

Systems are described in terms of their structure and relationships (Fig. 2.3). The interactions between the system's agents create an emergent order resulting in the formation of patterns—the process is entirely self-organising [6].

2.2 The Essence of Systems Thinking

As Gene Bellinger put it so succinctly: the *Essence of Systems Thinking* is *Understanding Relationships and Their Implications*.[3]

Systems thinking is an approach to solve problems, where problems are the gap between the existing state and a desired state. Solution narrows or overcomes that gap. Understanding the complexities of a complex adaptive problem in their entirety and finding the *best* solution to overcome such a problem requires (1) the

[3]https://www.linkedin.com/pulse/essence-systems-thinking-gene-bellinger.

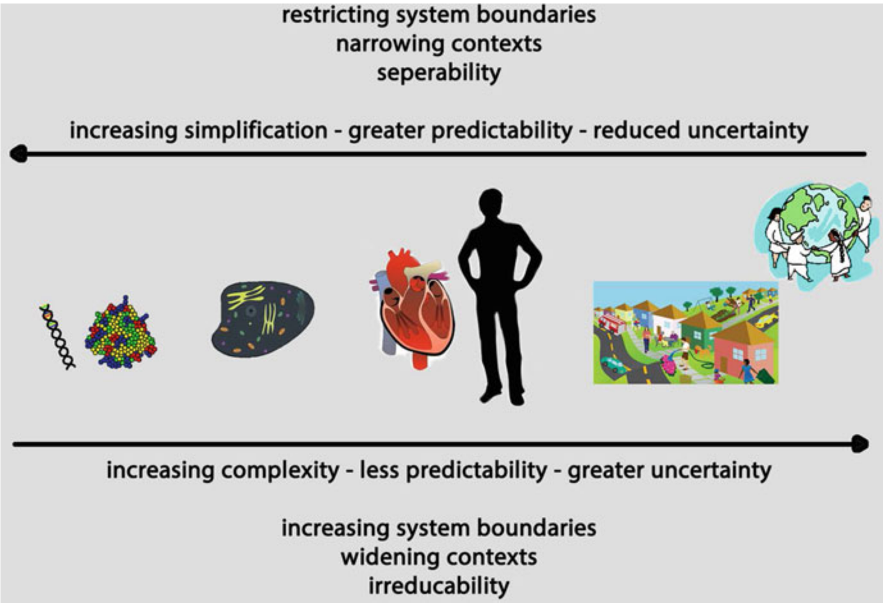


Fig. 2.2 The scale relationship and its impact on complexity and context. At the small scale we have greater certainty but loose context, at the large scale we see the greater context but lose detail

appreciation of the linkages between the elements of the problem and (2) how changes to the behaviour of one element might affect the problem in its entirety. Will an intervention solve the problem, or will it result in unintended consequences making the problem worse or will it create entirely new problems (Fig. 2.4)?

2.3 Complex Systems Theory: An Overview

Complex systems theory has arisen from two main schools of thought—general systems theory and cybernetics. As a theory it provides a ***model of reality NOT reality itself***. However, models provide a useful frame to solve many common problems.

We can use systems theory to distinguish between different types of systems. Along a continuum, they can be classified as simple, complicated, complex (dynamic), and complex adaptive systems (differences are summarised in Table 2.1). Systems theory provides a means to help us make sense of our "wicked" world.

In *simple systems*, elements of the system interact in one-to-one relationships producing predictable outcomes. Simple systems can be engineered and controlled. They are closed to and therefore not influenced by their external environment.

Complicated systems display some of the same characteristics of simple systems in that interactions between elements in the systems are predictable, although

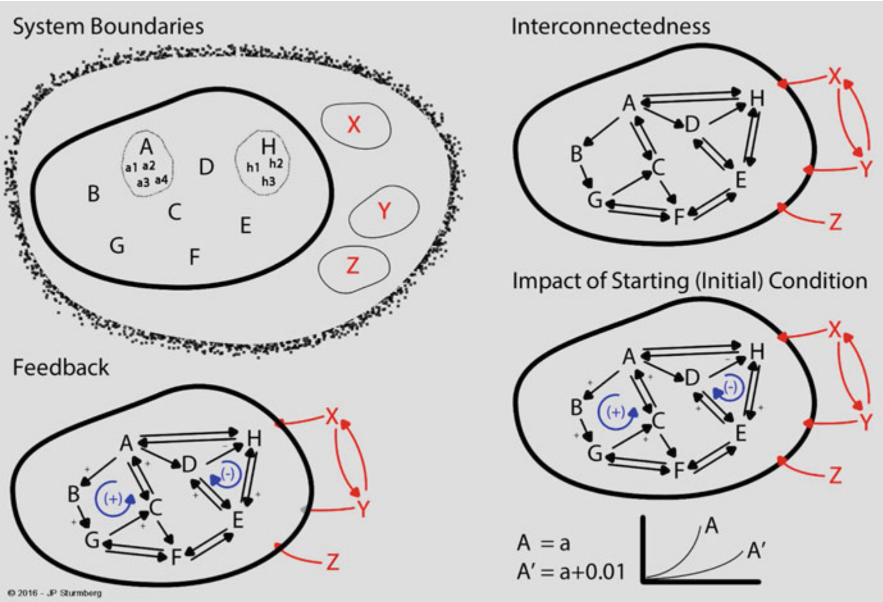


Fig. 2.3 Key features of complex systems. A complex system's structure describes the collection of agents (A–H) contained within a permeable or *fuzzy boundary* (*black circle*), where each agent represents a smaller subsystems (a1–a4) and is part of a larger supra-system (*dotted line*) (*top left*). Agents are interconnected in multiple ways (*top right*), and interconnection often result in *feedback loops* that either *reinforce* (+) or *self-stabilise* (−) the system's dynamic behaviour (*bottom left*). The dynamic behaviour of a complex system can vary greatly with even small changes in a variable's *starting (initial) condition* (*bottom right*). Whilst systems are bounded they receive inputs from and provide outputs to other systems (X–Z) within a larger supra-system

any one element of the system may interact with multiple other elements of the system. Relationships are still linear and outcomes remain predictable. Generally speaking, "complicated" refers to systems with sophisticated configurations but highly predictable behaviours (e.g. a car or a plane)—the whole can be *decomposed* into its parts and when reassembled will look and behave again exactly like the whole. They are also closed to and therefore not influenced by the external environment.

Complex dynamic systems have two key characteristics, they *self-organise* without external control and exhibit *feedback* resulting in newly created, i.e. *emergent* (at times unforeseen), behaviours. ***Complexity*** is the *dynamic property of the system*; it results from the interactions between its parts. The more parts interact in a nonlinear way in a system the more complex it will be. Complex systems are also open, loosely bounded, and influenced by their environment. Such *fuzzy boundaries* entail some arbitrariness in defining a system.

While any one system as a whole may be defined as a complex system, inevitably subunits are also complex systems in their own right. Thus any defined complex system has to be thought of as being simultaneously a subsystem of a larger system

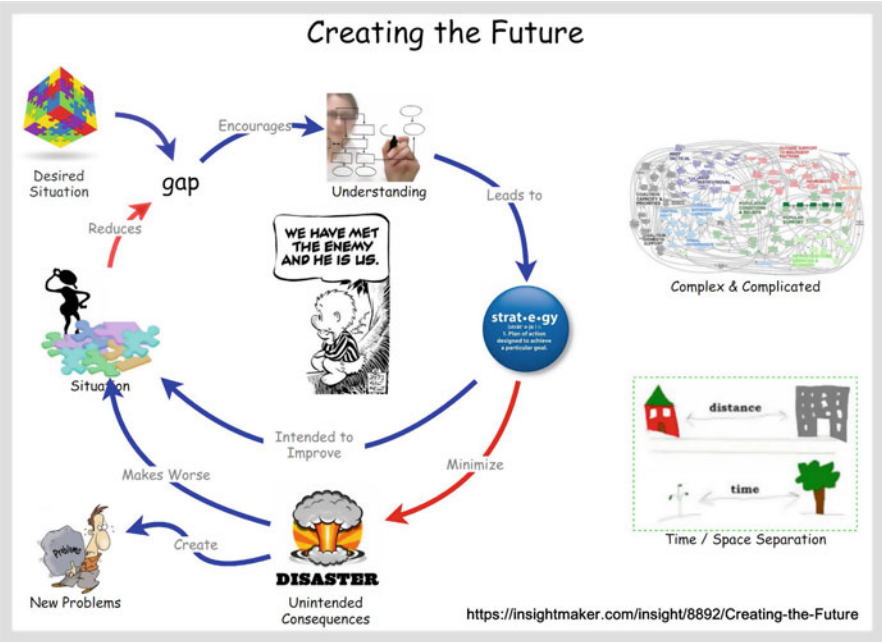


Fig. 2.4 The essence of systems thinking. Created by Gene Bellinger in Insightmaker, https://insightmaker.com/insight/8892/Creating-the-Future (Creative commons attribution licence)

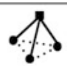
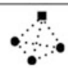
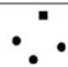
(or a supra-system) and a supra-system constituted by a number of subsystems (defining the nested structure of systems).

Complex adaptive systems (CAS) are complex dynamic systems whose elements (agents) learn and adapt their behaviours to changing environments. In the complex adaptive systems literature the elements of the system are referred to as agents. Complex dynamic and complex adaptive system behaviour is influenced by the *system's history*, i.e. influences that have resulted in the current state of a system have ongoing effects on future states.

The make-up of the complex and complex adaptive systems presents certain problems in terms of being able to understand, describe, and analyse them. While simple and complicated systems lend themselves to cause-and-effect analysis, complex and complex adaptive systems require a mapping of relationships and drawing of inferences that may be theory based or drawn from multiple sources of knowledge. The Cynefin Framework [6] provides an excellent way to understand the different degrees of complexity in CAS and is discussed in detail in the next chapter.

Understanding the differences between types of systems is often the clearest way to differentiate the various types of systems. Table 2.1 summarises features of simple, complicated, and complex systems and the language used in the literature to describe them.

Table 2.1 Result of a long day at work

Types of Systems	Simple	Complicated	Complex	
	Mechanical systems		Complex (dynamic) systems	Complex adaptive systems
				
Structure of System	One-to-one relationships 	One-to-many relationships 	Many-to-many and system-to-system relationships (nested systems) 	
Outcomes	Highly predictable	Mostly predictable	Alter with history and initial conditions Unpredictable/emergent Complex - Chaotic	
	Linear			
Outcome Patterns	A change in x results in a proportional change in y		A change in x results in a disproportional change in y	Attractor patterns that may be appear chaotic
Control of System	*Engineered*		*Living systems follow the laws of nature*	*Social "laws"*. No controlling agent
				Purpose, goals and values define *simple rules* for interactions
Properties of System			*Self-organisation* results in *emergent* behaviour Complexity of systems increases with the rise in number of agents	
Relationship to environment	Closed		Open âĂŞ loosely bounded	
Relationship of components/agents				
Behaviour of components/agents	Cause and effect repeatable, predictable	Cause and effect are separated over time and space	Cause and effect only coherent in retrospect and are not repeatable	No cause and effect relationships are perceivable (might or might not exist)
Analysis	Cause and effect analysis (reductionism)		Structure: mapping Function: inference based on pattern recognition	Structure: mapping Function: inference based on pattern recognition and/or prior knowledge
Testing	Lab	Lab/Discrete event and/or system dynamics modelling	Lab/field and/or system dynamics modelling	Agent-based modelling Field trials
Generalizability	Yes	Yes	No	No

2.4 A Detailed Description of "Complex Adaptive Systems"

CAS are systems whose components/agents can change in their characteristics and behaviours over time as they are able to learn and adapt. Characteristics and behaviours of individual components/agents are often well understood; however, when components/agents interact in nonlinear ways and provide feedback to each other, the outcomes of the system's behaviour have a level of unpredictability. While the underlying "cause and effect relationships" resulting in the observed system's behaviour are understandable in retrospect, their behaviour cannot be precisely predicted looking forward [7].

Detailed definitions of the main CAS properties are listed in Table 2.2 and illustrated in relation to healthcare delivery and health policy.

The key concepts of a CAS [7, 36–49] are:

- *Agents* (or components) are connected within loosely defined or *fuzzy boundaries*; each CAS is simultaneously a subsystem of a larger system (or a supra-system) and is itself constituted by a number of subsystems (the nested structure of systems)
- *Agents* (e.g. humans) in a CAS can change in terms of their structural position in the system as in their relational behaviour
- The interactions between agents within a CAS define the systems *typically nonlinear dynamic*. Interactions are:
  - *Sensitive to initial condition*, i.e. bound by their historical and contextual conditions
  - "*Path dependent*", i.e. prior decisions result in bifurcation (branching) of the systems behaviour
  - Are stable to many interventions, but change suddenly when reaching a *tipping point*
  - Result in *feedback loops*, i.e. an output becomes a new input, which modifies agents future behaviour (reinforcing or self-stabilising/balancing feedback)
  - *Emergent*, thus *self-organising*, as a result of the above
- For a social system to be a "goal-delivering CAS" its *purpose, goals, and values* need to be clearly defined a priori[4] [42, 49–54]
- Agreed *purpose, goals, and values statements* are the basis for defining the driver of the system; together they give rise to the "operational instructions" that coherently direct the interactions within a CAS. These are termed "*simple (or operating) rules*", usually 3 but never more than 5, and must not be contradictory

[4]To avoid confusion: from a systems theoretical perspective (and design thinking approach) purpose, goals, and values are defined a priori, when exploring existing systems they can be deduced a posteriori. The analysis of systems will be explored in Part III.

Table 2.2 Key properties of complex adaptive systems (CAS)

Nonlinearity • Results not proportional to stimulus • Can lead to sudden massive and stochastic changes of the system • Sensitive to initial conditions • Accumulations, delays, and feedbacks	• Allergic responses and anaphylaxis • More intensive glucose control increase mortality [8] • Response to coumadin-therapy • Increasing the dose of chemotherapy does not improve therapeutic response or survival [9] • Chemotherapy initially not only reduces tumour size but also induces the promotion of secondary tumours [10]	• Large investment in health services has not been matched by a similar magnitude of improvement in inequity between social classes [11] • The introduction of electronic prescribing systems had mixed impacts on appropriateness and safety of prescribing and patient health outcomes [12, 13]
Open to environment • A system continuously interacts with its environment, e.g. exchanging material, energy, people, capital, and information • Nonlinear responses to the external environment can lead to sudden massive and stochastic changes	• Physiological function – Immune system – Respiratory tract – Gastrointestinal tract – Skin – Semi-permeable membranes • Pathological function – HIV/AIDS – Asbestosis – Food poisoning – Burns	• Strategies to train and maintain more health professionals need to account for competing individual, organisational and social factors in motivation, and other markets [14] • An epidemic like SARS arises from the global openness to fluidity, flows, mobility, and networks [15]
• Relies on four basic principles – Recursive feedback (positive and negative) – Balance of exploitation and exploration – Multiple interactions	• "Homeostasis" in health, e.g. – Blood glucose levels – Thyroxin levels – Water balance and creatinine levels • And disease, e.g. – Stable heart failure – Intermittent claudication – Hypogonadism	• DRG (Diagnostic Related Group) payment mechanisms leads to – Gaming – Category creep – Shift of emphasis [16] • The natural formation of viable high performing teams is based on multiple interactions and feedback [17]

(continued)

Table 2.2 (continued)

Self-organisation Emergence • Occurs when a number of simple entities (agents) operate in an environment, forming more complex behaviours as a collective • Arises from intricate causal relations across different scales and feedback—interconnectivity • The emergent behaviour or properties are not a property of any single such entity, nor can they easily be predicted or deduced from behaviour in the lower-level entities: they are irreducible	• Appearance of superbugs in response to antibiotic therapies • Appearance of previously unknown infectious disease epidemics like SARS [18] • Emergence of drug side effects in particular individuals • Emergence of new patterns of morbidity, gene expression, as the population ages • Brain function from complex cellular self-organisation	• Prevention paradox—inequities emerge when "innovative" health promotion guidelines are put into place without considering social and cultural assumptions between public health practitioners and target groups as is seen in – Screening programmes – Well baby checks – Teenage pregnancy education – Smoking cessation programmes [19] • The addition of nurse practitioners to primary care – Did not alter costs or efficiencies – Did address considerable other unmet needs [20]
Pattern of interaction • Different combinations of agents lead to the same outcome, or • The same combination of agents leads to different outcomes	• Sinus-rhythm heart-rate variability in patients with severe congestive heart failure [21] • Loss of beat-to-beat variability in autonomic neuropathy [22] • Cheyne–Stokes breathing [21] • Most patients with cancer display drastically different patterns of genetic aberrations [23] • Many biological factors (genetic and epigenetic variations, metabolic processes) and environmental influences can increase the probability of cancer formation, depending on the given circumstances [24]	• Patterns of maternity provider interaction appropriate for the local context influence the emotional well-being of rural mothers [25] • International comparison shows that many diverse multifaceted health services lead to remarkably similar outcomes – Smoking cessation successes [26] – Obesity challenges exist across diverse cultures and levels of development despite evidence-based national dietary guidelines [27]

Adaptation and evolution • In the clinical context, numerous diseases develop over many years, during which time the "whole body system" has adapted to function in the altered environment • Changes involve the whole system and are not restricted to a few clinically measurable factors • Adaptation leads to a new homeostasis with new dynamic interactions [28]	• Hypothyroidism • Coronary artery disease due to stable plaques • "Burnt-out" rheumatoid arthritis • Stable chronic obstructive airways disease • Coeliac disease • Cataract • Hearing impairment	• Adjustments to the health care system due to challenges in – Health care delivery – Financing – The rate of development of new health technologies – Rising community expectations [29] • Stable ritual of clinical care delivery despite ongoing reforms, research, and interventions [30] • Healing tradition moves from mainstream health care to alternative health care [31]
Co-evolution • Each agent in the exchange is changed • Parallel development of a subsystem with new characteristics and dynamics	• The physician learns from the patient and the patient learns from the physician [32] • A person becomes blind AND develops superb hearing • Microorganisms succumb to antibiotic therapies AND some develop drug resistance	• Local systems function well in response to local need in spite of or in parallel to top-down health initiatives – User driven health care [33] – Self-help groups [34] – Health 2.0 [35]

The 2nd and 3rd columns provide examples that illustrate the effect of a property in the context of clinical care and health system reform

- "Simple rules" reflect the core values of a social systems. *Core values* are those that remain unchanged in a changing world.[5] If internalised and adhered to by all agents it results in the "smooth running" of the system (e.g. the flocking birds) [43, 47, 54, 55]
- "*Simple rules*" provide the necessary "safe space/freedom" to adapt an agent's behaviour under changing conditions. Adaptation is desirable; it fosters creativity and provides flexibility; it is the prerequisite for the emergence of the system and the achievement of its goals (learning) [43, 47, 54, 55]

In CAS "control" tends to be highly dispersed and decentralised [38]. CAS activity results in patterned outcomes, based on purpose, goals, and values within the constraints of the local context. These outcomes, while not necessarily intuitively obvious, are the result of the emergent and self-organising behaviour of the system. Local outcome patterns, while different, are "*mutually agreeable*".

Of note, system solutions—often termed innovations—are unique; they *cannot be transferred* from one place to another as the local conditions that resulted in the system's outcome will be different, the reason why even proven innovations fail when transferred into a different context [56].

2.5 Consequences of Complex Adaptive System Behaviour

Understanding the structure and dynamic behaviours of complex adaptive systems explains some of the seemingly perplexing observations:

- Nonlinearity means disproportional outcome responses to rising inputs, very small inputs may result in very large ("chaotic") responses and vice versa large inputs may result in no change whatsoever
- Nonlinear behaviour makes outcomes less predictable
- The "same" intervention in different location often results in a number of outcome patterns as the *initial conditions* vary somewhat between locations. *These patterns describe mutually agreeable outcomes*
- Feedback loops contribute to the robustness of a system
- Core values define a system's driver and "determine" the direction the system takes. Different core values within a system's subsystems can result in very different system behaviours which may or may not lead to conflict, e.g. the "*cure*-focus" of an oncologist may lead to desperate interventions whereas the "*care*-focus" of a palliative care physician may lead to ceasing treatments in favour of improving the patient's remaining quality of life

[5] [What are core values? http://www.nps.gov/training/uc/whcv.htm, How Will Core Values be Used? http://www.nps.gov/training/uc/hwcvbu.htm]. Together they provide the foundation for solving emerging problems and conflict.

- In an integrated system, subsystems may have a set of unique purpose, goals, and values; however, in overall terms they need to align themselves with the main purpose, goals, and values of the system to contribute seamlessly to its overall function

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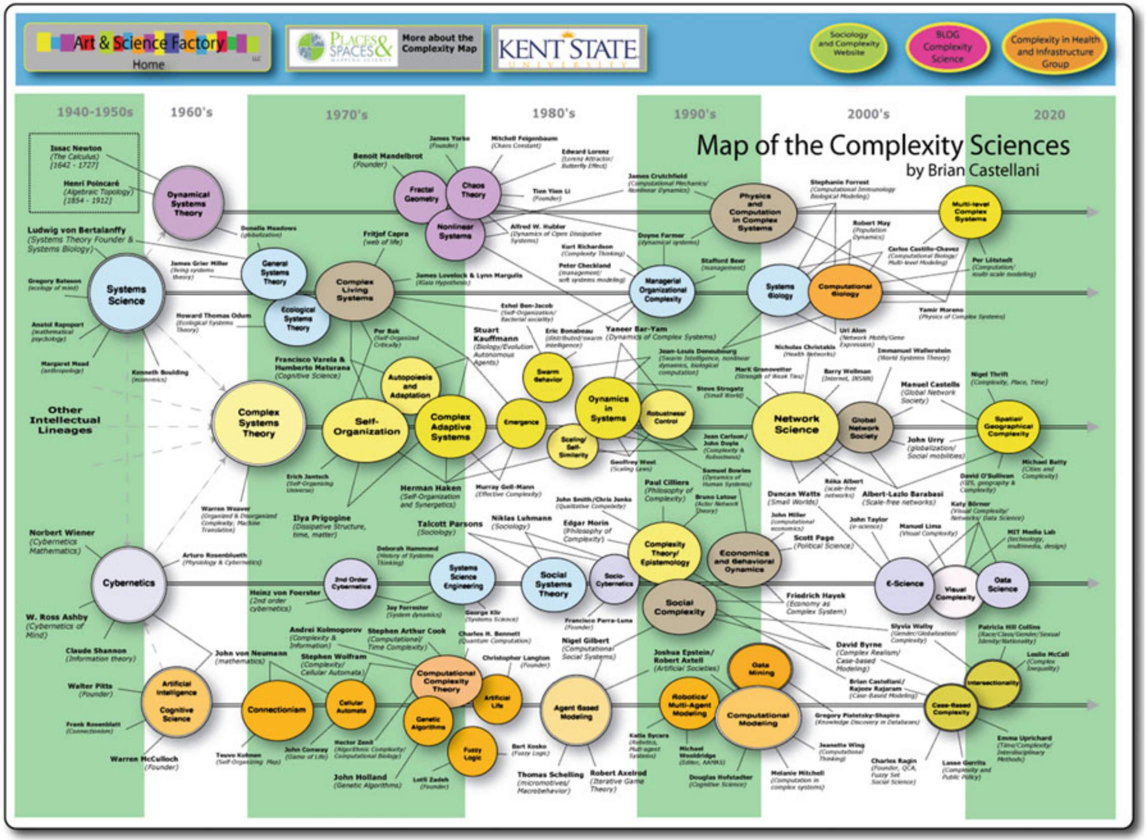
Addendum 1

The History of Complexity Sciences



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Addendum 2

The Philosophy of CAS - Paul Cilliers [57]

The notion "complexity" has up to now been used in a somewhat general way, as if we know what the word means. According to conventional academic practise it would now be appropriate to provide a definition of "complexity". I will nevertheless resist this convention. There is something inherently reductionist in the process of definition. This process tries to capture the precise meaning of a concept in terms of its essential properties. It would be self-defeating to start an investigation into the nature of complexity by using exactly those methods we are trying to criticise! On the other hand, we cannot leave the notion of "complexity" merely dangling in the air; we have to give it some content. This will be done by making a number of distinctions which will constrain the meaning of the notion[6] without pinning it down in a final way. The characterisation developed in this way is thus not final—in specific contexts there may be more characteristics one could add, and some of those presented here may not always be applicable—but it helps us to make substantial claims about the nature of complexity, claims that may shift our understanding in radical ways.

In the first place one should recognise that complexity is a characteristic of a system. Complex behaviour arises because of the interaction between the components of a system. One can, therefore, not focus on individual components, but on their relationships. The properties of the system emerge as a result of these interactions; they are not contained within individual components.

A second important issue is to recognise that a complex system generates new structure internally. It is not reliant on an external designer. This process is called self-organisation. In reaction to the conditions in the environment, the system has to adjust some of its internal structure. In order to survive, or even flourish, the tempo at which these changes take place is vital (see Cilliers, 2007 for detail in this regard). A comprehensive discussion of self-organisation is beyond the scope of this chapter (see Chap. 6 in Cilliers, 1998 for such a discussion), but some aspects of self-organisation will become clear as we proceed.

An important distinction can be made between "complex" and "complicated" systems. Certain systems may be quite intricate, say something like a jumbo jet. Nevertheless, one can take it apart and put it together again. Even if such a system cannot be understood by a single person, it is understandable in principle. Complex systems, on the other hand, come to be in the interaction of the components. If one takes it apart, the emergent properties are destroyed. If one wishes to study such systems, examples of which are the brain, living systems, social systems, ecological systems, and social-ecological systems, one has to investigate the system as such. It is exactly at this point that reductionist methods fail.

[6]The significance of "constraints" is discussed in the chapter.

One could argue, however, that emergence is a name for those properties we do not fully understand yet. Then complexity is merely a function of our present understanding of the system, not of the system itself. Thus one could distinguish between epistemological complexity—complexity as a function of our description of the system—and ontological complexity—complexity as an inherent characteristic of the system itself. Perhaps, the argument might go, all complexity is merely epistemological, that finally all complex systems are actually just complicated and that we will eventually be able to understand them perfectly.

If one follows an open research strategy—a strategy which is open to new insights as well as to its own limitations—one cannot dismiss the argument above in any final way. Nevertheless, until such time as the emergent properties of a system are fully understood, it is foolish to treat them as if we understand them already. Given the finitude of human understanding, some aspects of a complex system may always be beyond our grasp. This is no reason to give up on our efforts to understand as clearly as possible. It is the role of scientific enquiry to be as exact as possible. However, there are good reasons why we have to be extremely careful about the reach of the scientific claims we make. In order to examine these reasons in more detail, a more systematic discussion of the nature of complex systems is required. The following characteristics will help us to do this[7]:

1. Complex systems are open systems.
2. They operate under conditions not at equilibrium.
3. Complex systems consist of many components. The components themselves are often simple (or can be treated as such).
4. The output of components is a function of their inputs. At least some of these functions must be nonlinear.
5. The state of the system is determined by the values of the inputs and outputs.
6. Interactions are defined by actual input–output relationships and these are dynamic (the strength of the interactions changes over time).
7. Components, on average, interact with many others. There are often multiple routes possible between components, mediated in different ways.
8. Many sequences of interaction will provide feedback routes, whether long or short.
9. Complex systems display behaviour that results from the interaction between components and not from characteristics inherent to the components themselves. This is sometimes called emergence.
10. Asymmetrical structure (temporal, spatial, and functional organisation) is developed, maintained, and adapted in complex systems through internal dynamic processes. Structure is maintained even though the components themselves are exchanged or renewed.

[7]These characteristics were formulated in collaboration with Fred Boogerd and Frank Bruggemans at the Department of Molecular Cell Physiology at the Free University, Amsterdam, based on the arguments in Cilliers (1998), and used in Cilliers (2005).

11. Complex systems display behaviour over a divergent range of timescales. This is necessary in order for the system to cope with its environment. It must adapt to changes in the environment quickly, but it can only sustain itself if at least part of the system changes at a slower rate than changes in the environment. This part can be seen as the "memory" of the system.
12. More than one legitimate description of a complex system is possible. Different descriptions will decompose the system in different ways and are not reducible to one another. Different descriptions may also have different degrees of complexity.

If one considers the implications of these characteristics carefully a number of insights and problems arise:

- The structure of a complex system enables it to behave in complex ways. If there is too little structure (i.e. many degrees of freedom), the system can behave more randomly, but not more functionally. The mere "capacity" of the system (i.e. the total amount of degrees of freedom available if the system was not structured in any way) does not serve as a meaningful indicator of the complexity of the system. Complex behaviour is possible when the behaviour of the system is constrained. On the other hand, a fully constrained system has no capacity for complex behaviour either. This claim is not quite the same as saying that complexity exists somewhere on the edge between order and chaos. A wide range of structured systems display complex behaviour
- Since different descriptions of a complex system decompose the system in different ways, the knowledge gained by any description is always relative to the perspective from which the description was made. This does not imply that any description is as good as any other. It is merely the result of the fact that only a limited number of characteristics of the system can be taken into account by any specific description. Although there is no a priori procedure for deciding which description is correct, some descriptions will deliver more interesting results than others
- In describing the macro-behaviour (or emergent behaviour) of the system, not all the micro-features can be taken into account. The description on the macro-level is thus a reduction of complexity, and cannot be an exact description of what the system actually does. Moreover, the emergent properties on the macro-level can influence the micro-activities, a phenomenon sometimes referred to as "top-down causation". Nevertheless, macro-behaviour is not the result of anything else but the micro-activities of the system, keeping in mind that these are not only influenced by their mutual interaction and by top-down effects, but also by the interaction of the system with its environment. When we do science, we usually work with descriptions which operate mainly on a macro-level. These descriptions will always be approximations of some kind

These insights have important implications for the knowledge-claims we make when dealing with complex systems. Since we do not have direct access to the complexity itself, our knowledge of such systems is in principle limited. The problematic status of our knowledge of complexity needs to be discussed in a little more detail. Before doing that, some attention will be paid to three problems: identifying the boundaries of complex systems, the role of hierarchical structure, and the difficulties involved in modelling complexity.

Addendum 3

Why Do We Need the Science of Complexity to Tackle the Most Difficult Questions? - David Krakauer

One quite useful distinction that one can make is between the merely complicated and the complex. So the universe is complicated in many parts; the sun is complicated, but in fact I can represent in a few pages of formula how the sun works. We understand plasma physics; we understand nuclear fusion; we understand star formation.

Now, take an object that's vastly smaller. A virus, Ebola virus. Got a few genes. What do we know about it? Nothing. So how can it be that an object that we'll never get anywhere close to, that's vast, that powers the Earth, that is responsible in some indirect way for the origin of life, is so well understood, but something tiny and inconsequential and relatively new, in terms of Earth years, is totally not understood? And it's because it's complex, not just complicated. And what does that mean?

So one way of thinking about complexity is adaptive, many body systems. The sun is not an adaptive system; the sun doesn't really learn. These do; these are learning systems. And we've never really successfully had a theory for many body learning systems. So just to make that a little clearer, the brain would be an example. There are many neurons interacting adaptively to form a representation, for example, of a visual scene; in economy, there are many individual agents deciding on the price of a good, and so forth; a political system voting for the next president. All of these systems have individual entities that are heterogeneous and acquire information according to a unique history about the world in which they live. That is not a world that Newton could deal with. There's a very famous quote where he says something like, I have been able to understand the motion of the planets, but I will never understand the madness of men. What Newton was saying is, I don't understand complexity.

So complexity science essentially is the attempt to come up with a mathematical theory of the everyday, of the experiential, of the touchable, of the things that we see, smell, and touch, and that's the goal. Over the last 10, 20 years, a series of mathematical frameworks—a little bit like the calculus or graph theory or combinatorics in mathematics that prove so important in physics—have been emerging for us to understand the complex system, network theory, agent-based modeling, scaling theory, the theory of neutral networks, non-equilibrium statistical mechanics, nonlinear dynamics. These are new, and relatively, I mean on the order of decades instead of centuries; and so we're at a very exciting time where I think we're starting to build up our inventory of ideas and principles and tools. We're starting to see common principles of organisation that span things that appear to be very different—the economy, the brain, and so on. So complexity science ultimately seeks unification—what are the common principles shared—but also provides us with tools for understanding adaptive, many body systems. And intelligence for me is in some sense, the prototypical example of an adaptive, many body system.

Ingenious: David Krakauer. The systems theorist explains what's wrong with standard models of intelligence. http://nautil.us/issue/23/dominoes/ingenious-david-krakauer

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