An introduction to complexity theory

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"Complexus" (Latin) – braided together

Complexity theory grew out of the observation that there are many phenomena that modern scientific analysis could not adequately describe or predict. Taking as its starting point a model of a non-linear network, it offers an alternative perspective on organisational life where we operate under the constraints of limited time, knowledge and processing power. Where the bulk of our activity is to establish and modify relationships rather than seeking an endless series of goals each of which disappear on attainment. This chapter describes some basic principles of this new paradigm.

Key points

- Complexity focuses on a perspective that sees systems undergoing continual transformation in a network of non-linear interactions.
- The emphasis moves away from prediction and control to an appreciation of the configuration of relationships amongst a system's components and an understanding of what creates patterns of order and behaviour among them.
- The important features are connectivity, feedback, and the existence of self-ordering rules that give systems the capacity to emerge to new patterns of order.
- Different metaphors are derived from the study of complexity across different disciplines. We should be cautious when importing these insights into an understanding of health care organisation.

From Complicated to Complex Networks

A jumbo jet is a complicated network of interacting elements. Its action can be determined by an analysis of its component parts and its behaviour is linear and predictable. Each part of the system will behave in the same way wherever it is installed. The intelligence of the designer resides in the system and it can be controlled from without.

A rose is a complex network of interacting elements. As it unfolds, its future shape has boundaries that can be described but it cannot be predicted in detail. There is no pre-defined geometric plan or any one element in control. The pattern that emerges is the result of interaction between its

elements as they respond to the information they are presented with at a local level, a response that is directed by the recursive application of a small number of simple rules.

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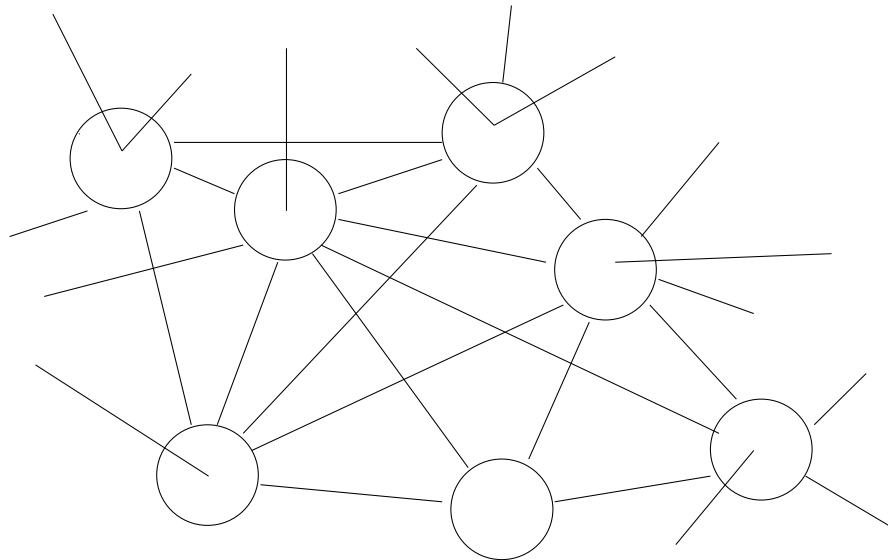
What is complexity?

A complex system is a network of elements (agents) that exchange information in such a way that change in the context of one element changes the context for all others. Complexity is the result of the interaction of elements that only respond to the limited information they are presented with[1]. Orderly pattern arise that could not have been predicted from the study of individual elements due to the presence of reiterative positive and negative feedback loops

Approaches to Complexity

The study of Complex Systems originated in the field of mathematics in the late 1980's and described how certain computer models of neural networks and artificial life behaved[2] [3]. Other disciplines from the natural sciences adopted these concepts based on a model of multiple iterative interactions in a network of individual elements that produced orderly patterns of behaviour.

The study of complex systems can be divided depending on the focus of the investigation. Unfortunately, confusion often arises from insights from one perspective being imported into another. For example, humans in organisations behave very differently from mathematical equations in computers or animals in eco-systems. There is also a problem with a lack of consensus over complexity definitions and terminology - 45 definitions have been identified[4]!

Some contrasting approaches to complexity are:

- *Simple complex systems* – the manner in which information is processed by individual elements does not change with time. For example, a biochemical reaction.

- *Complex adaptive systems* – the processing of information by elements changes with time as they learn and adapt in response to other elements or their environment. For example, evolutionary computer programmes biological systems. Complex adaptive systems need processes that both generate and prune variation to evolve[5].
- *Complex cognitive systems* - this approaches complexity from a psychological perspective and offers a useful organisational definition of a complex system: a highly flexible system with a large behavioural repertoire; one for which its future behaviour is difficult to predict with any certainty; that generates novel information processing mechanisms resulting in interesting and unexpected emergent phenomena; in which behaviour evolves over time given appropriate resources[6].
- *Complex social systems* – organisations are studied as complex social systems in their own right, not as metaphors or analogies of physical, chemical or biological systems.
- *Complex responsive processes* – the focus of study is on the interaction between individuals at the local level from which an unpredictable future emerges.

We next briefly look at the features of the individual elements in complex systems before describing how they interact to give the characteristics of complex adaptive systems and in particular the features of emergence and self-organisation. Finally we discuss insights from some important metaphors, focussing on the metaphors derived from chaos theory and the concept of "the edge of chaos."

The behaviour of individual elements - mental models and local rules

Each system element (called an agent in complexity terminology) takes in information, processes it and forwards it to other elements as an output. (See figure 1). Complexity theory stresses the importance of the connections and relationships between the agents rather than the properties of the agents themselves.
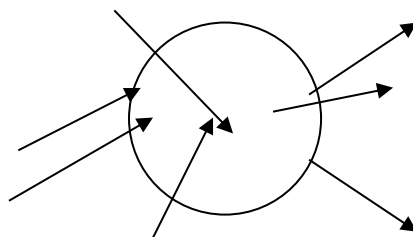

Figure 1 – An element or agent in a complex system element takes in information, processes it and forwards it to other elements within a process of perception, decision-making and action.

Elements respond to their environment using internalised rules that direct action. In a simple complex system such as a biochemical system, the rules could be a series of chemical reactions. At a human level, as we saw in chapter 1, these rules form the basis of our mental models or map of the world. They manifest in the way in which we respond to changes in our environment.

There are a number of important features of human agents:

- Our mental models change with time as we learn and adapt. Because of this, a rigorous mathematical analysis of human systems will be difficult. Complexity therefore focuses on the qualitative aspects of dynamic non-linear systems.

- We can have some awareness of the whole system and not just our local environment. Our technological artefacts such as TV and internet allow us to respond to global information, unlike simple complex systems that act only on local information.

- Our ability to hold mental images and project them into the future enables us to make sense of our environment. We can identify goals and purposes, develop strategies and chose amongst several alternatives. We are able to formulate values and social rules of behaviour.

- Our interactions take place within a network influenced by language and other symbolic forms. Through a shared context of meaning, we can acquire identities as members of social networks that generate the boundary of an organisation. However, we are also capable of disingenuity - what we say is not always how we intend to act

Characteristics of Complex Adaptive Systems

In this section we consider some basic characteristics of complex systems:

(i) Complex systems consist of a large number of elements that interact. Iinteractions are predominately short-range with information being received from near neighbours. However, the richness of network connections means that communications will pass across the system but will be modified on the way.

(ii) There are reiterative feedback loops in network interactions. The effects of an agent's actions are fed back to the agent and this in turn affects the way the agent behaves in the future. Negative (damping/stable) and positive (amplifying/unstable) feedback give rise to non-linearity which is the unique feature that makes a complex system different from a complicated system. These non-linear instabilities lead to novelty and innovation and make the future behaviour of such systems unpredictable.

Due to non-linear characteristics, small changes in one area can occasionally have large effects across the whole system. This has been called the 'butterfly effect.' (A butterfly in New York can flap its wings and cause a hurricane in Tokyo.) For example, the riding accident of the actor Christopher Reeves had a large but probably inappropriate impact on the redistribution of research funding into spinal injuries in the US[7]. Conversely, large influences may only have a negligible impact. *The Health of the Nation* initiative was a major strategic UK government initiative designed to influence the health of the public but had little impact on the targets it sought to influence.[8]

(iii) Systems are invariably nested within other systems. For example, my consultation sits within my health centre within my primary care organisation within the health authority within the NHS. All these systems are nested complex adaptive systems - including myself which in turn is a collection of nested systems.

(iv) It is difficult to determine the boundaries of a complex system. The boundary is often based on the observer's needs and prejudices rather than any intrinsic property of the system itself. For example, Primary Care Practitioners find it difficult to define the

boundaries between health and social care in their work but these organisational demarcations are rigorously enforced.

(v) History is important in complex systems. The past influences present behaviour. For example, it would be unwise to plan new primary care structures without recognition of what has gone before.

(vi) The system is different from the sum of the parts. In attempting to understand a system by reducing it into its component parts, the analytical method destroys what it seeks to understand. The corollary is that the parts cannot contain the whole and any one agent cannot "know" what is happening in the system as a whole. If they could, all the complexity would have to be present in that element. Therefore, no one can stand outside the system and hope to understand and engineer it to a pre-determined future as approaches to organisational change in the NHS have repeatedly demonstrated.

(vii) The behaviour of complex systems evolves from the interaction of agents at a local level without external direction or the presence of internal control. This property is known as emergence and gives systems the flexibility to adapt and self-organise in response to external challenge. Emergence is a pattern of system behaviour that could not have been predicted by an analysis of the component parts of that system.

Emergence and self-organisation and central features of complex systems and are considered in more detail in the next section.

Emergence and Self-organisation

Emergence in complex adaptive systems

The idea of emergence is used to indicate the development of unpredictable patterns that cannot be adequately explained by an understanding of the systems components at a lower level. Emergent behaviour is shown when a number of agents form more complex patterns of behaviour as a collective. Due to the presence of multiple feedback loops, properties of the system that shape both its identity and purpose emerge without the intervention of an external designer or the presence of any centralised form of control. The emergent behaviour is not a property of any single entity, nor can it easily be predicted or deduced from behaviour in the lower-level entities.

Emergent behaviour can be seen in areas ranging from traffic patterns, multicellular biological organism to organizational phenomena. For example, each individual brain cell functions in a simple manner but the system of brain cells perform highly complex tasks that could not have been predicted by an analysis of the individual components. Complex behaviour emerges from the interaction between many simple elements that respond in a non-linear fashion to the local information that is presented to them. There is no central control. No one cell or groups of cells is in charge. A health centre demonstrates similar properties. Although each individual employee has a defined role, the patterns of behaviour that emerge as staff interact with each other are very different from predictions derived from analysis of the individuals.

Emergence is a key feature of complex systems but to date, no general laws or principals have been identified to explain this property.

Self-organisation in complex adaptive systems

Closely aligned to the concept of emergence is the principal of self-organisation. The evolution of all living systems has been underpinned by this principle whereby a dynamic system reorganises its structure so that it can more effectively cope with environmental demands.   When change is introduced from outside, the system self-organises around the disturbance that is created. For example, Lipsky[9] studied the behaviour of public servants in New York. He identified that when top down policy directives were issued, these "street bureaucrats" re-organised the initiation of policy influenced by their local circumstances and only by doing so did the system survive.

As the self-organising process is not necessarily guided or determined by specific goals it may be difficult to talk about the function of a system. Patterns emerge that satisfy the constraints put upon it. This concept runs against traditional organisational thinking that emphasis control of organisational relationships as the system is engineered towards its strategic goals.

In human systems, precursors for self-organisation are:

- Shared principles - systems align themselves around core values even if system goals are not articulated.
- Connectivity and feedback - self-organisation emerges from non-linear processes arising from feedback at a local level
- Dialogue - this involves a sensitivity to other perspectives and a willingness to change our mental models and paradigms
- Memory - without memory the system can do no better than mirror the environment. As any system has a finite memory capacity, there must also be some form of selective forgetting.
- Interdependency - self-organisation is driven by both competition and co-operation amongst system elements but against a background of interdependency.

A self-organising system will attempt to balance itself at a point known as *self organised criticality* (alternatively known as *the edge of chaos*) where it is able to adapt with the least amount of effort in response to a wide variety of external challenges. This phenomenon is considered in more detail below.

There is considerable debate over the concept of self-organisation. In natural ecologies, the recursive interplay of competition and co-operation of system elements leads to the emergence of co-evolving patterns of behaviour that fit with environmental demands. However, we need to be cautious when applying this thinking to human systems. It may be wishful thinking to suggest that left to their own devises, individuals will self-organise to the benefit of the system of which they are a part. Human motivations can be destructive leading to anarchy and system collapse.   Experience suggests that we need formal structures to facilitate a constructive mode of human self-organisation. For example, market economies can be successful methods of self-organisation that allocate societies limited resources but have strict rules of transaction to enable them to operate

effectively. Perhaps the best we can say is that human systems will flourish with less external control than we currently think and focus on more useful concepts such as "the edge of chaos" which appears throughout this book and is considered in the next section.

Using complexity metaphors and analogies for understanding organisations

Complexity insights are being developed across a number of disciplines and insights and metaphors from one area are invariably invoked in another. Caution is needed when transferring metaphors derived from non-human systems into organisational thinking. There is also a danger of importing complexity insights from commerce where the focus is on competition, to public health systems where competition is usually limited. Some imported metaphors and their sources are shown in figure 2.

Different writers are attracted to different metaphors. I find the metaphors from chaos theory and self-organised criticality useful and these are expanded below. The other metaphors are briefly reviewed in the appendix.

Metaphor	Discipline
Chaos – phase space/attractors/fractals	Mathematics
Dissipative structures	Chemistry and physics
Auto-catalytic sets	Biology
Auto-poesies	Biology, psychology
Fitness landscapes	Ecology
Self-organised criticality (Edge of chaos)	Biology, ecology, physics

Figure 2 – Some metaphors imported from other disciplines (See appendix for more details)

Insights and metaphors imported from Chaos theory

I previously suggested that a useful starting point from an organisational perspective was to consider chaos theory as the quantitative study of non-linear systems and complexity as the qualitative approach drawing upon chaos metaphors. This section explores how insights from chaos theory might be applied to the study of organisations viewed as complex systems. Four concepts are considered:

i) *Simple Rules* - In chapter 2 we saw how complex patterns could emerge from the recursive application of simple non-linear equations or "rules". An important but contested insight is that the capacity of systems to evolve to new patterns of order can emerge from the recursive application of a small number of simple rules. For example, the complex phenomenon of bird-flocking or fish-shoaling emerges from the recursive application of three simple rules: move to the centre of the

crowd; maintain a minimum distance from your neighbour; and move at the speed of the element in front of you.

The suggestion is that underpinning complex behaviour in organisations are a small number of simple rules or guiding principles. For example, Plampling[10] identifies three simple rules that have traditionally underpinned the NHS and offers an alternative set which maybe more applicable:

- I am responsible – I am responsible in partnership
- Can do should do – maximise the health gain for the population within the available resources
- Doing means treatment – doing takes place within a broader social action

Plsek[11] identifies three general types of simple rules for human systems: general direction pointing; system prohibition i.e. setting boundaries; resource or permission providing

Simple rules have found favour as a practical framework in which complexity insights can be utilised. Exposing and changing the rules is seen as a method of instigating change. Major concerns are that this approach reflects the ideology of control that the complexity framework seeks to avoid and the focus of attention is removed from the importance of interaction between system elements. The concept of simple rules is considered in more detail in section 3.

ii) *Multi dimensional phase space - An* important use of metaphor drawn from chaos theory is to view complex systems as a multi-dimensional phase space. Each system variable is defined and quantified in one dimension. The system is described in terms of a multi-dimensional phase space with the number of dimensions depending on the number of variables required to describe it. Agents will follow trajectories through this space with time. Although trajectories cannot be predicted with certainty, they are bounded by areas of phase-space known as attractors. These are areas of phase space where trajectories tend to be found and place limits on the room for manoeuvre.

For example, two current NHS attractors are equity and efficiency. In the US health care system, profit is a powerful attractor. One suggestion is that an attractor is a system property that emerges from the recursive application of simple rules at a local level. The attractor then feeds back and re-enforces or modulates the simple rules. Figure 3 shows some possible simple rules and attractors for sub-cultures within the NHS primary care sector. At a more local level, Miller[12] has offered insights into the organisation of individual primary care practices by identifying practice attractors such as maximisation of income or rapid access to health care provision.

Culture	PRIMARY CARE TRUST

Attractors	INDIVIDUAL HEALTH, EFFECTIVENESS	COMMUNITY HEALTH, EQUITY	ORGANISATION EFFICIENCY
Sub-Cultures	**Health Professional**	**Social Care Professionals**	**Managers**
Simple rules	Do what is best for the patient. Act autonomously. Base decision on quantitative evidence where available.	Act in the interests of the community. Reflect legislative frameworks.	Define objectives. Monitor performance. Respond to authority.

Figure 3 Sub-cultures within a primary care organisation, their simple rules and attractors

iii)   *Self-similarity at different scales* - Fractals are patterns that repeat themselves at different levels of scale and we may expect to see this phenomenon in organisations. For example a dissonance between rhetoric and reality occurs at every administrative level of the NHS!

iv)   *The importance of initial conditions* - What has gone before is important. For example, it would be inadvisable to consider the current developments in primary care in the NHS without an understanding of their historical context. Davies[13] has warned of the dangers of comparing health systems where the historical context is often different. Systems develop within the framework that they have inherited, building on what has gone before. Often, organisations are memorials to old problems, institutional residues that reflect the historical processes through which problems have been tackled.[14]

The Edge of Chaos or self-organised criticality
This important metaphor is a recurring theme throughout the book. This insight was derived and explored using computer modelling and despite its attractions we must be aware of the dangers of importing such models into human organisations.
In a complex network, three system states can be described depending on the strength and number of connections between elements[a]:

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[a] We can look at the edge of chaos phenomena in a different way using the metaphor of a multi-dimensional phase space. A stable non-linear system eventually reaches either a fixed point (a point attractor) or a closed set of points such as an oscillatory cycle (a periodic attractor). Such a system is stable and any disruption will be compensated by the system's tendency to resume limit cycle behaviour. Under other system parameters, the system response is represented by a more complex trajectory within a strange attractor and under these circumstances the system's dynamics are chaotic. Between these stable and chaotic attractors is a phase transition where highly ordered structure emerges spontaneously.   The attainment of this phase is only observed for an extremely narrow critical range of the system's parameters and it is here that the most productive information processing is thought to occur and the system responds adaptively to changes in its environment with the least amount of effort

i)   *Stable state*

In this state there are a limited number of strong interactions between system elements with little feedback. As a result, there is a simple linear relationship between cause and effect.   The system is stable and predictable and organisational decisions can be taken within a rational framework. This assumes that the costs and consequences of alternative courses of action can be predicted and a choice made that reflects explicit values and goals.

ii)   *Chaotic state*

Here there are large numbers of weak and rapidly changing connections. Although system behaviour appears random, there may be underlying features that can be described by the mathematical approaches of chaos theory. Chaotic systems have little memory and mental models change rapidly from novelty to novelty without consolidating gains.

The 'garbage can model' of organisational change is the antithesis of the rational approach and can be seen as one interpretation of this zone. It sees organisations as a continual mixture of people, choices and problems circulating aimlessly and occasionally coinciding to create a juncture at which a decision is made. A collection of choices looking for problems and solutions looking for the issues to which they might be the answer[15].

There are advantages and disadvantages to both tightly and loosely coupled systems. For example:

- Loosely coupled systems allow parts of an organisation to evolve independently rather than forcing the entire system to move at once. However, systems aren't pressurised to discontinue non-productive practices

- Loosely coupled systems are more sensitive to environmental changes, but this may subject the system to the whims of fads.

- Loosely coupled systems can permit isolated systems to experiment without committing the entire system but may inhibit the diffusion of experiments that are productive.

- Loosely coupled systems are less vulnerable to problems or break downs

- Loosely coupled systems may be cheaper to run rather than co-ordinated systems but the trade off is loss of control

iii)   *The edge of chaos*

Many complex systems organise themselves to a state known as self organised criticality. (Sometimes termed "zone of complexity" or the "edge of chaos.") Here each element is optimally fit at a level that does not disrupt the fitness of others in the network[16]. This area has been defined as the transition band between chaos and predictable stability where systems are maximally fit and adaptive.[17] The important features of this zone are:

- Dynamics are still chaotic but they also possess characteristics of order.

- The organisation is sufficiently rigid to carry information about itself and to perform its task adequately but at the same time sufficiently chaotic to allow it to use its information creatively.

- The system is robust to the influences of external forces and operates at a point of maximum efficiency so that an increase in either order or chaos will reduce the system's efficiency.

- There is scale invariance i.e. patterns repeat themselves at different levels of scale (or fractals)

- The system often demonstrates power law scaling. ie where x and y are system variables and c and a are constants:
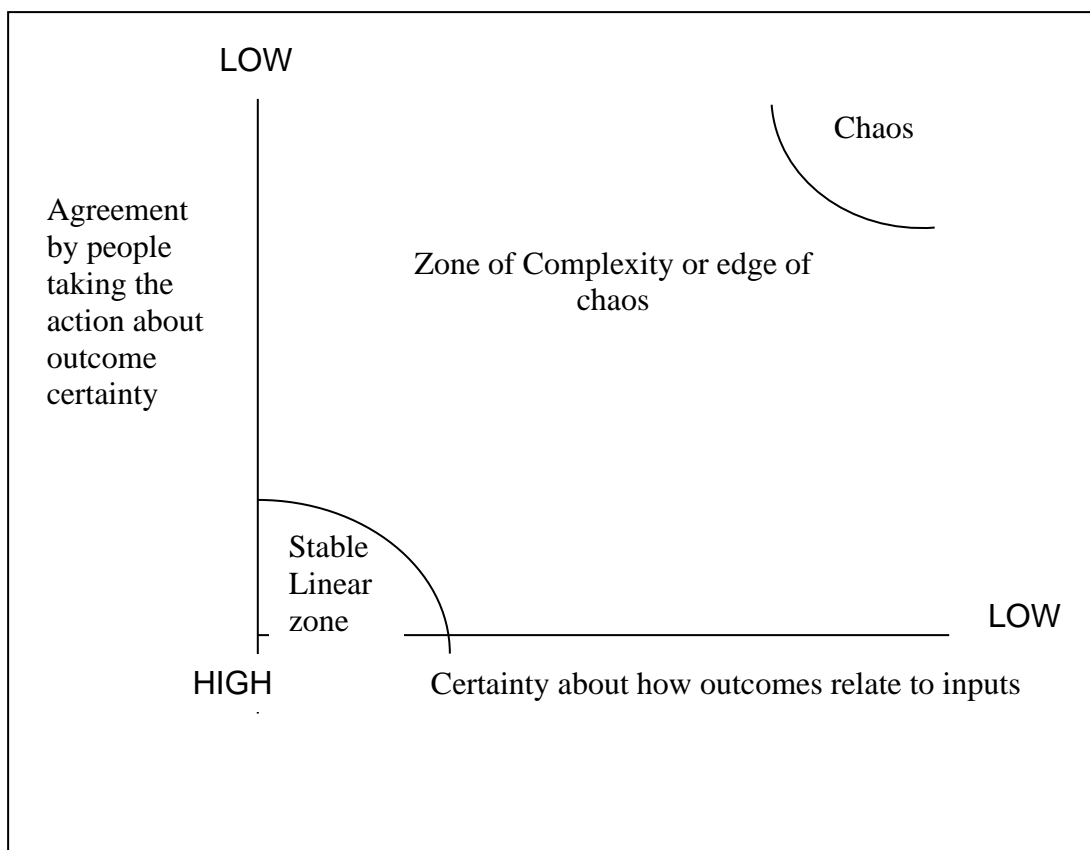
$$y = c.x^a$$

Y is usually plotted as the frequency of a system event and x the size of the event. This power-law distribution is a footprint of the edge of chaos and not diagnostic of it. Never the less, a large number of physical systems ranging from earthquakes to traffic jams demonstrate this behaviour and evidence is beginning to accumulate that it exists in healthcare systems.[18]

> The edge of chaos isn't an edge - it is a class of behaviours where an orderly system starts to break down but before the system is chaotic. Some people find the analogy of a wave useful. Stability is represented by the ordered wave pattern out to sea. The edge of chaos is the area under the wave about to break which is known as the tube. Surfers are in tune with this complex region until the wave hits the beach and chaos ensues.
>
> A surfer's guide to the edge of chaos

The edge of chaos metaphor has been interpreted diagrammatically by Stacy who applies it to organisational understanding and decision making.[19] He identifies three areas of organisational life depending on the certainty about the relationship between cause and effect between system variables and the agreement between agents on this relationship[b]. This is shown in figure 5.

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[b] Despite its attractions and use throughout this book, Stacey has rather distanced himself from this model. It is seen as too reductionist and diverting attention from the central role of human relating at a local level from which outcomes emerge.

LOW

Chaos

Agreement
by people
taking the
action about
outcome
certainty

Zone of Complexity or edge of
chaos

Stable
Linear
zone

LOW

HIGH

Certainty about how outcomes relate to inputs

When there is a high degree of certainty as to outcomes from actions and a high degree of agreement amongst the people involved in the actions about the relationship between actions and outcomes, machine systems thinking with detailed planning and control may be appropriate. The instinct of reductionist science is to resolve ambiguity and paradox and move into this linear, rational zone on the underlying assumption that there is a correct answer to any problem.

The upper right hand segment represents a system of anarchy where chaos reigns and is to be avoided. However most issues in healthcare are in the "zone of complexity" where there are only modest levels of certainty and agreement and where it would be most appropriate to use the paradigm of complex adaptive systems. This perspective would be to accommodate paradox and value the inherent tension that arises from it. The attention focuses on things that seem to working best and learning incrementally.

A third dimension could be added to the model, the degree to which agents agree about the purpose or goals of a system[20]. For example, cause and effect may be uncertain with high agreement on system goals. In this area, detailed planning is of limited use and the emphasis is on the articulation of a vision and underpinning values of the system. Alternatively, there may be agreement amongst agents over system certainty but there may be disagreement over system goals. Here decision making is based on compromise and negotiation. If there is disagreement in all dimensions, then all we can hope for is inspiration!

The Stacey model has been developed by a number of writers. For example, Kurtz and Snowden[21] emphasis the importance of boundaries between preferences for action. (See Appendix 2)

Conclusion

Engaging with complexity challenges a number of current assumptions and offers an alternative perspective from which to analyse social systems. It cautions that complex systems cannot be described and predicted using simple linear models. That activity and performance cannot be precisely controlled by rational technical fixes that have predictable outcomes. Organisations cannot be re-engineered within hierarchical command and control frameworks and attempts to understand them by a reduction into their constituent elements will invariably destroy what they seek to understand. However, given certain dynamic relationships, patterns of behaviour can develop as organisations adapt in response to changes in their environment. By taking a broader view, perhaps we can retain some predictive power - concentrating on being vaguely right rather than being precisely wrong

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