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Complexity Science in Healthcare

ASPIRATIONS, APPROACHES, APPLICATIONS AND ACCOMPLISHMENTS

A WHITE PAPER

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Complexity Science in Healthcare — Aspirations, Approaches, Applications and Accomplishments: A White Paper

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This word cloud displays the 80 highest frequency words in the abstracts of the publications cited in this White Paper. It provides a neat encapsulation of the core themes covered in this document. Source: generated using http://www.wordle.net/.

Preface

Victor Hugo once wrote "Greater than the march of mighty armies is an idea whose time has come". Complexity science is not a new idea, but in 2017 its time has surely come in relation to healthcare provision. Health systems around the world are struggling with the unprecedented interacting challenges of—among others—increased life expectancy (and the concomitant increase in chronic illness, multi-morbidity and frailty), technological progress (both real and imagined), the convergence of "health" and "care" needs (along with increasingly messy disputes over who should pay for them), fragmentation of services, mismatches between workforce supply and system demand, a mushrooming of regulations and protocols, diminishing public trust in health professionals, and shrinking budgets. On top of that, a suite of actions in the area of preventive public policy could reduce the burden of disease, if only governments felt able to tackle vested interests that perpetuate poor health.

Whether we are experts on complexity theory or not (and most of us are not), we know in our bones that delivering high-quality services in such a complex environment will not be achieved merely by following a standard operating procedure, inserting the results of a randomised controlled trial or adopting the seven habits of highly successful people. We have tried to improve aspects of the healthcare system, only to experience surprises—often disappointing ones.

In a complex universe, intervention A does not predictably lead to outcome B. Stuff happens. Things get in the way. Something we could not have predicted pops up—and gives an initiative a boost. A key person leaves the organisation—and a crucial project grinds to a halt. A new government is voted in—and fiscal incentives are soon re-jigged in a way that renders a carefully-crafted strategic plan obsolete. Two people meet in a training course— and a collaboration is born.

Complexity science will not tell us how to resolve the tensions and paradoxes in contemporary healthcare systems, because those tensions and paradoxes are *inherent*. Applying complexity science means accepting uncertainty. There is no simple or easy answer waiting to be discovered that will allow us to present the evidence base, achieve consensus and (thereby) resolve the numerous operational, ethical and political conundrums facing us.

Applying complexity science also means figuring out how to move forward despite this uncertainty. We must muddle through in situations where there is no agreement on

what the question is (or whose perspective counts), or where evidence is absent, incomplete or contested. Evidence is never neutral; "facts" are value-laden and success is—quite appropriately—measured differently by different stakeholders.

University-based researchers have long sought to determine how the principles of complexity science might be applied to improve the performance of health systems (and indeed, to stop health system performance deteriorating as the interacting challenges they face grow inexorably). As the work summarised in this monograph attests, the academic literature is steadily accumulating an evidence base on "the science of muddling through in real-world situations" that (mostly) complements and (occasionally) challenges the findings of more conventional basic science research, observational epidemiology and randomised controlled trials. This work points us in potential directions to explore and apply complexity science, principles and ideas.

It is timely indeed that Jeffrey Braithwaite and his team have moved to summarise this literature and offer recommendations for taking the key ideas forward. We are proud to have contributed to the global effort on complexity science and to be cited and quoted in this landmark volume.

Few researchers can boast the dual pedigree of an international reputation as an academic scholar <u>and</u> high credibility among policymakers as a straight-taking researcher who actually gets things done. He is the author of multiple academic works and has helped launch the careers of many young academics, attempting to break new ground in understanding complex health care along the way. We can think of no better authority to speak on complexity science and we hope readers enjoy this White Paper as much as we have.

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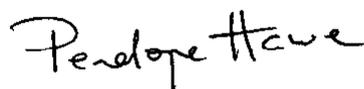
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Executive summary

Many people believe that healthcare is the example *par excellence* of a complex adaptive system (CAS). It has a daunting range of diverse stakeholders (citizens, taxpayers, politicians, policymakers, providers, managers, clinicians, patients and patient groups), spans the public and private sectors and delivers care across many settings and through varied types of organisations (public health settings, community centres, hospitals, aged-care facilities, and family or general practices, for example). The individuals delivering care, and the groups, teams, networks, bodies and organisations through which they provide services, interact in intricate configurations, longitudinally.

Said that way, certain consequences arise. The system, of necessity, will be adapting to circumstances over time, behaviours won't necessarily be predictable, the sum of the parts will be greater and different from the individual elements making up the system, and the inputs and outputs will not match because relationships within the system are not straightforward—they are non-linear.

The complexity science approach to understanding, acting on, and researching health systems is becoming increasingly popular. It is therefore timely to release an analysis of complexity and its characteristics, and apply them to healthcare. This is the objective of this White Paper.

Beginning with Part I, we look at what people hope for when they apply a complexity lens to entrenched healthcare problems. We tease out subtle and important differences between *complicated* and *complex*, and articulate a framework for complexity, drawing attention to some key features such as individual agents, their interactions, the dynamic nature of their activities within the system, and the ubiquitous rules and governance mechanisms that emerge over time. Central concepts include the interdependence of actors, their capacity to self-organise, the co-evolution of their interactions, the emergent properties of their behaviours, feedback loops within the system which act to enable or constrain further behaviours, the networked-nature of relationships, and the different scales of the system (e.g., micro, meso, macro) and the fractal behaviour patterns. CASs are path-dependent, meaning that what happens in the
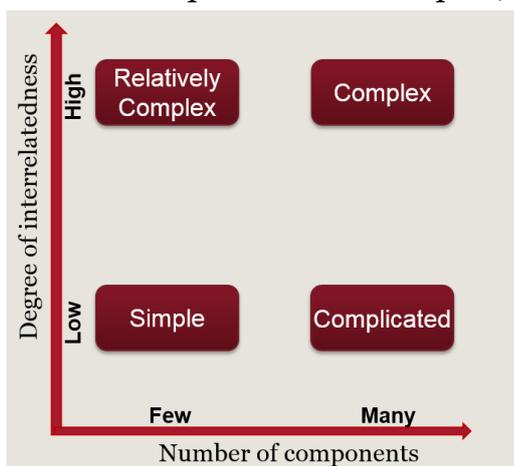
Complicated versus complex systems.

past dictates at least some of what happens in the present. CASs are changeable over time, but also characterised by forces of inertia.

In Part II, we delve deeper into the characteristics of complexity. We attempt to understand healthcare through an analysis of linear versus complexity thinking. We provide a multitude of images, models, and conceptualisations, as well as quotes and phrases which people have used to apprehend the multi-dimensional nature of complexity. We also examine two important corollaries of complexity: uncertainty, and emergence.
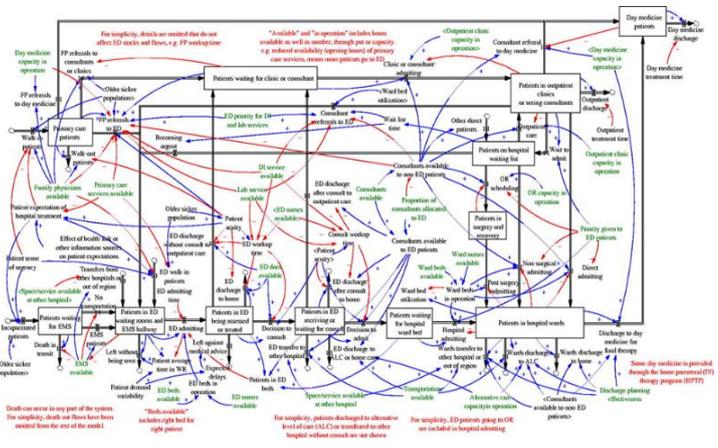
The organisational complexity in part of one hospital.

Turning to Part III, we change the focus and look at how we can deal with complexity, making multiple observations about the way the ideas drawn from complexity science can be, and have been, applied to healthcare. At the core of this Part is an analysis of networks over time, the actors who matter, and how control in complex organisations is, and must be, distributed. Also germane to an understanding of complexity in healthcare are characteristics such as the natural resilience of healthcare settings and the cultural characteristics these settings exhibit. Rounding off this Part, we have a look at complexity and implementation science, and some selected research-led applications to healthcare.
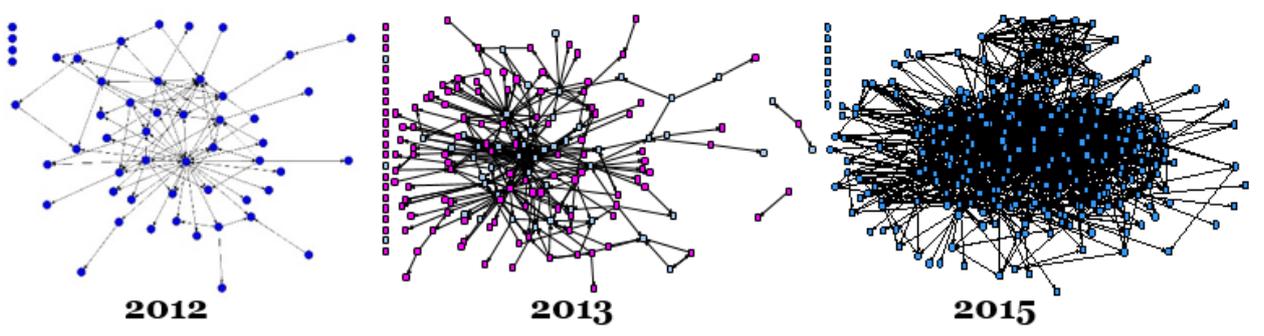
A network diagram at three time points of collaboration among cancer clinicians and researchers.

Part IV changes the pace once more, adducing examples of what complexity science has achieved to date, and the implications of drawing on complexity science conceptualisations to make them relevant to the care of patients. Here we deal with

specific accomplishments of complexity theory in past empirical studies, and look at how complexity thinking has been applied in not only developed health systems, but in low- and middle-income countries.
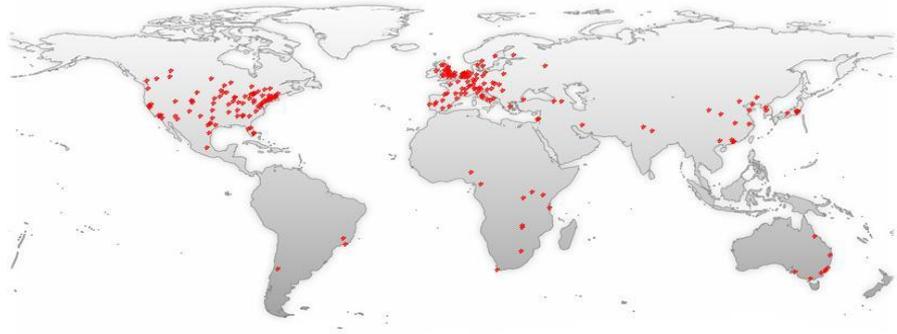
Distribution of countries where complexity studies are published.

Part V provides our conclusion. Here, we make some synthesising observations, drawing on key points made throughout the preceding parts.

A visual representation of the 80 most frequent terms in this White Paper. Source: generated with https://wordart.com/create

Finally, in Part VI, we provide a range of resources, including a selection of images of complexity and CASs, some aphoristic quotes on complexity, a glossary of abbreviations and a glossary of terms. Concluding the White Paper, we provide a biography on each of the contributors.

The plan of the White Paper

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Aspirations for Complexity Science

Part II

Characterising Complexity Science:

Approaches to Understanding

Part III

Dealing with Complexity:

Applications to Healthcare

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Part I – Getting Started: Aspirations for Complexity

INTRODUCTION

Health systems are there to care and cure, to prevent poor health, or promote and educate about good health. But they are troublesome. They cost lots of money to run; are distributed unevenly across countries and communities; are large, unwieldy and hard to coordinate; have many kinds of staff, types of technology and other moving parts; can provide very good and very poor services; and defy simplistic solutions.

There is help at hand, however. Old ways of thinking about healthcare systems, working in them and attempting to improve them are giving way to new paradigms of understanding.

We believe that at the heart of these fresh approaches in conceptualising healthcare lies complexity science. Traditionally, reflecting on the system and providing care within it relied on linear perspectives. By way of contrast, complexity science argues that healthcare systems are non-linear. They comprise clusters of interacting agents whose interconnections and activities in real time, and over time, alter the contexts, outcomes and behaviours both for others and themselves (Braithwaite, Clay-Williams, Nugus and Plumb, 2013; Hawe, Bond and Butler, 2009; Plsek and Greenhalgh, 2001). Any health system is also path-dependent and sensitive to initial conditions, meaning that the current state-of-play owes its dues to its historical origins and the trajectory it has taken to get where it is now.

Health systems have, in short, a memory. While they can and do change over time, health systems also exhibit root-bound practices, roles and organisational arrangements—which we call inertia (Coiera, 2011). This is in part because there are positive and negative forces at work, in the form of feedback loops, which act to enable and constrain behaviours and systems change.

Complex systems are thus unpredictable. Practices and behaviours emerge in unexpected ways, local rules arise and adapt over time, and the system sustains perturbations brought on by external and internal events—sometimes haphazardly, with no apparent rhyme or reason. Despite this messiness and lack of standardised responses, there are patterns in the social structures, aggregating to a kind of equilibrium. So while there is change, people form into relatively enduring networks, groups and teams, partly of their choosing, partly through organisational demands, partly because of patient requirements. Other manifestations of patterned social

structures occur in the deeply ingrained cultural and political arrangements. Complex systems are always in a state of flux and behaviours are created and re-created continuously, but the underlying social structures and cultural settings tend to solidify and perpetuate.

In this White Paper, we analyse these and related ideas about complexity, and apply them to healthcare. Our aim is to provide a deeper explanation for healthcare and its characteristics by looking at its predisposing features through a complexity lens. This is a timely exercise, as interest in complexity science has been accelerating in recent years (Figure 1).
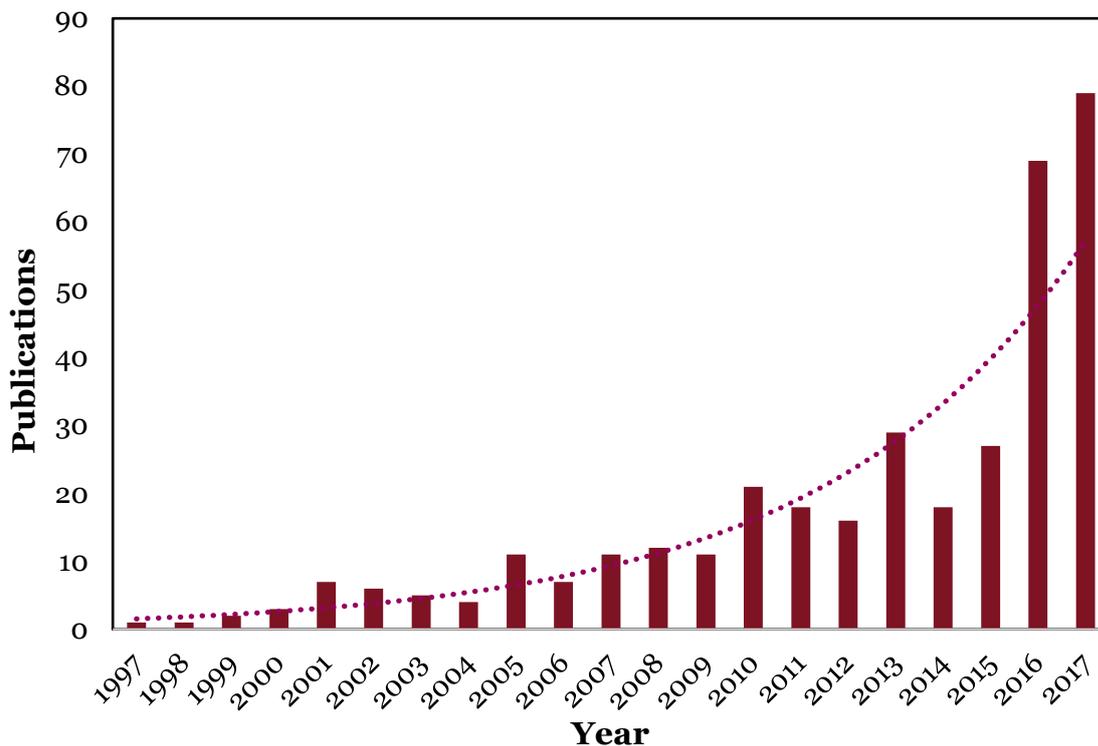
Figure 1 - Increases in publications on complexity over the last 20 years (based on publications in MEDLINE using search terms "complexity science" OR "complex adaptive systems"). Source: adapted from data generated on 19 April, 2017, using www.gopubmed.org.

A health system user's guide to complexity

Complexity refers to the density of interactions between different components (agents, parts, elements, artefacts) in a system or a model representing a system, and which produce roles and behaviours that emerge from those interactions. Complex systems are rich in collective behaviour: in healthcare, this typically means assemblies of networked clinicians, managers, policymakers and patients, alongside their tools, equipment and procedures, all relating for common purpose (Braithwaite, Clay-Williams, Nugus and Plumb, 2013; Plsek and Greenhalgh, 2001).

The interconnections between the agents are dynamic, and the stakeholders interrelate in unanticipated ways (Rychetnik, Frommer, Hawe and Shiell, 2002). Everyone knows this: people go to work, and their day unfolds in unpredictable fashion. Relationships fluctuate depending on people's mood, the circumstances encountered, what transpires during the day, and who's rostered on to the shift. Events occur, patients differ, snags or problems become apparent, someone makes a mistake, someone else is very efficient, a patient's condition deteriorates or their X-rays go missing, or things take longer or sometimes shorter than planned. This provides challenges to understanding the way systems unfurl over time, to apprehending the system's performance and what drives it, to designing interventions to alter that performance, to improving systems and workflows, and to measuring the outcomes of any intervention in the system (Craig, Dieppe, Macintyre, Michie, Nazareth and Petticrew, 2008; Datta and Petticrew, 2013; Petticrew, 2011).

Orchestrated change occurs when those with sufficient authority try to coordinate or control these processes, or to tune or fine-tune the system, by attempting to modify structures, behaviours and relationships, or introduce tools or initiatives, in order to improve things. In healthcare this is usually incremental rather than transformative (Locock, 2003). Rarely, if ever, do we achieve a complete revamp of how we deliver care. Nevertheless, governments and managers attempt improvements or reforms via policy, financial or structural levers. Yet for all the endeavours, efforts often fall short of what is intended (Braithwaite, Mannion, Matsuyama, Shekelle, Whittaker and Al-Adawi, 2017; Braithwaite, Matsuyama, Mannion and Johnson, 2015). It is very hard to engineer what complexity science calls a "phase transition", whereby radical or transformative change in the state of the system occurs. If and when it does, it often follows a long period of stasis. The tipping point is often unexpected, and leverage is exercised very swiftly. Laparoscopic technologies, for example, spread across health systems in only a decade or so, and robotic surgery is being adopted widely now (Lanfranco, Castellanos, Desai and Meyers, 2004).

Nevertheless, local, small-scale adaptations occur all the time. They are not necessarily realised through formally mandated changes, but often more modest system alterations are enabled by those on the front-lines of care who subtly alter practices or priorities (Debono, Greenfield, Black and Braithwaite, 2012; Wears, Hollnagel and Braithwaite, 2015). Clinicians, for example, embrace initiatives such as a new test or procedure based on new technology which are absorbed into current workflows—adopted and spread, typically through informal channels, by word of

mouth, through the influence of an opinion leader, or by teaching someone about it, or because of a company marketing it.

These multiple minor alterations (system tweaks, nudges, workarounds or actively prescribed modifications to the system) are taking place all the time. Sometimes these on-the-ground changes are directly related to what is envisioned by management or policymakers and championed by those higher in the hierarchy, but far more often they are variations from the original intent. This is because front-line operators and patients are self-organised and tightly coupled, but they also have considerable degrees of discretion *vis a vis* those suggesting, prescribing or mandating new ways of doing things. These are known by many names, but we may use the common descriptors *clinical autonomy* and *patient choice*. They affect how change is taken on in local settings (Dopson, Locock, Gabbay, Ferlie and Fitzgerald, 2003). And, while there are local adaptations and variations in behaviour and practices occurring, there is also inertia, as strong forces inhibit change because of trade-offs amongst stakeholders, and role rigidities (Coiera, 2011).

Studying complexity

In complexity science, we don't aim to study the components of a system individually as that can be self-defeating. Reducing the system to its parts in order to study it is a barrier to understanding the whole, like inspecting the legs, body, neck and head separately and expecting to understand how a giraffe works. Instead of pursuing such reductionism, complexity scientists aim to study the properties and characteristics of the system.

We can model a human system to attempt to understand it, such as through a systems dynamics approach (Peters, 2014). But that also simplifies complexity, often unduly. There's no substitute, in fact, to studying the actual system that is the subject of our interest, rather than a model, wherever possible. What we want to do is examine the characteristics that are important, striving to understand the underlying dynamics and emergent behaviours of the system on which we are focussed, rather than its specific parts. In order to deeply appreciate a system, we also want to look at complexity at different scales (see Box 1). That is, the behaviours of individuals and small groups (cliques, dyads, localised interactions), middle-range collectives (divisions or defined networks within a larger structure) or entire communities, populations or organisations (large networks, entire hospitals, the whole of healthcare), are fractal, looking similar at different scales—a kind of universality of properties.

Box 1: Complexity and organisational structures for public health and healthcare.

Healthcare systems were originally designed to respond to the individual needs of a self-presenting patient. Increasingly, they are also required to engage in population health activities. Using concepts of *complexity* and *scale,* Bar-Yam (2006) notes the problems that ensue in imposing the need for health systems to play a role in fundamentally distinct tasks: the "large scale", repetitive public health ones, and the numerous but variable, "fine scale" and "highly complex" tasks of patient care. He argues that the "serial coupling of large-scale financial flows and complex medical decisionmaking is largely responsible for organizational turbulence and ineffectiveness in the health care system" (p. 459), with low quality and high rates of medical error despite high costs and increasing medical knowledge and expertise.

Source: adapted from work in Bar-Yam, Y. (2006). Improving the Effectiveness of Health Care and Public Health: A Multiscale Complex Systems Analysis. *Am J Public Health, 96*(3), 459-466.

A hypothecated example

At this point, it's useful to draw out the layers of healthcare, and illuminate the distinctions between the concepts *complicated* and *complex*, if we are to add to our understanding of the intricacies of the health system. Consider a hospital, viewed from afar. We might see the buildings, and know that it has 800 beds, employs 6,000 staff, and treats 70,000 inpatients annually. It may have a very large budget—millions of dollars, pounds, or euros are expended by it, for example. It has a management structure, with multiple layers and hierarchies: the macro, meso and micro levels. This scenario presents a complicated picture, meaning that there's a lot going on with all the components (see Figure 2). A complicated system may still be predictable if interactions occur in a relatively simple way (Greenhalgh, 2000). The parts we are noting in this healthcare organisation are combined and connected in different ways. It is hard to analyse or explain the full circumstances of the entire setting, the admixture of people, equipment, money and structures that make it work. But we can, in principle, reach a level of understanding that enables us to predict, broadly, what happens.

Now look deeper inside, at the ecosystem—the interacting people, the cliques, the clinical professionals, and informal and formal groups and teams; and the wards, units and departments, ranging from the emergency department (ED) through to the operating theatres to the different kinds of wards, to the jumble of maintenance, IT, human resources, anaesthetics, pathology, and dermatology departments, through to the executive offices, and outpatient clinics. If we sharpen our focus we can see the cultural and sub-cultural features, good and bad relationships amongst the groups and teams, emergent behaviours, politics, and all manner of connections, formal and

informal, forming and re-forming dynamically over time, some loosely, some tightly connected, and all kinds of inter-relations in-between. We can also observe in our mind's eye the artefacts that the interacting staff use to produce care—computers, MRI scanners, x-ray machines, post-it notes, computers, scalpels, medical record systems, and stethoscopes—to the mix. Then there are the patient flows, and the aspirations, hopes and fears of patients and staff. If we are to look even more closely at all this complexity, we will observe people being variously motivated and demotivated, careful and meticulous, organised, disorganised, and self-organised, and see them making, breaking and following the local rules of the game to achieve their own, others', and the organisation's goals.

In the first scenario, we were articulating how complicated the hospital is. Our focus was largely structural, and the analysis, mechanistic. In the second part, by introducing concepts of interrelatedness such as the interacting agents, the emergent behaviours that develop from these interactions, the

Figure 2 – Illustrative, idealised distinction between simple, complicated and complex systems. Source: adapted from Kannampallil, T. G., Schauer, G. F., Cohen, T. and Patel, V. L. (2011). Considering complexity in healthcare systems. J Biomed Inform, 44(6), 943-947.

properties of self-organisation, and the dynamics of the setting, we were focusing on its complexities. This distinction between complicated and complex is further illustrated in Figure 2.

In complex settings, sometimes the rules are visible to us, and sometimes the networks, groups, collectives and aggregations, and the behaviours that emerge, are hidden. Whether behaviours are overt or covert, the participants are in a state of flux,

flexing and adjusting to each other, and circumstances, over time, through their high degrees of interrelatedness (Rickles, Hawe and Shiell, 2007). All-in-all, healthcare is highly interconnected, and has many components operating in interconnected ways to achieve non-linear system behaviours and self-organisation. In the jargon, it's a complex adaptive system (CAS), which we will get to next.

TOWARD A FRAMEWORK FOR COMPLEXITY IN HEALTHCARE

There are many ways to think about complexity and how to apply it conceptually and practically to healthcare. A useful departure point is to think of healthcare settings as CASs (Plsek and Greenhalgh, 2001). This means that they are complex in the way we have been describing; and adaptive, in that behaviours and group compositions alter and mutate, and participants learn, over time (Tan, Wen and Awad, 2005). As the agents interact alongside their artefacts, they organise and self-organise, meet goals and solve problems interdependently, conjoined either physically, in the same location, or mediated distally, usually through communication or information technology.

As discussed, complexity scientists take the view that a CAS cannot be reduced to the sum of its parts; that is, it cannot be broken down into smaller pieces in order to understand the behaviour of the system as a whole. This is because the whole is not just more than, but inherently different from, the

"A complex adaptive system is a collection of individual agents with freedom to act in ways that are not always totally predictable, and whose actions are interconnected so that one agent's actions changes the context for other agents. Examples include the immune system, a colony of termites, the financial market, and just about any collection of humans (for example, a family, a committee, or a primary healthcare team)."

Paul Plsek and Trisha Greenhalgh (2001)

Source: Plsek, P. E. and Greenhalgh, T. (2001). Complexity science: The challenge of complexity in health care. *Br Med J (Clin Res Ed), 323*(7313), 625-628.

constituent components of a CAS. Indeed, even articulating the "parts" of a CAS is problematic, because they are constantly in motion, and considered open-systems, with fuzzy boundaries and emergent behaviours. While not rejecting this important point, furthering our explanation of healthcare complexity necessarily requires some delineation of its characteristics. In view of this, we can conceptualise CASs as having at base four prevailing features: individual agents, interconnections, dynamic behaviours, and rules and governance.

1. **Individual agents.** In healthcare systems, these include an array of diverse people and roles, for example, policymakers, managers, doctors, nurses, allied health staff and patients, who run, act on, work in, provide or receive care from organisations such as hospitals, general practices or community-based provider groups, or sub-units such as an identifiable section, profession, group or department. Agents are capable of acting within the system at differing scales and levels of granularity (see Box 2 for an example of challenges facing agents, and the

tensions between scales). They make decisions under real-world conditions, and learn by processing information from the environment, adapting behaviours and accommodating to the system and others' activities over time by making sense of what's going on (McDaniel and Driebe, 2001). In short, agents act, react, think and perceive, communicate, adapt and accommodate to their context and others; and they learn, and self-organise, over time. What they do is sometimes predictable, but only within limits. The sense-making

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Box 2: The challenge of being an agent in a complex system

It is not the complexity of any interventions that diminishes capacity for successful implementation, but the complexity of the system, particularly its multiple and often conflicting goals and agents. Take the case of the "Ottawa ankle rules", a *large-scale* recommendation intended to reduce unnecessary x-rays by mandating ankle injury scans only for patients with specific pain. Tell that to the ED nurse working on the front-lines of care who has to deal with the parents of a little boy who has presented with a painful ankle after falling off the swing set. The parents are unlikely to be pleased at being sent home with lingering uncertainty about whether their son's ankle is fractured or not. The nurse is 'concurrently expected to get people in and out of the department within target times, avoid re-presentation of patients, and provide patient centred care'. At the *fine-grain scale* of patient interaction, the improved overall efficiency of the system through reduced x-rays is of little concern to the nurse. She may have few misgivings about ordering that x-ray however 'unnecessary' current policy suggests it is.

Source: adapted from work in Weaver, T. D. and Patterson, S. (2009). The myth of complexity. *Br Med J (Online)*, 339: b3505.

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capacities of agents in healthcare systems mean, for example, that doctors learn about their own work, the patients they care for, others' activities, and the conditions and contexts of the system they work in, amongst other things. Patients find out or absorb information about their health status, their place in the system, and whether and the extent to which they have a say—that is, whether they are enabled or constrained in having a voice, and how much of one, in considerations about their treatment and its follow-up. Agents learn dynamically, and have tendencies to behave at least to some extent, and often largely, according to simple internalised rules (e.g., "I'll keep my patient alive at any cost", "It's someone else's job to order the tests", or "I prefer palliative care to an invasive procedure"), rather than merely in response to some top-down prescription or higher order instruction (Plsek and Greenhalgh, 2001). These rules are not necessarily shared among all agents of a system, although they can be, and nor are they fixed in time or space or across stakeholder groups (Rouse, 2008).

2. **Interconnections.** There are many relationships and connections which manifest among agents. Nurses, doctors, patients, services and organisations relate intensively within a CAS; they are not isolated from each other, but behave interactively, to accomplish tasks and meet goals. They share information from their environment, and from their own resources, and act concertedly, for example, to develop and deliver care for patients through group actions and teamwork. There are emergent social structures such as networks that are produced, reproduced and changed through these interactions (Long, Cunningham and Braithwaite, 2013). In the myriad of networks in healthcare, agents may be disproportionately connected to none or a small few, or to many others. They form into vertical hierarchies (e.g., clinical pecking orders, or as represented by organisational charts depicting the reporting arrangements) and horizontal heterarchies (e.g., a team of surgeons, the staff of ward 1a, or a group of patients and relatives who band together as a support network) (Rouse, 2008). See Figure 3 for illustrations.
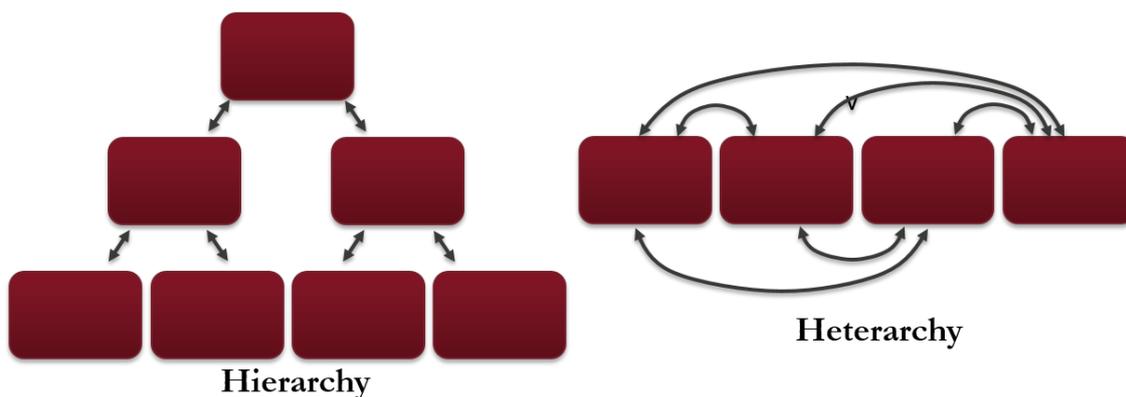
Figure 3 – Organisational structures of hierarchy and heterarchy. Source: Authors' conceptualisation.

When interacting, agents bridge, mediate or navigate gaps in the system—between groups, silos, networks, and institutions, for example. Agents' collective, emergent behaviours and rules lead to social, professional and organisational structures; thus, people in the system organise, partly through the organisation's structured arrangements, and partly by self-organising (Rouse, 2008). Interacting over time, dynamically, means that the behaviours of agents within a CAS affect others, directly and indirectly (McDaniel and Driebe, 2001). Relationships are always changing, as is the context, the environment, and the behaviour of other agents, and participants learn about, and from, this. In essence, players, relationships and rules in a CAS co-evolve; people are adjusting and flexing in response to each other, especially those who are close by, or influential, all the time.

3. **Dynamic systems**. As discussed, a CAS is a descriptor of a special kind of system—one that is dynamic, and perennially changing (Robson, 2015). The diversity of agents and the multiplicity of interactions in a CAS means that relationships are always shifting, mutating and modifying, because, for example, participants interact idiosyncratically, process information in different ways and respond to their environment and each other distinctively. This can create tensions and innovations (McDaniel and Driebe, 2001). The system can be perturbed by internal events (e.g., a new software system or guideline for managing patients is introduced) or by external events (e.g., a flu outbreak or train crash, affecting the capacity of a healthcare system to cope with the flow of patients). Through adapting to these perturbations, the system generates response mechanisms such as feedback loops, which, over time, can either enhance or dampen the effects of a perturbation. Indeed negative feedback loops pulling the system back to its prior position are thought to explain some of the difficulty of sustaining the positive change of improvement strategies (Byng, Norman and Redfern, 2005), while positive feedback loops can be harnessed to strengthen momentum for change in large-scale system transformation (Best, Greenhalgh, Lewis, Saul, Carroll and Bitz, 2012). CASs also experience periods of equilibrium, where things might be in relative stasis, and remain in a patterned state, until some new perturbations arise. Things might still be changing, of course, but in microscopic or subtle ways rather than dramatically. Emergence is a fundamental property of these longitudinal dynamics. It means that material changes in the behaviour and characteristics of the system, even modest ones, promote or facilitate rules and further changes, some of which can eventually be far-reaching. This is the so-called "Butterfly Effect" (Begun, Zimmerman and Dooley, 2003). Here, small changes can sometimes have big consequences. So, new ideas, drugs, techniques, internalised rules, policies, practices, a new piece of hardware or software system are applied or emerge, and then are taken up within a group or social structure, and spread across one or more networks of agents. These downstream effects can be beneficial, or detrimental, or have mixed results. When the consequences are detrimental, it can manifest as what we think of as the "for want of a nail, the shoe was lost" phenomenon. This can be truly devastating. For example, a test result missed because someone was simply distracted and forgot to read it, or it wasn't sent, or the support staff mislaid or misinterpreted it, can be rather irrelevant to the patient's health, or catastrophic if it leads to delays

in getting a vital diagnosis or crucial treatment. On the other hand, larger, intended, planned changes can sometimes have modest effects (McDaniel and Driebe, 2001). For example, a large-scale restructuring of an entire hospital or chain can have limited effects on the deeply ingrained culture of the organisation, or its rusted-on, routinised front-line practices (Braithwaite, Westbrook, Hindle, Iedema and Black, 2006). All changes and transformations, and their consequential outcomes, whether stimulated by top-down or bottom-up means, typically occur in non-predictable, non-linear ways.

4. **Rules and governance**. CASs, as we have already begun to suggest, are characterised by rules and governance. They can be top-down, bottom-up, or middle out (Coiera, 2009). The rules that matter may be, but are not necessarily (and often aren't), the formalised rules of the prescribed policy landscape, or reflective of the governance mechanisms depicted on boxes of organisational charts (Rouse, 2008). More frequently, we are referring in complexity thinking to the localised rules that small-scale groups develop and adopt, and which are expressions of, and embedded in, their cultures. The formal rules and prescriptions count, of course, but often not as much as those in authority think they do in a system with high levels of clinician autonomy and patient discretion. Regardless of which have most effect on behaviours, once we put together formal policies and procedures, the internalised rules of individual agents, the interactions between them, and the self-organisation and bottom-up tendencies of multiple stakeholder groups as they respond to their local circumstances, then the shared "rules of the game" and social forces for governing behaviours emerge. The interactions among agents, for example, produce and reproduce social structures (i.e., networks, cliques, hierarchies and heterarchies that enable work to be done; they also shape ideas to be shared, or communication and messages to be sent and received). The patterns of the entire system thereby emerge, based on these interactions and exchanges. The system in addition, as we have seen, constantly accommodates to external perturbations and internal interactivity. Emergence essentially means that one level up from front-line behaviours, there are structured, patterned collectives and clusters, and social and organisational governance arrangements, which arise over time (McDaniel and Driebe, 2001). All-in-all this means that despite the potential for unpredictability, non-linearity, and even messiness and chaos, there are patterns, behaviours, structures and routines which together define the system, and guide behaviour within it.

Part I

Getting Started:

Aspirations for Complexity Science

Part II

Characterising Complexity Science:

Approaches to Understanding

You are here

Part III

Dealing with Complexity:

Applications to Healthcare

Part IV

Implications:

Accomplishments of Complexity Science

Part V

Conclusion

Part VI

Appendices
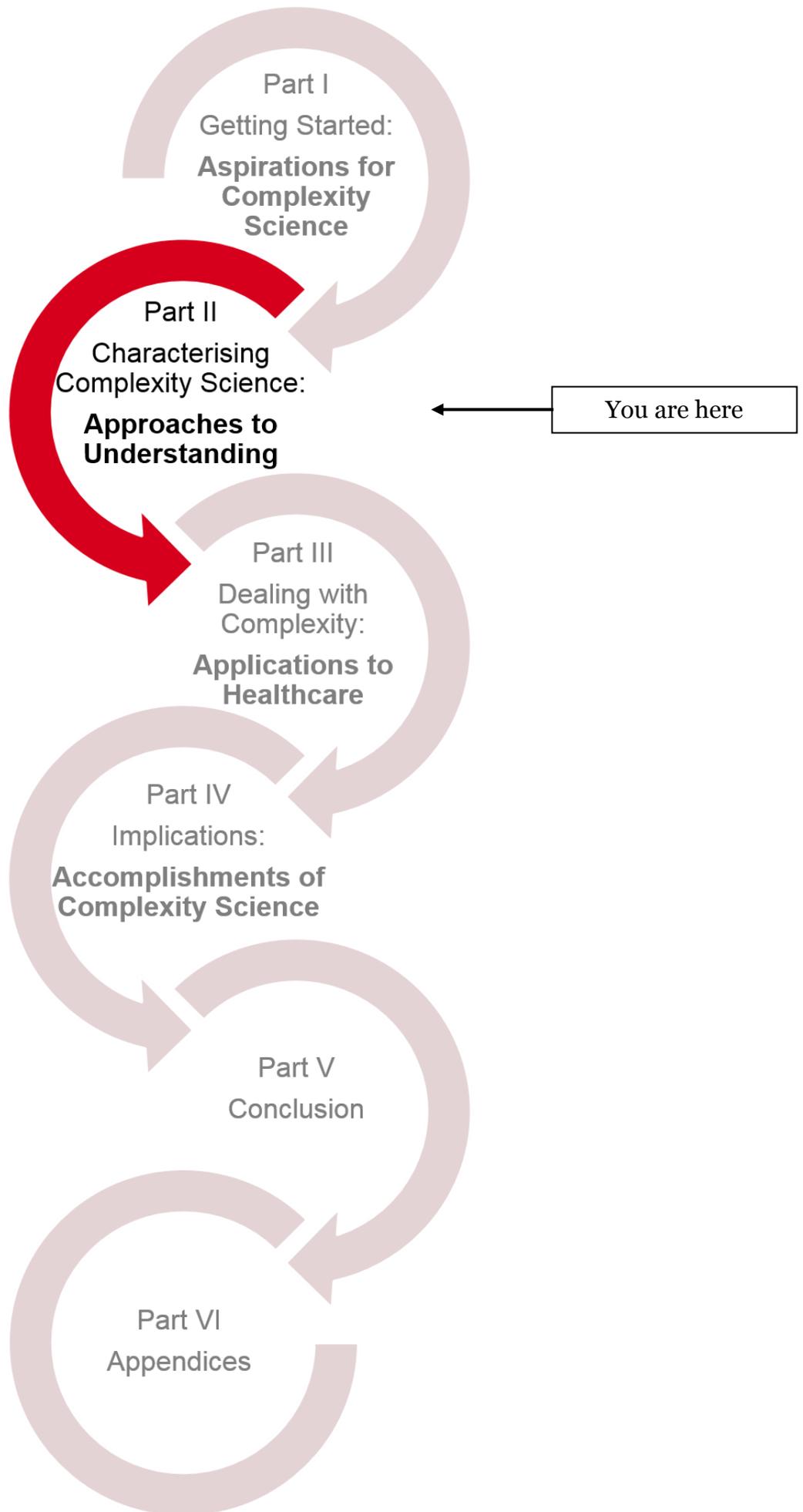
Part II – Characterising Complexity Science: Approaches to Understanding

COMPLEXITY AND LINEARITY

With this framework in mind, a CAS involves a picture of the world that is different from that which is held in the mind of those who adopt a linear stance. For example, working in a CAS, *people can't for much of the time see the forest through the trees;* and, *they won't necessarily realise what's happening until it's happening* or even, *until it's happened.*

> *"Where the world is dynamic, evolving, and interconnected, we tend to make decisions using mental models that are static, narrow, and reductionist."*
>
> **John D Sterman**

Source: Sterman, J. D. (2006). Learning from evidence in a complex world. *Am J Public Health, 96*(3), 505-514.

In other words, CASs can't be described as simply an aggregation of individual behaviours without reference to the larger whole and its emergent properties. Neither observers nor participants can see the whole system (Sterman, 2006). It's too intricate and convoluted, and in any case, behaviours aggregate to patterns in the here-and-now, which means the social structure isn't evident until it's there. That's the point about it being emergent: the patterns and properties of the CAS are not always directly observable or predictable, and are often apparent only by their instantiation, or effects. What emerges from the system consists of unexpected, unintended consequences, new patterns of behaviour, fresh relationships, and so forth, which arise from the reverberating interactions of agents. The context and environment alters from one moment to another, as people go along collectively learning, interacting and self-organising. To capture this distinction between complexity and linearity, we present two depictions of a hospital.

The first diagram (Figure 4), is an example of a formal organisation chart showing the reporting arrangements, levels of authority, and differing roles. Like all charts of its kind, it purports to portray who is in charge, where people fit in the hierarchy, who has responsibility for which function, or how accountability and control are being exercised, and so on.

The second is a diagram showing some of the CAS properties (Figure 5), displaying various interacting feedback loops, iterative connections, chance encounters and the like. It purports to portray the recursive, emergent, messy, self-organising properties of the CAS.
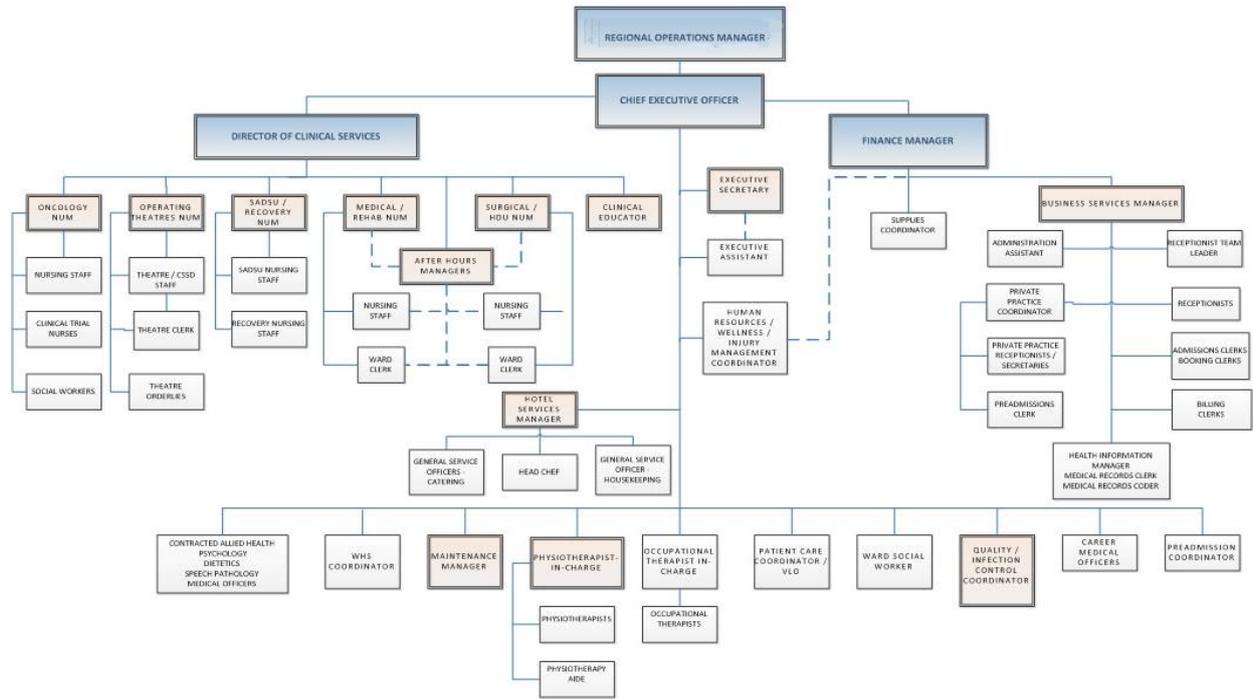
Figure 4 – Linear hospital organisational chart providing a structured view of the reporting and authority relationships. A representation of a complicated system. Source: adapted from Southern Highlands Private Hospital (2017) http://www.southernhighlandsprivate.com.au/About-Us/Organisational-Chart
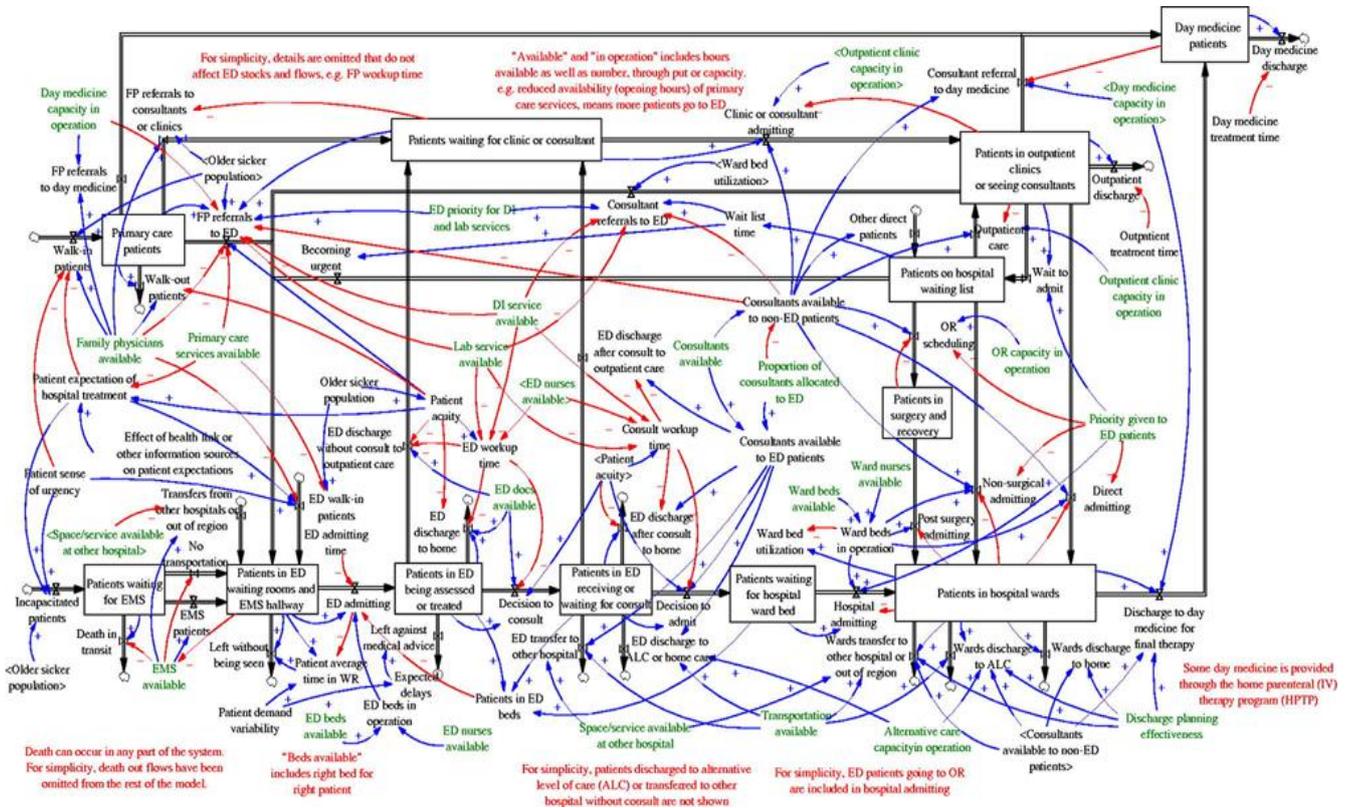
Figure 5 – Hospital as a CAS depicted through a Causal Loop Diagram, representing aspects of the dynamic complexity of the organisational interactions. A representation of a complex system. Source: Braithwaite, J. (2015). Modelling causal pathways in health services: A critique. Retrieved from https://www.slideshare.net/CLAHRC_WM/modelling-causal-pathways-in-health-services-critique-jeffrey-braithwaite

Both depictions are "right" to some extent. The organisational chart version shows the formalised arrangements and attempts to represent who reports to whom in a logical configuration. It tends toward the normative, not the descriptive—the way those in authority positions would like the world to be. The interactive, systems version emphasises the informal arrangements, and attempts to represent how people self-organise and relate in an iterative fashion. It tends toward the descriptive, not normative—the way things unfold in a busy configuration as a web of interconnections. One draws predominantly on linear thinking, the other, complexity thinking.

We want to point out that most people, for much of the time, don't see or even reflect on the complexity that they are part of, and which emerges from their interactions. In some respects, they "do" complexity but don't "see" complexity. Instead, despite functioning in CASs such as in the way portrayed in Figure 5, participants mostly navigate the CAS, but think about it in linear terms. That's a key component of being a human being, and solving problems as economically as possible. For example, we imagine that if we drive to work and navigate the traffic as we always do, in a predictable, half-hour journey, we *will thereby arrive* at our appointed time. Doctors try and secure a diagnosis, *and then* treat people according to their well-rehearsed clinical routines for that condition. Sick patients often assume that taking their medicine *will lead to* a return to good health. In other words, people operate in the world by the logic of *if I do X, Y will occur* or *if A happens, then B will follow*. Yet *Y* often does not happen, and *B* will not always follow (Box 3). For example, Greenhalgh,

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Box 3: Complexity, nonlinearity and the human brain

Consider the paradox between the increasingly complex world we inhabit and our limitations to apprehend such complexity. To attempt to understand the infinite world around us with our finite faculties we use "cognitive approximation". Our representations of the world around us affect not only how we make sense, but how we take action. When we use linear thinking—the assumption of proportionality between inputs and outputs—we approximate the complexity of our world in the same way "we use frequently linear segments to approximate curves of different shapes". Linear thinking also works hand-in-hand with reductionism: breaking problems down into smaller and smaller parts, finding their solution first, then aggregating the solution to the whole. However, this solution only holds if the real overarching problem is of some linear phenomenon. In a complex world, this is rarely the case.

Sources: adapted from work in Bratianu, C. (2007). *Thinking patterns and knowledge dynamics*. Paper presented at the European Conference on Knowledge Management, Barcelona, Spain; and in Jones, W. and Hughes, S. H. (2003). Complexity, conflict resolution, and how the mind works. *Conflict Resol Q, 20*(4), 485-494.

Russell, Ashcroft and Parsons (2011) highlight the limitations of linear thinking, which have seen the failure of a nation-wide e-health implementation in the English National Health Service (NHS). The complexity of this healthcare system, the sheer impossibility of fully appreciating this complexity, inflexible models for change and success, as well as substantial differences between agents/stakeholders, have ensured this remains a "wicked problem".

Even a cursory inspection of a hospital or community health setting or an aged care facility (or indeed, any healthcare CAS), will illuminate complexity characteristics. In such settings, linear thinking will only get you so far, and will often prove to be deceptive. For an aphorism, we might say: *you can't apply simplistic, linear thinking to complex adaptive problems and expect to get what you want, or even necessarily to explain, the dimensions of the problems and their nuances.* Each of the examples we gave, of driving to work, securing a diagnosis, or getting well, present on the surface as linear matters, but are actually complex problems. Much can go wrong. There are many alternative pathways and potential perturbations to the system involving getting to work on time, caring for patients, and getting well, and lots of unpredictabilities.

Similarly, human experiences of health and illness are not simple, linear or predictable. The interacting biochemical, cellular, physiological, psychological and social systems through which such experiences emerge force us to recognise the complexity of not only healthcare, but of our own humanity (Wilson and Holt, 2001). Because of the architecture of the brain, and the way it is structured to solve problems, we are drawn to linear explanations and solutions. But complexity is what we encounter when we attempt to apply our solutions.

So, it requires effort to think in complex terms, and solve problems taking into account their multifaceted nature. Decision-making in CASs is not like playing snakes and ladders; it's more like driving for the first-time while simultaneously solving Rubik's cube from first principles, without instructions about either activity. On the surface, working inside organisations, although always challenging, rarely seems *that* hard. Notwithstanding that, healthcare organisations have frequently been conceptualised as machines, with the corollary implication that improvements are possible, predictable, and easily implemented (Plsek and Greenhalgh, 2001). As we shall see, this is simply not the case.

IMAGES AND WORDS OF COMPLEXITY

Images of complexity

To better understand how researchers, experts and modelers see complexity and CASs, a Google Image search using the term "complex adaptive system" was conducted. The first 50 unique visual representations were collated (see Figure 6, and, for a fuller version, Appendix A) and similarities across the visual representations were synthesised.
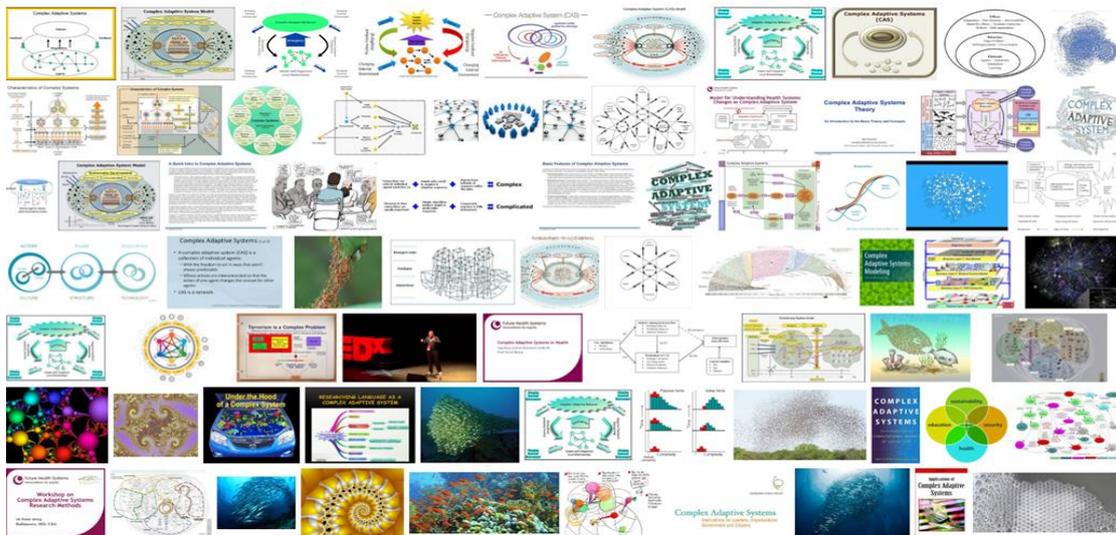

Figure 6 – The first 50 unique models assembled by using the search term "complex adaptive system" in Google Images. Source: generated on 23 May, 2017 using www.google.com/images

Most images provided models or frameworks by which to understand CASs (Box 4). In essence, the models attempt to represent CASs as non-linear in nature, in three recurring ways. First, the system is invariably represented as a web, or network, of connections and interactions. These webs may be presented as chaotic, or more uniformly structured. Second, the system is portrayed as hierarchical, where individual agents are situated at the lowest level of the hierarchy, and the system as a whole is positioned at the highest level. Third, a combination of both webs and hierarchies is incorporated into some of the visual representations.

> **Box 4: Common features of CAS models**
> - Non-linear
> - Visually represented by networks, hierarchies, or a mixture of both
> - Nodes represent agents
> - Vectors represent connections, relationships or interactions between agents
> - Directional arrows represent feedback mechanisms
>
> Source: Authors' synthesis.

One of the most common features of CAS models is the depiction of agents. Individuals are typically portrayed as nodes (points, or small circles)—connected

through vectors (lines) to other nodes, to illuminate connections. In some models, these nodes-as-agents vary in size to demonstrate the strength of certain relationships, or, their seniority, or the location or standing of key players within the network or the system.

Across the models, adaptive learning and emergent patterns of behaviour are illustrated by depicting positive and negative feedback mechanisms, the flow of information, and external environmental influences. These constructs feed in and out of boundaries of the system and are represented through directional arrows. In some models, emergence is shown as originating from the whole system towards individual agents, and in other images, the direction is reversed, where emergence comes from the networked behaviours of agents and feeds into the CAS as a whole.

Another recurring subject throughout the search was images portraying groups of organisms (schools of fish, flocks of birds, armies of ants). These images depict CASs occurring in nature, where a group of organisms is self-organised, and unified in movement, behaviour, or shared goal (Janssen, 2010). Within these groups there is no "leader". Individuals do not direct behaviour, but rather patterns of behaviour emerge from interactions between individual members of the group, guided by a set of rules (Janssen, 2010; Plsek, 2001).

Words of complexity

Another way to understand how complexity and CASs are explicated is through language—across literature, poetry, science and philosophy. We sourced representative quotes about complexity, extracted from the websites such as the link https://en.wikiquote.org/wiki/Complexity as well as another website at http://www.goodreads.com/quotes/tag/complexity. The common themes in these quotes were identified. Appendix B provides a collection of ones we found most evocative or useful, or both, and a selection of others is sprinkled throughout the White Paper. An overarching message from the quotes is that complexity is counterintuitive, in that, making human systems complex is actually rather easy, and something that people have a tendency to do. However, making something simple is extremely hard, a skill or capacity which a lot of people do not possess. This partly explains why organisations, institutions, and daily life, seem to be getting more complex. We're designing and building in more complexity to human existence: more rules, inventions, policies, technology, choices, opportunities, science, discoveries, applications, and knowledge.

COMPLEXITY AND UNCERTAINTY

Conceptualising healthcare as a CAS, in images and language, leads to an appreciation that the system is inherently unpredictable, dynamic, and, consequently, that there are inherent uncertainties (Begun and Kaissi, 2004). The characteristics we have seen earlier—of self-organisation, emergence and co-evolution, instantiated in any CAS—guarantee that uncertainties will manifest, and persist over time. As we have noted, healthcare is made up of a collection of individual agents interacting in non-linear and non-forecastable ways (Plsek and Greenhalgh, 2001). The unpredictable actions of these agents alongside the complexity of the human body and its disease processes, and the challenge in caring for and curing these, leads to situations of ambiguity (McDaniel, Lanham and Anderson, 2009). An example of this, amongst many we could have chosen, is in Box 5. Agents must and do co-evolve as they work to address the constant dynamism and uncertainties in the system (McDaniel and Driebe, 2001) and emanating from their patients' conditions. The ability to deal with such unanticipated events is essential to, and rooted in, the effective functioning of healthcare systems (Rose, Riolo, Hovmand, Cherng, Ferrer, Katerndahl, Jaén, Hower, Ruhe, Aungst, Roux and Stange, 2013), particularly for those working on the front-lines of care.

> **Box 5: Uncertainty in the life of a healthcare professional**
>
> Dr Karen Walker was a medical resident working at a public hospital. One of the patients on her floor coded, experiencing cardiopulmonary arrest, and was intubated by the ward nurses. The nurses found difficulty in getting a good connection to the heart monitor leads. It is common protocol in medicine to rely on the heart rhythm indicated on the monitor to decide the set of medications to give to a coded patient. Without a good connection, and no indication of the heart rhythm of her patient, Walker was faced with a situation of uncertainty; she was unsure of the process of care required to keep her patient alive.
>
> In this situation of uncertainty, Walker did what doctors do—she made a decision based on training and experience because of a lack of information. Knowing that epinephrine was the first drug in a code, she made an order. All this occurred in the face of immense time pressure and uncertainty. Luckily, the patient responded to the drug and Walker was later assisted by the lead cardiologist. By working together, they saved the patient's life. Clearly, the human body is complex and doctors aren't perfect; uncertainty is experienced regularly by healthcare professionals and they must be able to cope with lack of information and make quick and well-justified decisions even when results are unpredictable.
>
> Source: adapted from work in Lowes, R. (2003, October 24). Coping with clinical uncertainty. *Medical Economics*. Retrieved from http://medicaleconomics.modernmedicine.com/medical-economics/content/coping-clinical-uncertainty

Uncertainty is a contributor to the emotional labour and stress of healthcare professionals (Mann and Cowburn, 2005) and affects patient satisfaction (Gordon,

Joos and Byrne, 2000). However, the problem facing researchers and agents in CASs is that there are many types of uncertainty, such as those related to aspects of care delivery (diagnosis, prognosis, and the structure of care, e.g., Han, Klein and Arora, 2011) as well as professional roles (Williams and Sibbald, 1999). The specifics of these and other uncertainties as well as their extent of occurrence across the healthcare system and within different settings (e.g., primary, acute) have not been explored in great detail (Han, Klein and Arora, 2011).

Generally, uncertainty in healthcare depends on contextual factors such as the clinical task; disease occurrence, reoccurrence, and behavioural patterns of both clinicians and patients; the local circumstances embodied in the structures, policies and culture; and the interdependencies among them (Leykum, Lanham, Pugh, Parchman, Anderson, Crabtree, Nutting, Miller, Stange and McDaniel, 2014). Uncertainty therefore can be seen as emerging through the complex interplay of these different properties and components of a healthcare system, and is integral to it—it comes with the territory. High levels of complexity makes the consistent differentiation, operationalisation or classification of uncertainty a tricky feat. For example, Leykum and colleagues (2014) discern two types of uncertainty in healthcare (disease-related and task-related), whereas Han, Klein and Arora (2011) classify the varieties of uncertainty in healthcare in a three-dimensional taxonomy, referring to its sources, issues and loci (see Figure 7). Evidently, there is uncertainty about uncertainty.

Regardless of how we end up categorising uncertainty, we will have to figure out ways to live with it. In the meantime, it would be a useful thing to unify conceptualisations of uncertainty in order to accommodate the range of situations of unpredictability in healthcare. Such consensus will improve our understanding of the manifestations of uncertainty, their occurrences and their effects. While we strive to positively manage aspects of the complexity of life in a CAS, such as by improving how agents in the healthcare system respond to (Han, Klein and Arora, 2011) and cope with (Hamui-Sutton, Vives-Varela, Gutierrez-Barreto, Leenen and Sanchez-Mendiola, 2015) different types of uncertainty, those working in the here-and-now of healthcare, or supporting or researching it, must accept that it is common, and factor it into our decision-making, and accommodate to it.
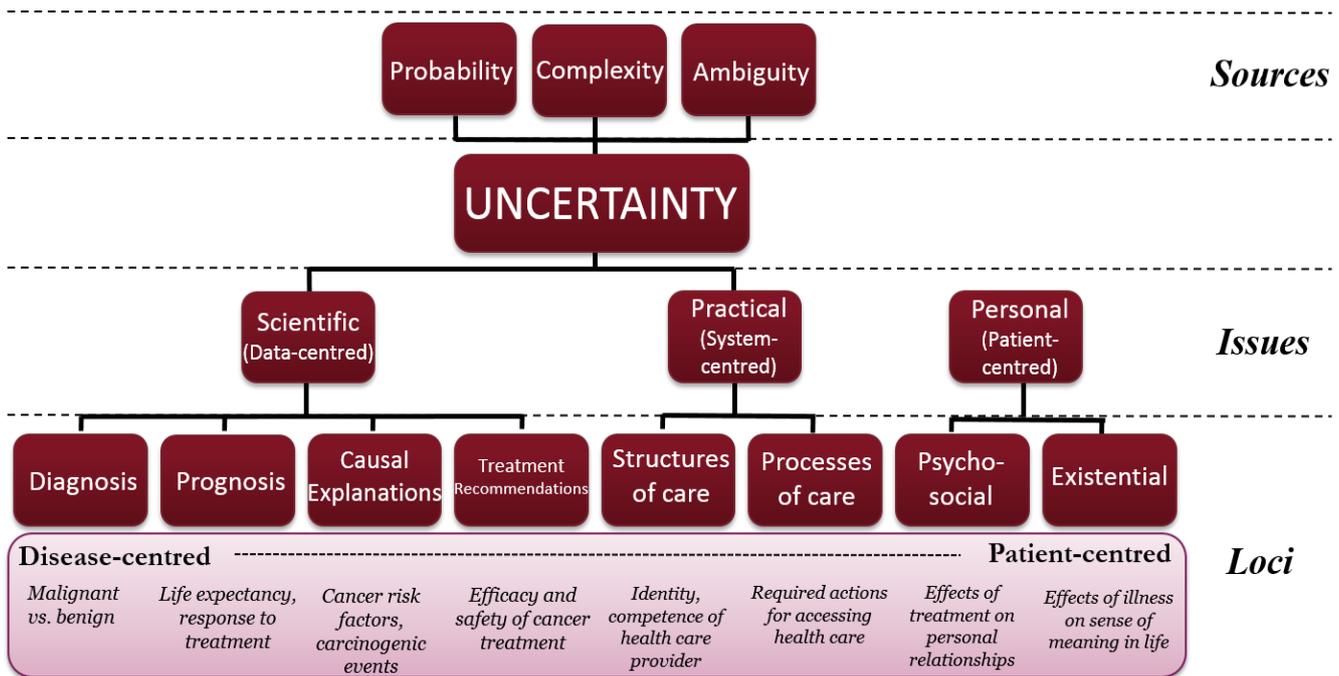
Figure 7 – Uncertainty taxonomy. Source: adapted from Han, P., Klein, W. and Arora, N. (2011). Varieties of uncertainty in health care: A conceptual taxonomy. Med Decis Making, 31(6), 828-838.

In any case, a more general antidote for the uncertainty of healthcare comes from the characteristics of complexity itself, in particular the interconnectedness of agents and their capacity to process information about other agents and their environment. These capabilities allow for "sense-making", a social rather than individual process in which agents come to a shared understanding, or meaning, of their experience (Lanham, Leykum, Taylor, McCannon, Lindberg and Lester, 2013). In terms of engendering sense-making among clinical staff, this can involve them collectively responding to questions such as "who are we?", "why are we here?", and "what is going on around us?" (Weick, 1995), as well as building trust, attention to new ideas and mindfulness (Lanham, McDaniel, Crabtree, Miller, Stange, Tallia and Nutting, 2009; Lanham, Palmer, Leykum, McDaniel, Nutting, Stange, Crabtree, Miller and Jaén, 2016; McAllister, Leykum, Lanham, Reisinger, Kohn, Palmer, Pezzia, Agar, Parchman, Pugh and McDaniel, 2014). Opportunities for sense-making abound, for example, in healthcare "huddles", where teams have a focused gathering, such as interdepartmental briefings or unit planning sessions that provide opportunity for meaningful communications; these interaction may enhance relationships and a learning culture and have been linked to improved patient safety (Provost, Lanham, Leykum, McDaniel and Pugh, 2015).

Sense-making is perhaps a useful contributor to managerial decision-making in the face of the uncertainties of a complex system (McDaniel and Driebe, 2001). It can

promote adaptive performance among clinicians in the face of disturbances (Nyssen and Berastegui, 2017), facilitate communication with patients (Leykum, Lanham, Provost, McDaniel and Pugh, 2014), and provide a means for improving quality in healthcare (Leykum, Chesser, Lanham, Carla, Palmer, Ratcliffe, Reisinger, Agar and Pugh, 2015). This, in particular is accomplished by emphasising the understanding of how everyday clinical work is actually accomplished rather than focusing on what "should" be done (Sheps, Cardiff, Pelletier and Robson, 2015).

COMPLEXITY AND EMERGENCE

We've been discussing concepts in healthcare, and its CAS features, but how do things happen? Complexity science helps us to understand, and clarify, much about how dynamic systems operate, and adapt, over time. In Darwinian natural selection, adaptation under modification explains how things start with a few simple rules (have self-replicating cells, time, and some energy to fuel growth), and then develop over long sweeps of time. From such humble beginnings, evolution produces variation and diversity amongst species; and complex forms and new adaptive behaviours follow.

Emergence explains much of this. It says entities downstream in a system come into being through the interactions of those upstream. Thus, life emerges from chemistry, cognitive processes from synapses in the brain, and the fundamental phenomena of physics such as space, time and mass emerge from interacting particles, bosons or strings.

"The theory of evolution by cumulative natural selection is the only theory we know of that is in principle capable of explaining the existence of organized complexity."

Richard Dawkins

Source: Dawkins, R. (1986). The Blind Watchmaker: Why the Evidence of Evolution Reveals a Universe Without Design. UK: Norton and Company, Inc.

Swarming is often used as a behavioural example of emergence. Swarming is common in many species such as in flocking birds, herding quadrupeds, and schooling fish (Spector, Klein, Perry and Feinstein, 2003). The swarm is produced and reproduced from simple, local rules: no-one is in charge, follow the direction of your neighbours, remain close to others, but don't bump into anyone. From these modest rules, complex, patterned swarming behaviours arise (Mataric, 1993).

A message for those interested in human systems like healthcare is that nothing in these examples needs deliberate leadership, or active agency, to make things work. They function just fine by letting the bottom-up rules operate.

Indeed, one challenge for those who seek to improve human systems such as healthcare, knowing this, is to appreciate that the law of unintended consequences with human action is that you may well produce a worse health system if you meddle, or try to orchestrate the structure of the system, even with the best of intentions. Trying to improve health services and offering better care will usually be better achieved by working with, rather than against, the localised rules produced by, and which guide, the front-lines of care. Running human systems like healthcare, on this

analysis, should be more like tending to a forest than prescribing detailed software code.

Yet people do try and prescribe, and even mandate, all the rules in health systems. A central problem with healthcare, however, is that many people who fund it or are *ostensibly* in charge—Government Ministers, policymakers, for example—have decided they *are* in charge, and act accordingly. They seek to exercise control, and organise things, by fiddling with the organisational structure, imposing policies, or prescribing procedures. By way of contrast, Senge (2006) once observed that people in the upper echelons of any decent sized system at best have the illusion of control. Nevertheless, people in positions of authority either come to believe they are running the system, or want to be seen to be doing so. Johnson (2002) describes this as the myth of the ant queen. We see a complex system and assume that something or someone is in charge—or should be. So, health systems, ant colonies and rainforests have hierarchies and look like there's something in charge (the Ministry of Health, God, the ant queen, the top species or predator), but there isn't, in the end, in reality.

Behaviour happens, though, and things develop in both evolutionary and human-mediated systems. How? Because of this property of CASs we've come to call emergence (see Box 6). Much of the structure through which things get done is not that which is prescribed from above, imposed by the people who issue the organisational chart. It's from below, from the collective interactions of the elements in the CAS.

The way this works is that people at one scale—in healthcare, those individuals on the clinical front-lines, or in nature,

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Box 6: The emergence of threats to safety

In contrast to the conventional "*root cause* analysis", complexity science suggests that errors, threats to safety and accidents are not caused by any one thing, but emerge from the non-linear interactions of people, machines and policy—'resonance' in resilience theory (Sheps, Cardiff, Pelletier and Robson, 2015). For example, a wrong blood transfusion for a patient in a Japanese university hospital can be reduced to underlying problems of deviation in the delivery of blood product, nurse manpower, and the hospital's system for electronic health records (EHR) (Nakajima, 2015). Alternatively, this event can be understood as emerging through the confluence of a number of normative and often reasonable variations in everyday clinical work, which are produced in response to the requirements of delivering care within a complex, pressurised sociotechnical system where there is often conflicting guidance, and multiple reasons for how to use EHR systems. The different interpretations of the same event—reductionist or complex—have distinct implications for attempting to reduce such an error in the future.

Source: adapted from work in Wears, R. L., Hollnagel, E. and Braithwaite, J. (Eds.). (2015). *Resilient Health Care: The Resilience of Everyday Clinical Work* (Vol. II). Farnham, Surrey, England: Ashgate Publishing, Ltd.

ants gathering food or those looking after the queen's eggs, and plants and animals deep in jungles—interacting—produce behaviour which is expressed in structure one scale above them. This is how clinical services and teams emerge, as do ant colonies and rainforest ecosystems. And it is not just the front-lines of the system that make things work. All types of CAS are relatively immune from top-down instructions. Try telling ants how to behave, or flora and fauna, or independently-minded clinicians. By interacting laterally, and following localised rules rather than prescriptions from above, structures, or meso-level behaviours, arise. These behaviours are always feeding into the shape of the entity and its contours. In short, emergent behaviours produce structure at the next level up.

A reader paying close attention might object, saying that human systems are different. There's conscious agency at work, not blind evolution. After all, someone pays for healthcare, the salaries of the providers and their expensive equipment, so they or their representatives should, and do, call the shots. People with the power and levers, depicted so at the apex of the organisation chart, this argument suggests, have the capacity and in fact do organise care, specify the way it should be delivered, mandate some things and not others, issue instructions, determine procedures to be followed, fund some services and not alternatives, articulate the organisation's strategic direction and support some plans and not others. All of this is meant to guide behaviour now, and into the future.

But it's also the case that the in-charge folks can't ultimately control many, or even most, things that matter. The decisions surgeons make on whether or not to operate, or how deep to cut, or what kind of operation is done, for example. Or how much time a ward nurse spends with that special patient in bed 14. Or what is discussed or emphasised at shift handover. Or the quality of the explanations about the patients' conditions in a case conference. Or whether the radiologists' unwritten plan to get a second opinion on a hard to decipher MRI scan is operationalised every time. Or how well the ED will cope when a spike of patients presents following a bus crash at 2:00 am. Autonomy is the guiding principle for many behaviours, not just in nature, but in much of healthcare. This means that any one healthcare decision is almost never simple; indeed, interconnections of agents with a finger in every decision pie make them tryingly difficult (see Box 7).

And so it transpires that health systems, even highly structured ones with lots of formal or mandated rules, are much more like natural systems than many politicians, policymakers and managers suspect, or choose to believe. For large slabs of time and

across many circumstances, no one up the line in the offices of the in-charge people is doing any conjuring.

If you ask clinicians to keep behaving and interacting, providing care and services on the front-lines of care, however, patterns emerge. Keep repeating these, and they get elaborated, and take root. Simple local rules (e.g., "let's deliver care with the resources we have at our disposal as best we can in the environment, and act concertedly together to do so") lead to complex, recurring patterns by which care is delivered, just like in nature. A seed becomes a flower, an embryo an elephant, a group of workers and machinery aggregates into a factory, and a clinical workforce creates a health service.

> **Box 7: Can we be patient-centred in a complex system?**
>
> In a complex system, even the most well intended rules, policies and guidelines may have unintended consequences. Take "patient-centred care", which, in attempting to put the patient at the centre of decisions, belies the fact that healthcare is a complex network of interdependent components. For example, Dr Jones, a GP, consults with 14-year old Susan, who is seeking a prescription for the contraceptive pill. However, this same GP has also treated Susan's boyfriend Steve a few weeks earlier for a sexually transmitted illness, and is the family physician for her parents, who are known to have strong moral principles related to sex and contraception. A range of ethical and medical issues are brought forth, and the question, not easily resolved, becomes to whom does Dr Jones owe a duty of care? Who—Susan, Steve, Susan's parents—is the patient at the centre? In a similar vein, another doctor must decide whether to treat her patient with an effective but overpriced drug. This may not seem too tricky a decision—if the patient needs the medication, then they need it— but the cost of that treatment might come at the expense of more cost-effective treatments for multiple patients in other parts of the system. The importance and interdependency of all elements of the healthcare system means that true patient centredness may come at the expense of another agent, including past or future patients. In CASs, there are always trade-offs to be made.
>
> Source: adapted from work in Aronson, J. (2016). "Collaborative care" is preferable to "patient centred care". *Br Med J (Online), 353*.

The phenomon that structure is created from the bottom-up, without a controlling hand, is what puzzled Turing, expressed in his famous paper on morphogenesis, or how shape originates (Turing, 1952). It explains a lot: it's why almost all large hospitals, aged care facilities, and community-based health services look similar to others across the world, regardless of funding arrangements and policy settings. Despite all those in-charge-people having appropriate authority and flexibility (some owners of private facilities have complete discretion, a free rein) to be able to organise the clinical workforce and care they offer in ways they wish, organisational structures and delivery arrangements are similar in health settings everywhere. If the controller did really have ultimate discretion, and

exercised it, we would see much more diversity in organisational structures and models of care. We don't. Instead, we see this isomorphism, or similarity in structures. Emergence tends to produce self-similarity.

This also explains why, when those in the upper levels of the system fiddle with the organisational chart, restructuring the organisation, so little happens to the actual delivery of care to the patient and the configuration of services, and almost nothing to the fundamental organisational culture (Braithwaite, Hyde and Pope, 2010). The coal-face settings in hospitals, community health centres and residential aged care are far more reactive to, and influenced by, the overarching way medicine organises itself into specialties and how nurses and allied health professionals structure themselves locally on-the-ground, than any other factors. Emergence, and bottom-up activities, are powerful determinants of what happens at the next level up in structural terms. That's the power of the CAS, and emergence, at work.

We don't mean that top-level leadership should be done away with. There are many functions that need to be coordinated from above: overarching financial allocations, broad-based policy, and longer-term strategic choices, for instance. But, like Greenhalgh, Plsek, Wilson, Fraser and Holt (2010), we argue that "tight centred control, can be counterproductive, not that organisations work better with nobody in charge" (p. 115). Forms of distributed leadership (Greenfield, Braithwaite, Pawsey, Johnson and Robinson, 2009) are much better models for healthcare than micro-management and rigid impositions from above.

So far, we've attempted to characterise complexity science, understand the dynamics of CASs, and sought to improve our appreciation of systems, including healthcare, through a complexity lens. It's time to move to Part III, and look at ways to deal with complexity—specifically, applying these ideas to healthcare settings and problems.
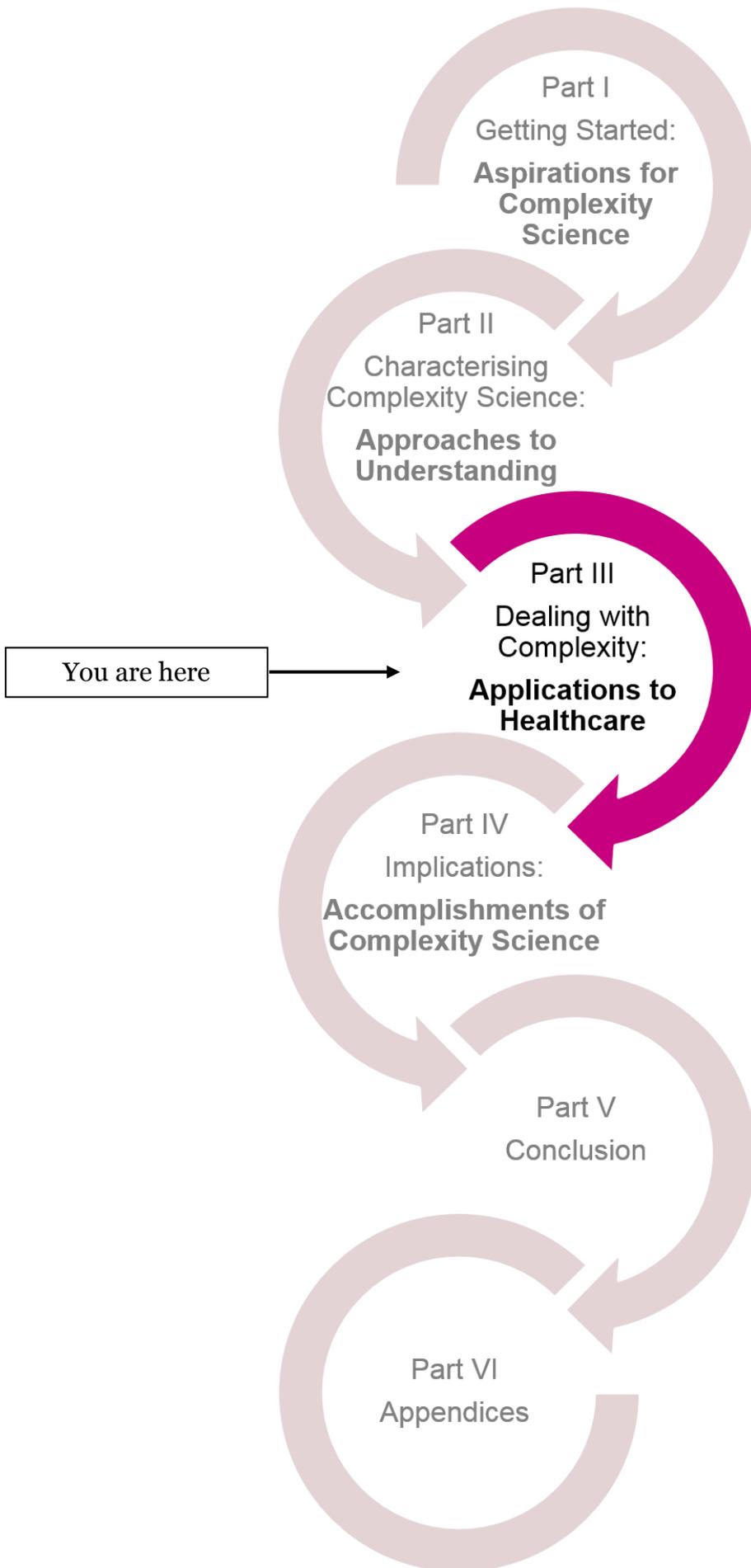
Part I

Getting Started:

Aspirations for Complexity Science

Part II

Characterising Complexity Science:

Approaches to Understanding

Part III

Dealing with Complexity:

Applications to Healthcare

You are here

Part IV

Implications:

Accomplishments of Complexity Science

Part V

Conclusion

Part VI

Appendices

Part III – Dealing with Complexity: Applications to Healthcare

COMPLEXITY AND NETWORKS

An increasingly popular way to describe core dimensions of complexity, and bring out some of its key features, is by depicting its network characteristics. Social network theory provides a powerful lens through which to understand complex health systems as whole, or network structures within them. Health services research is often reductionist, separating out small parts of a complex heath system or a section of it, and studying them in isolation. As useful as microsystem research (Mohr, Batalden and Barach, 2004) and single practitioner group studies are (e.g., of nurses in operating teams), to more deeply understand a process, we must recognise that the parts do not explain the whole. Studying one aspect of a system does not account for how the elements become organised into a complex system, factoring in the multiple interactions, feedback mechanisms, constraints and promoters (Bárabasi, 2002).

Network theory is the study of how the elements within a system interact following a set of principles. This has led to the discovery of consistent similarities between such diverse systems as neural networks of nematodes (Morita, Oshio, Osana, Funabashi, Oka and Kawamura, 2001), power grids (Das, Panda, Muduli and Rath, 2014) and the internet (Carmi, Havlin, Kirkpatrick, Shavitt and Shir, 2007). Within social groups, the structure of the network is determined, and mediated by, the relationships between the group members (Wellman, 2007)—for example, the staff in a hospital or those providing services in a community setting. Relationships that link (or isolate) people within such a network include the exchange of patient information (Benham-Hutchins and Effken, 2010; Chan, Reeve, Matthews, Carroll, Long, Held, Latt, Naganathan, Caplan and Hilmer, 2017; Patterson, Pfeiffer, Weaver, Krackhardt, Arnold, Yealy and Lave, 2013) or requesting or receiving work-related advice (Creswick and Westbrook, 2007, 2010; Creswick, Westbrook and Braithwaite, 2009). Social network theory is used to explain the context for individuals' actions including constraining and enabling factors that affect behaviour (Emirbayer and Goodwin, 1994).

Driven by this theory, social network analysis (SNA; see Box 8) can help people discern such complex system phenomena as the tendency for disciplines and clinical specialties to organise themselves into silos (homophily); differences in the quality of

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Box 8 – Features of SNA

Four defining features of SNA:

1. Motivated by a "structural intuition," where social or interactional ties between pairs of actors and their distance from each other are mapped.

2. Grounded in systematically gathered empirical data.

3. Draws on graphic imagery to produce representations where nodes are individual actors linked by their ties.

4. Relies on mathematical and computational models allowing measurement of a range of parameters.

Source: Freeman, L. C. (2004). *The development of social network analysis: A study in the sociology of science*. Vancouver, CAN: Empirical Press.

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communication between members (density, structural holes, and diffusion of innovations); and why group processes may be disrupted or fall apart completely when certain people leave (key players).

Figure 8 provides an illustration of this in the form of a network map of an ED, drawn from research contributed by our group (Creswick, Westbrook and Braithwaite, 2009). It shows how the ED's agents (doctors, nurses, allied health, and administrative staff) operate in silos, notwithstanding that there is a good deal of interaction going on across the professional groupings.
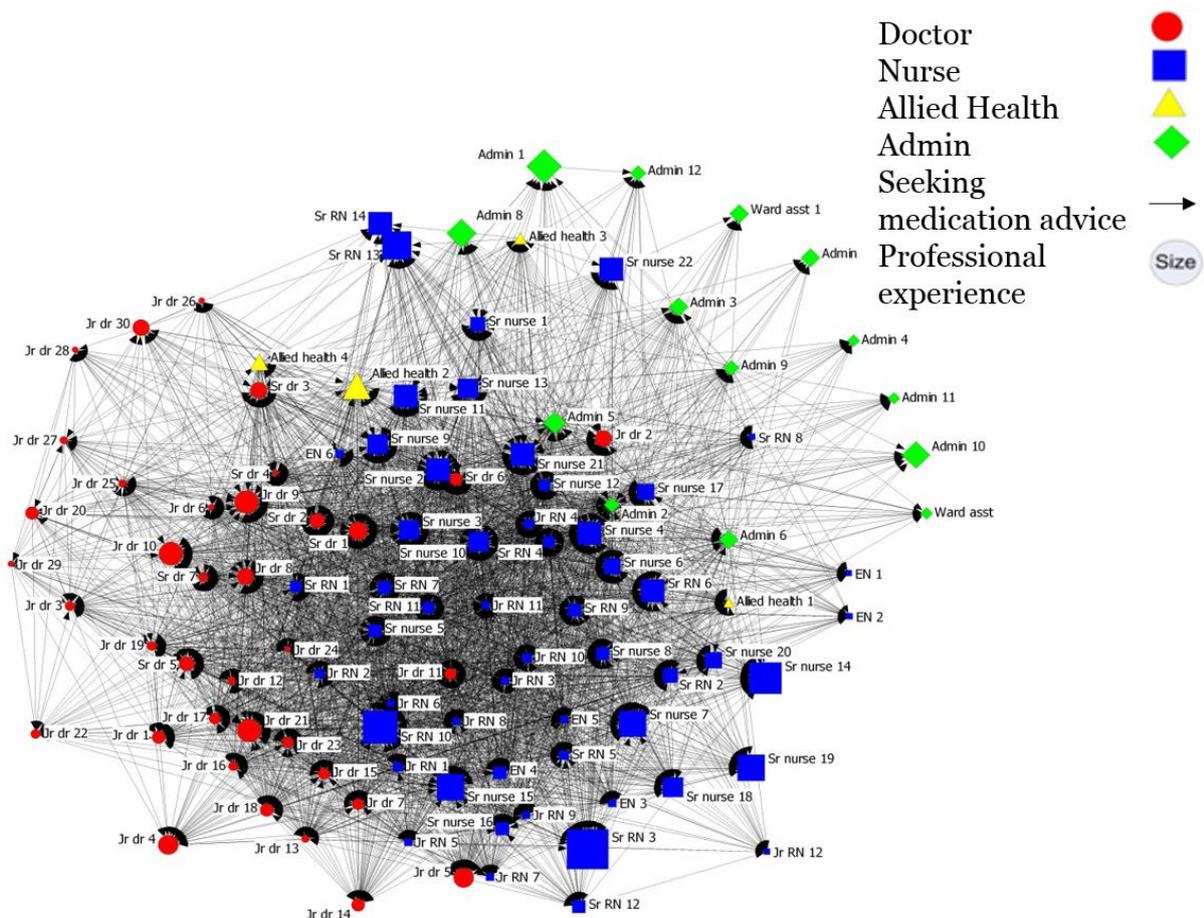

Figure 8 – A schematic of the medication advice-seeking network in an ED based on SNA. Source: adapted from Creswick, N., Westbrook, J. I. and Braithwaite, J. (2009). Understanding communication networks in the emergency department. BMC Health Serv Res, 9(1), 247.

Very few studies have followed networks over time in order to map, and expose the dynamic nature of systems. Aiming to address this failing, we (Long, Hibbert and Braithwaite, 2016) researched a Translational Cancer Network from 2012 to 2015. We surveyed clinicians (oncologists, cancer nurses and associated staff) and researchers to track their interactions over time. The density of connections increased dramatically during that period, as the research team encouraged relationships to flourish via multi-faceted projects designed to increase levels of collaboration. The network diagrams capture these activities across three time periods (Figure 9).
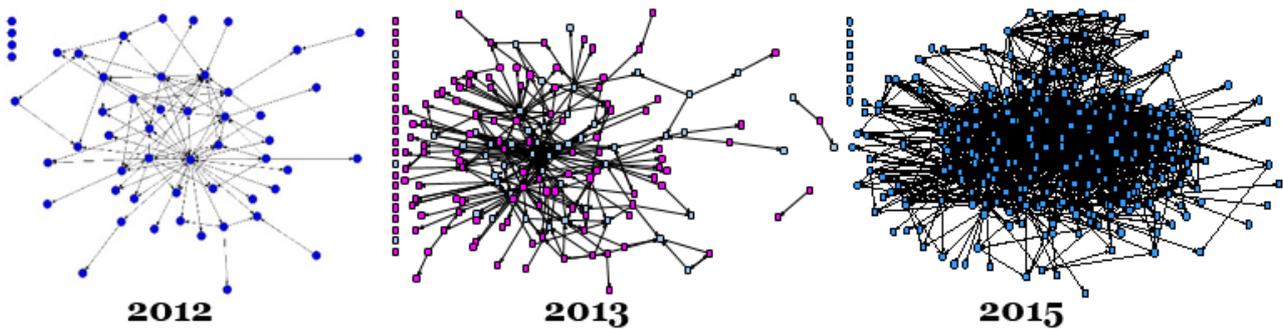

Figure 9 – A longitudinal study of collaboration in a translational cancer research network using SNA. Source: adapted from Long, J. C., Hibbert, P. and Braithwaite, J. (2016). Structuring successful collaboration: a longitudinal social network analysis of a translational research network. Implement Sci, 11(1), 19.

THE ACTORS WHO MATTER IN A COMPLEX ADAPTIVE SYSTEM

If network analyses expose the relationships of the actors in a network, and represents them as nodes, who are the actors behind the nodes? What do they do, and how do agents do what they do? In a healthcare CAS, as we have seen, agents include individual people such as physicians, nurses, allied health practitioners, and patients. But agents' behaviours and practices also involve processes such as nursing and medical procedures, administrative steps, and functional units' activities such as surgery, testing, accounting and marketing. Agents are loosely or tightly coupled depending on their team characteristics, broader cultural features, or roles or functions, but most teams in CASs are highly interconnected. They need to be, to deliver

> *"A clinician is ... part craftsman, part practical scientist, and part historian."*
>
> **Thomas Addis**
>
> Source: Addis, T. (1948). Glomerular Nephritis, Diagnosis and Treatment. University of Minnesota, USA: Macmillan

care effectively, otherwise patients might fall through the system's cracks. Agents are constantly acting and reacting to what other agents are doing, and as we have said, they tend to self-organise independently of any controlling hand. The essence of a CAS is therefore captured in the dynamic, non-linear relationships among agents—who are interconnected in self-organising, emergent, and co-evolving systems—rather than in the diverse agents themselves (Long, Hibbert and Braithwaite, 2016; McDaniel and Driebe, 2001).

In healthcare CASs, several key agent roles can be identified, although there are others beyond those we discuss here. Central agents gravitate to the middle of the network, and are often seen as experts or opinion leaders, interacting with most others in the system. They are influential and are most sought after for advice (Braithwaite, 2015; Long, Cunningham, Carswell and Braithwaite, 2013).

Once they get to a certain size, systems tend to parse into sub-systems, or "in" and "out" groups (Braithwaite, Clay-Williams, Vecellio, Marks, Hooper, Westbrook, Westbrook, Blakely and Ludlow, 2016). The common manifestation of bounded clusters—such as organisational silos and professional "tribes"—leads to gaps between groups of agents, for example at the boundaries of, and between, professions, departments, specialties, or local sites. "Bridge" is a generic linking descriptor of those agents who traverse or join up these gaps. Examples of gaps to be crossed include those between clinicians and managers, and clinician groups of differing kinds, as we showed in Figure 8. Yet another is the gap between patients and their

providers—for example, in terms of their understanding of the technical aspects of care. "Brokers"—also manifesting as mavens, go-betweens, liaisons, connectors, *tertius iungens* (Obstfeld, 2005), cosmopolites, and boundary spanners—play a crucial role in shortening or dissolving the gaps by linking two or more agents that are not themselves linked, and facilitating transactions and information flow between them. The value of brokerage to CASs is considerable: brokers can increase system connectivity and collaboration by liaising with agents from various sides of the gap, thereby generating a cross-fertilisation of innovative ideas, increasing accessibility of advice and knowledge, and mediating and resolving conflict (Braithwaite, 2010, 2015; Long, Cunningham and Braithwaite, 2013; Long, Cunningham, Carswell and Braithwaite, 2013).

Besides central players, brokerage agents and bridges, gatekeepers play an important protective role in healthcare CASs. In some countries, general practitioners, acting as the gatekeeper, prevent patients from unnecessarily or prematurely entering specialised healthcare, for example. Alternatively, gatekeepers can inhibit brokerage behaviours by acting to prevent interaction (Braithwaite, 2015). Inhibiting roles within a CAS network include those of blocker and manipulator; and those who take advantage of structural holes or divides in CASs for their own benefit, called *tertius gaudens* (Burt, 1995; Simmel, 1950).

Formal mandated roles and key agent roles do not always overlap in a CAS. The appointed head of a medical department is often the clinical leader, and can correspond to the role of central agent. However, there may be a persuasive opinion leader from amongst the clinical ranks with contrasting views to the formal, in-charge person.

Behaviours, and the roles people purportedly occupy, can also be deceptive. There is often a mismatch between actual and perceived brokers and the activities of blocking or manipulating agents can be hidden and not always apparent (Long, Cunningham, Carswell and Braithwaite, 2013). Interventions or improvement efforts seeking to support key agents in healthcare CASs could profitably start by accurately identifying them, to be able to enrol them in improvement activities, or have them help with take-up of new practices, for example.

DISTRIBUTED CONTROL AND ORGANISATIONAL COMPLEXITY IN HEALTHCARE

While the formal organisational chart, with its depiction of hierarchical accountabilities is ubiquitous in modern healthcare organisations, emphasising the value of less formalised structures like the natural networks of CASs is being recognised (Braithwaite, Runciman and Merry, 2009). For example, specific kinds of social and professional networks, known as "communities of practice", have been shown to improve the diffusion of medical innovations, and may be beneficial in the coordination of care, and collaborating to improve the quality and safety of care (Cunningham, Ranmuthugala, Plumb, Georgiou, Westbrook and Braithwaite, 2012). Communities of practice can also have a role in improving healthcare performance (Ranmuthugala, Plumb, Cunningham, Georgiou, Westbrook and Braithwaite, 2011).

Even more so, the increasing complexity of, not only modern healthcare systems but, whole societies, suggests that networks may be integral to the success of organisations in the future. Human social systems are capable of behaviours of greater complexity than the individual humans that comprise them, with, for example, corporations and organisations involving diverse and specialised individual behaviours that are coordinated via various mechanisms (Bar-Yam, 2002). This coordination is the result of the influence individuals have on one another; that is, through forms of control. In a completely hierarchical system, control is ceded to the one at the top, and communications within the organisation must run up the chain of command, through layers of management, and then back down. In actuality most organisations, especially those in healthcare, are hybrids of primary (hierarchical) and lateral (heterarchical) connections of communication. This is because hierarchically-arranged leadership structures have weaknesses that networks do not (see Figure 10).
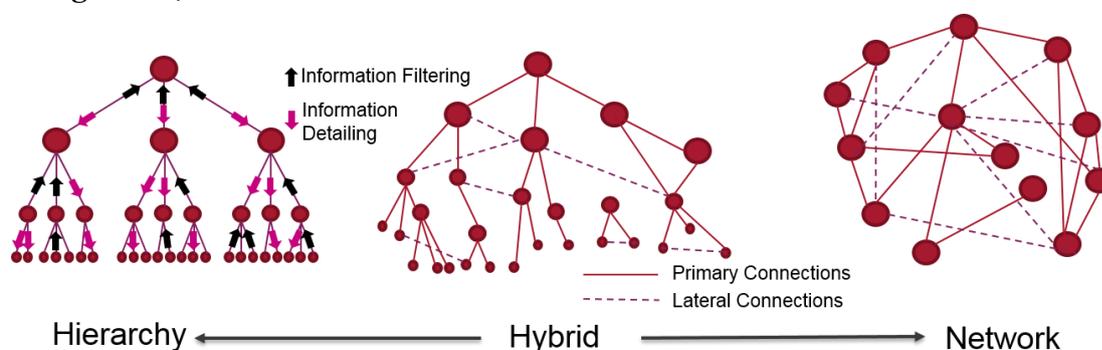

Figure 10 – Three types of organisational structures. Source: adapted from Bar-Yam, Y. (2002). Complexity rising: From human beings to human civilization, a complexity profile. Encyclopedia of Life Support Systems. Oxford, UK: UNESCO Publishers.

As the figure shows, hierarchies "limit the degree of complexity of collective behaviours of the system" (Bar-Yam, 2002). This is because their organisational structure, in which the coordination of agents and parts of the system is relatively centralised in the hands of one individual, puts limits upon the flow of information and control. Bar-Yam (2002) argues that the controller's behaviour must involve cognizance of the different aspects of the system and their effects on one another; "this implies that the collective actions of the system ... must be no more complex than the controller". Lateral connections as in networked organisations, on the other hand, provide the opportunity for more people dealing with greater complexity through their self-organisation, just as the sum total of neural activity in the brain is more complex than single neurons. Hybrid structures have emerged as an interim to the problems of hierarchical organisations, with lateral connections required to coordinate worker actions, because management, unable to deal exercise control, is separated from other levels. Indeed, this is a well-recognised problem in healthcare where policymakers and managers, removed from the frontlines of care, tend to "work-as-imagined", articulating new policies and protocols that may have little correspondence to the "work-as-done" by clinicians (Braithwaite, Wears and Hollnagel, 2017).

Dealing with complexity is crucial, as the environment in which human social systems operate in, has, over time, become increasingly complex, evident through historical shifts away from dictatorships and empires, to democratic systems, globalisation and free market economies (Bar-Yam, 2002). In response, organisations are requested to be much more fluid. Generally, organisations that do not change in such an environment, and thus neglect to adapt, particularly in response to the competition created by various external forces, will fail. For healthcare organisations, the situation is perhaps not so dire. Government support and the lack of competition in most healthcare systems internationally may serve to insulate these organisations, to some extent, from failure that occurs when they do not adapt or manage complexity. Nevertheless, complacency is not an option. Numerous threats to healthcare organisations' sustainability are already evident, with ageing populations experiencing a greater number of comorbidities and people having higher expectations for their care. As well, there are many new innovations, pharmaceuticals, models of care and technology that systems will struggle to pay for (Coiera and Hovenga, 2007). This points to the fact that organisational structures that emphasise hierarchy over network, will not be optimised to deal with the

complexity of the environmental demands encountered in healthcare organisations, where a mix of diverse activities and challenging problems, must be resolved (McCallin, 2001).

Therefore, networks, teams, communities of practice and other coordinating mechanisms provide specific advantages such as more effective knowledge diffusion and efficient use of resources (Greenfield, Braithwaite, Pawsey, Johnson and Robinson, 2009). The distributed leadership, communication, and reciprocity that characterise them also holds the opportunity for dealing with environmental demands, by allowing for ways to handle the complexity of collective behaviour. Distributed leadership "is an emergent property of a group or network of interacting individuals; there is an openness of boundaries of leadership; and leadership expertise is spread amongst those involved" (Greenfield, Braithwaite, Pawsey, Johnson and Robinson, 2009, p. 256). This certainly doesn't mean that no one is in charge, but rather that control is not unduly constrained by centralisation (Greenhalgh, Plsek, Wilson, Fraser and Holt, 2010).

In healthcare, evidence suggests that widely distributed leadership is associated with improvement in service outcomes (Fitzgerald, Ferlie, McGivern and Buchanan, 2013) and the accomplishment of large scale system transformation (Best, Greenhalgh, Lewis, Saul, Carroll and Bitz, 2012). Indeed, healthcare organisations characterised by elements of a CAS—interconnections, self-organisation, and co-evolution—have had greater success with interventions such as improving patient outcomes for chronic diseases (Leykum, Parchman, Pugh, Lawrence, Noël and McDaniel, 2010; Leykum, Pugh, Lawrence, Parchman, Noël, Cornell and McDaniel, 2007). Hence, organisational complexity, evidenced in the interdependency and distributed control of networks, may be something to embrace rather than resist.

Harnessing the advantages of natural networks, distributed leadership and their propensity for innovation, coordination and improvement, should be part of the future of planning sustainable and adaptive healthcare systems and organisations. This is why Braithwaite, Runciman and Merry (2009) proposed a number of "bottom-up" strategies for facilitating coordination and natural networks, including taking advantage of "hubs", those agents centrally located in a network, to act as leaders and encourage best practice. Another factor considered important in developing distributed organisational structures includes building on a foundation of positive pre-existing relationships among agents (Fitzgerald, Ferlie, McGivern and Buchanan, 2013).

COMPLEXITY AND RESILIENCE

This analysis of networks and distributed leadership brings us to another cornerstone concept in complexity thinking—the idea of the natural resilience of health systems. In a simple or linear system, we can see causality, whereby action leads to outcome, as it occurs. If we look backwards from an unwanted outcome, we can determine a root cause and contributing factors—any or all of which can be fixed to prevent reoccurrence of the problem. Emergent outcomes, however, by their nature, are unable to be predicted and a singular root cause is unable to be determined, because there isn't a sole cause. Therefore, the usual methods of addressing unwanted outcomes—that is, controlling variation, putting barriers in place, fixing the primary or solitary determinant, and so on—do not work for complex processes. To adduce a practical example, paradoxically, the processes we put in place to try to stop errors from occurring often add to system complexity, thereby making it even more likely that things will go wrong (Braithwaite, Clay-Williams, Hunt and Wears, 2015; Wears, 2010). Instead, we need to be prepared to deal with an emerging event as it happens even if it is unpredictable—in short, we need to be resilient.

Resilience can be defined as "the ability of the health care system (a clinic, a ward, a hospital, a country) to adjust its functioning prior to, during, or following events (changes, disturbances, and opportunities), and thereby sustain required operations under both expected and unexpected conditions" (Wears, Hollnagel and Braithwaite, 2015, p. xxvii). From a resilience perspective, humans—with their inherent variability, and propensity to both get things right, and err—are seen as an asset rather than a liability. It is human variability, and the continual adjustments people make to their day-to-day work to meet emerging conditions, that contributes to success.

> *"Individuals self-organize not necessarily according to hierarchy or organizational structure but based on how the work actually is accomplished …"*
>
> **Luci Leykum and colleagues**
>
> Source: Leykum, L. K., Lanham, H. J., Pugh, J. A., Parchman, M., Anderson, R. A., Crabtree, B. F, … McDaniel, R. R. (2014). Manifestations and implications of uncertainty for improving healthcare systems: an analysis of observational and interventional studies grounded in complexity science. *Implement Sci, 9*, 165.

While we recognise the importance of resilience in determining how well an organisation will cope when challenged, we do not currently have ways to predict resilience ahead of a crisis. Current thinking is that there are four "abilities" of organisations that affect how they cope with unexpected or challenging events: How organisations monitor their performance, how they anticipate a crisis or adverse

event, how they respond to a crisis, and how they learn from experiencing a crisis (Hollnagel, 2011). By measuring these abilities, we can derive some estimate of organisational resilience. Increasingly too, attention has turned toward encouraging resilience among individuals, teams and organisations, with *in situ* simulation training considered particularly valuable in this regard (Deutsch, Fairbanks and Patterson, Forthcoming; Patterson, Deutsch and Jacobson, 2017).

In addition to the difficulties in predicting resilience, we also do not yet know how to improve (strengthen, bolster, enhance) resilience in an organisation. A new way to solve this dilemma is to shift our focus from preventing things going wrong, to emphasising the number of things that go right. We call this "productive safety", or "Safety-II" (Braithwaite, Wears and Hollnagel, 2015; Hollnagel, Wears and Braithwaite, 2015). Productive safety focuses on ensuring that as many things as possible go right, and on enabling humans to succeed when challenged by unexpected events, by improving our understanding of how everyday work is accomplished under varying conditions. In effect, this takes a whole-of-system, complexity science approach to the problems of safety management, and applies resilience engineering perspectives to it (Braithwaite, Clay-Williams, Nugus and Plumb, 2013; Braithwaite, Wears and Hollnagel, 2015, 2017; Clay-Williams, 2013; Hollnagel, Braithwaite and Wears, 2013; Wears, Hollnagel and Braithwaite, 2015).

Productive safety is a worthwhile capacity to understand, and enhance; indeed, once we begin to recognise the enormous complexity of the healthcare system it becomes increasingly astounding that we do not encounter higher rates of medical errors than already reported. Bar-Yam (2004), for example, highlights the space of possibilities related to the seemingly simple task of medication administration. The thousands of medications available, in the variety of dosages, and forms of administrations to the hundreds of patients in one hospital, means there are far more opportunities for things to go wrong than right. In such circumstances, building redundancies into procedures is highly likely to enhance system resilience and safety.

The key message from this research is to work with, not against the natural properties of the complex system. On the front lines of care, clinicians are flexing and adjusting to circumstances, rather than slavishly following policies, guidelines or standard operating procedures—in short, behaving in resilient ways. Strengthening the capacity of them to do so, providing a few simple rules or "minimum specifications" (Plsek and Wilson, 2001), rather than over-managing, or restricting and constraining their adaptive capacities, is likely to prove fruitful.

COMPLEXITY AND CULTURE

Organisational culture is an important contextual factor in health systems performance. Culture underpins and explains much of the collective behaviours and jointly-held mental models of the participants in the organisation or setting. Culture is defined as the shared behaviours and practices, and the values, attitudes and beliefs that are held, consciously or unconsciously, by employees within an enterprise (Braithwaite, Herkes, Ludlow, Lamprell and Testa, 2016). For a model, the iceberg metaphor is useful: above the waterline is the visible behaviours and practices on display, whilst values, attitudes and beliefs of the collective lie below the waterline (see Figure 11).

Observable behaviours, practices and discourse: 'the way we do things around here'

Waterline

Underlying beliefs, attitudes, values, philosophies and taken-for-granted aspects of workplace life: '*why* we do the things we do around here'
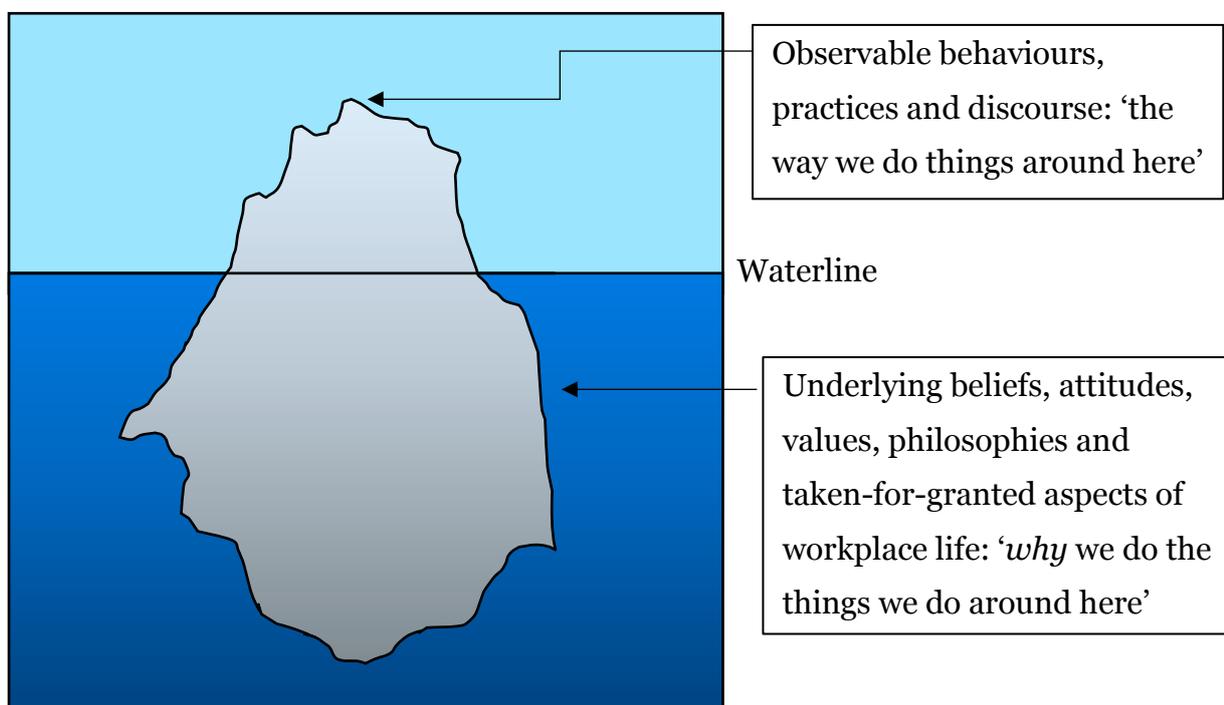
Figure 11 – The "Iceberg" model of organisational culture. Source: based on a conceptualisation by Sackmann, S. A. (1991). Uncovering Culture in Organizations. J Appl Behav Sci, 27(3), 295-317. See also Braithwaite, J. (2011). A lasting legacy from Tony Blair? NHS culture change. J R Soc Med, 104(2), 87-89.

Another way of looking at it is to say that culture is analogous to the water surrounding a fish (see Figure 12 and Appendix A). The fish doesn't know it is swimming in water, although it may recognise it swims in the same direction as the fish like it, just as people who are immersed in culture do not apprehend their own cultural milieu until it is pointed out to them.

Organisations are never entirely cohesive, with a ubiquitous, unidimensional culture. Within any organisation there arise identifiable sub-cultures, such as workplace cultures where professions or co-workers cluster together and exhibit their own unique cultural characteristics but within, and influenced by, the dominant

culture (Braithwaite, 2011; Braithwaite, Hyde and Pope, 2010; Callen, Braithwaite and Westbrook, 2007; Martin, 2002). This means that each agent within the complex healthcare system is linked to and enmeshed in multiple group cultures—the main currents of culture in their organisations, and the sub-cultural clusters in which they are a participant, for example.
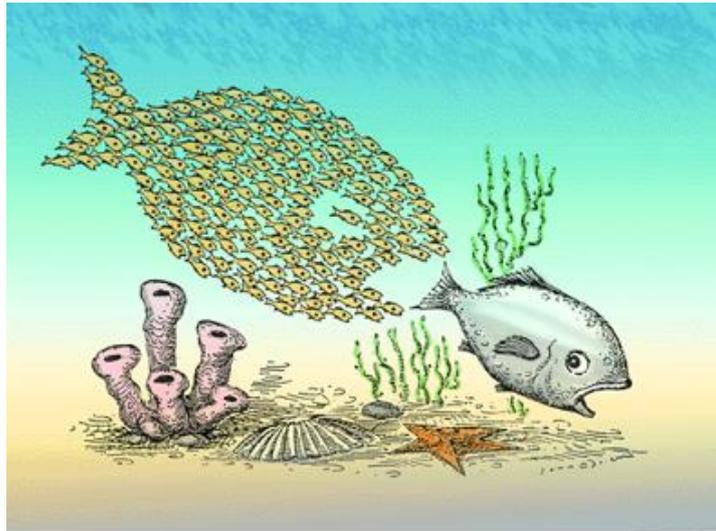
Figure 12 – From Images of Complexity #37. Source:
https://www.openabm.org/book/export/html/1929

Any one person will have multiple, overlapping cultural memberships. A female medical oncology specialist can be a member of several sub-cultures including those identifiable as being "the doctors", "the clinicians", "the lung cancer team", "the women in the organisation", "the people who oppose the surgeons' boys-only approach to recruitment of replacement surgeons", "the Tuesday night mah-jong club", "the chief executive officer's secret kitchen cabinet", and "the Health Minister's planning committee for cancer services over the next ten years". That's apart from being a wife, mother, daughter, sister, guitar player and practising Catholic, which aren't part of the workplace culture but can occasionally impinge on it. And that's only the cultural memberships of one person. Put lots of people together in one organisation, and the sum total of their doing things and ways of thinking becomes the cultural milieu.

Although they tend to endure over time, the cultural characteristics of each group are by no means static; they evolve and adapt in response to changes to the composition of the participants, the addition of team members, and the re-shuffling of social and professional relationships, for example. It follows that the complexities, nuances and adaptabilities of culture within healthcare, and the propensity for change, must be

"The crucial point of the complex systems approach is that from a macroscopic point of view the development of political, social, or cultural order is not only the sum of individual intentions, but the collective result of nonlinear interactions."

Klaus Mainzer

Source: Mainzer, K. (2007). *Thinking in complexity: The computational dynamics of matter, mind, and mankind.* New York, NY, USA: Springer-Verlag.

understood and influenced if we are to make progress and improve outcomes for both

employees (MacDavitt, Chou and Stone, 2007) and patients (Parmelli, Flodgren, Beyer, Baillie, Schaafsma and Eccles, 2011).

An important and poorly understood facet of organisational and workplace culture is employees' "fit", and their perception of their "fit". Are individuals compatible with their organisation and work group, and do they perceive they are? Fit research has identified that there are multiple inter-relating factors that contribute to the person's fit or feeling of fit, with his or her environment; including person-supervisor, person-job, person-group, person-organisation, and person-vocation fit (Kristof, 1996) (Box 9).

For culture research, measures of person-group (P-G) and person-organisation (P-O) fit are most relevant as these variables map to workplace and organisational culture respectively. Adding to the theoretical ideas in this area, P-O and P-G fit can be held to comprise several distinct but highly correlated components of fit; supplementary, complementary, needs-supplies and demands-abilities fit (Cable and DeRue, 2002; Piasentin and Chapman, 2006). What this means is that culture is an important factor in a healthcare organisations' performance, and how well an individual fits with the culture, and how well they perceive they do, are important dimensions in working in, understanding, or improving, a CAS.

> **Box 9: Researching Person-Organisation (P-O) and Person-Group (P-G) fit in mental healthcare**
>
> Future research is necessary to address the ambiguous and elusive nature of fit research in order to tame its complexity and understand how to make more effective and sustainable culture change initiatives.
>
> Members of the research team (JH, KC, LE, JB) have designed a study to investigate the complexity of organisational and workplace culture. Specifically, the focus will be on mental health facilities, a previously understudied area of healthcare within culture research (Morris, Bloom and Kang, 2007). The study involves developing and validating a new survey tool that, for the first time, will explicitly pinpoint what facet of P-O or P-G fit is being measured in each question. This will allow a more rigorous analysis of the relationship of fit with staff outcomes, including job satisfaction, burnout and stress. It is anticipated that the study will make a valuable contribution to understanding the complex, evolving, non-linear nature or organisational and workplace culture in healthcare.

COMPLEXITY AND IMPLEMENTATION SCIENCE

Implementation science is a multidisciplinary pursuit, attempting to develop scientific or social-scientific methods for the take-up, and spread, of research findings into clinical practice (Rapport, Clay-Williams, Churruca, Shih, Hogden and Braithwaite, 2017). The problem is that the routine adoption of things known to work well either via an intervention or by demonstrating efficacy in one or several settings, has often stalled. At best, progress has been painfully slow (Grimshaw, Eccles, Lavis, Hill and Squires, 2012).

In the healthcare CAS we are describing, this is a significant problem. There are 27 million papers in PubMed (US National Library of Medicine, 2017), the biomedical database, and 75 randomised trials and 11 systematic reviews published every day (Bastian, Glasziou and Chalmers, 2010). Just keeping up with the reading in one specialty area is an insurmountable challenge.

If viewed through a linear frame, the problem of embracing evidence-based medicine, and its solution, can be specified. All that has to happen is: do the studies or locate the extant research; assemble it; publicise it; and get it taken up by participants across healthcare, wherever it applies. The same goes

> *"Most people define complexity in terms of the number of components or possible states in a system … However, most cases of policy resistance arise from dynamic complexity—the often counterintuitive behavior of complex systems that arises from the interactions of the agents over time."*
>
> **John D Sterman**
>
> Source: Sterman, J. D. (2006). Learning from evidence in a complex world. *Am J Public Health, 96*(3), 505-514.

in reverse: non-evidence based practices should not be continued. Yet the success rate of retiring outmoded or ineffective clinical and organisational practices is poor, too.

Seen in the light of discussions about complexity science and the point that implementation and de-implementation have to take place in and across multiple CAS settings, then we can begin to discern the dimensions of the problem. Complexity science can help with specifying the magnitude of the challenge, and the barriers to implementation science activities.

As implementation science theory has grown, foundational concepts have emerged (Damschroder, Aron, Keith, Kirsh, Alexander and Lowery, 2009; Greenhalgh, Robert, Macfarlane, Bate and Kyriakidou, 2004). Chief amongst these are adoption, which is the degree to which things known to work are taken up via mechanisms such as new tools, policies, or changed practices. Diffusion refers to

spread of ideas, practices and findings. Dissemination, which is more intensive orchestration of spread, denotes the active mobilisation of ideas known to work. Implementation itself is stronger still, and is concerned with a staged, conscious approach to getting evidence into practice. And sustainability means helping make the newly-embraced practices stick and remain in place for the mid- to long-term, or until better evidence or a demonstrably better practice comes along.

The complexity lens illuminates the scope of the problem to be tackled here. Translation of evidence into new organisational or clinical practices must take place in a milieu that is comprised of multiples of agents with varying levels of interest, capacity, and time, interacting in ways that have already been agreed and have solidified (Hawe, Bond and Butler, 2009; Leykum, Lanham, Pugh, Parchman, Anderson, Crabtree, Nutting, Miller, Stange and McDaniel, 2014). In other words, the patterns by which healthcare is delivered, and the social structures, are already established. Adding something new into these crowded spaces, defined by their pre-existing intricate, layered behaviours and extant activities, will rarely if ever mean that there is simple "take-up." Spreading best or better practice across healthcare organisations, or systems-wide, is tough, too: contexts differ, and a "one-size-fits-all" approach will not necessarily work. Here too, though, complexity science may offer insights, with self-organisation recognised as a crucial factor producing the local variations in our innovations and effective practices in healthcare (Lanham, Leykum, Taylor, McCannon, Lindberg and Lester, 2013).

Implementation science clearly needs to factor in, and perhaps rely on, the dynamic, emergent nature of the system, in order to exploit the possibility of acceptance and adoption of new evidence and accompanying practices. This means focus on the changing context into which an intervention is introduced, rather than just the intervention itself (Hawe, Shiell and Riley, 2009); indeed, we must recognise the complexity of both the intervention and the system in which the intervention takes place (Shiell, Hawe and Gold, 2008). In attending to the context, rather than just the intervention, clearly, the new order of things—fresh evidence, or a different practice—will need to be communicated, endorsed and understood, and to appeal to local agents who believe it will be an advance over current care and treatment regimes in time-poor, multi-layered settings.

CAS theory would also suggest that any implementation has to be commensurate with, or at least not at odds with, the localised rules of the game. It must be better

than what happens now (or perceived that way), be feasible and customisable to local contexts.

One currently popular implementation science model is known as the Promoting Action on Research Implementation in Health Services (PARiHS) formula (Kitson, Rycroft-Malone, Harvey, McCormack, Seers and Titchen, 2008), which is written thus: SI = $\int$ (e, c, f). It means that successful implementation, SI, is a function, $\int$, of the interrelations between evidence, e, context, c, and facilitation, f. Put differently in terms of CAS thinking, practices targeted for change need to account for the local circumstances such as the culture and the density of relationships amongst current agents, and the evidence to change and arguments for it need to be persuasive amongst stakeholders. Those supporting the change must arrange for some sort of facilitation mechanism; practices will not change by osmosis or simply because there is evidence in the literature. Mobilising opinion leaders, bridges and mavens, for example, as discussed in the section on networks, will be an important mechanism by which to explain and demonstrate to others to adopt new ways of working (Braithwaite, Runciman and Merry, 2009). Factoring in CAS properties, such as emergence, unpredictability, the bottom-up nature of change and non-linearity, will also be important for implementation scientists wanting to make progress. For example, Simpson, Porter, McConnell, Colón-Emeric, Daily, Stalzer and Anderson (2013) have developed a tool based on a complexity framework that attempt to identify and manage challenges related to research implementation.

The interdependencies among agents, which affect the success of improvement efforts, are also rarely considered, though the increasing sophistication of computer simulations and particularly agent-based modelling can provide opportunities to reflect upon things prior to an intervention (Leykum, Kumar, Parchman, McDaniel, Lanham and Agar, 2012). Finally, facilitating sense-making among agents may encourage a shared understanding of problems, changes and improvement efforts. The trick is to work with the patterns of self-organisation that enable, rather than restrict, scale-up and spread of innovations (Lanham, Leykum, Taylor, McCannon, Lindberg and Lester, 2013).

CONCEPTUAL FUZZINESS IN APPLYING RESEARCH FINDINGS IN CASs

Perhaps because of the difficulties in understanding CASs and solving problems within them, and because it is easier to assume we can solve problems by linear means, the application of complexity theory to healthcare systems has, until now, been slow and haphazard. When it has been, it has been applied in a limited, inconsistent manner. This was highlighted recently when Thompson, Fazio, Kustra, Patrick and Stanley (2016) undertook a scoping review to examine how complexity theory had been utilised in health services research. They found that studies using complexity tended primarily to have exploratory or descriptive purposes, rather than explicitly attempting to predict or intervene. Much of the research was qualitative, conducted in the US and with nurses as the primary sample. In the studies Thompson and colleagues (2016) identified, there was variation in the way CAS theory was utilised (e.g., as a conceptual framework, for classification, data analysis or interpretation) and how complexity and its attributes were defined. In the main, studies tended to focus on the diversity of relationships and communication patterns of the actors, and the unpredictability of change in their descriptions; however, there was enough discrepancy in the literature to raise concerns that researchers might not, even metaphorically, be always talking about the same concepts when discussing CASs (Thompson, Fazio, Kustra, Patrick and Stanley, 2016, p. 10). More positively, the findings of the review suggested that the use of CAS theory was increasing in health services research, and also highlighted the array of research topics that draw on or can draw on complexity (e.g., change, leadership, management, relationships, culture, working environments), as well as the diversity of agents (e.g., nurses, doctors, allied health staff) and settings (e.g., community health centres, aged care facilities).

Parallel to the issues identified in the application of CAS theory to health services research, Brainard and Hunter (2016) conducted a scoping review of complexity-informed interventions in healthcare. They showed that there was inconsistent use of CAS principles, with some studies (e.g., Kottke, 2013) claiming they were using complexity without incorporating many or any of its concepts into the conceptual framework that underpinned their intervention design. Furthermore, all-too-frequently research which explicitly uses CAS theory in the design phase of the intervention does not also apply its principles—such as looking for unintended consequences—to the evaluation component (see for example Boustani, Sachs, Alder,

Munger, Schubert, Guerriero Austrom, Hake, Unverzagt, Farlow, Matthews, Perkins, Beck and Callahan, 2011; Solberg, Klevan and Asche, 2007).

These issues point to a greater need to clarify our understanding of CASs, how to study them, and how to apply their principles. This applies both to descriptive and interventional research designs.

Part I

Getting Started:

Aspirations for Complexity Science

Part II

Characterising Complexity Science:

Approaches to Understanding

Part III

Dealing with Complexity:

Applications to Healthcare

Part IV

Implications:

Accomplishments of Complexity Science

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Part V

Conclusion

Part VI

Appendices
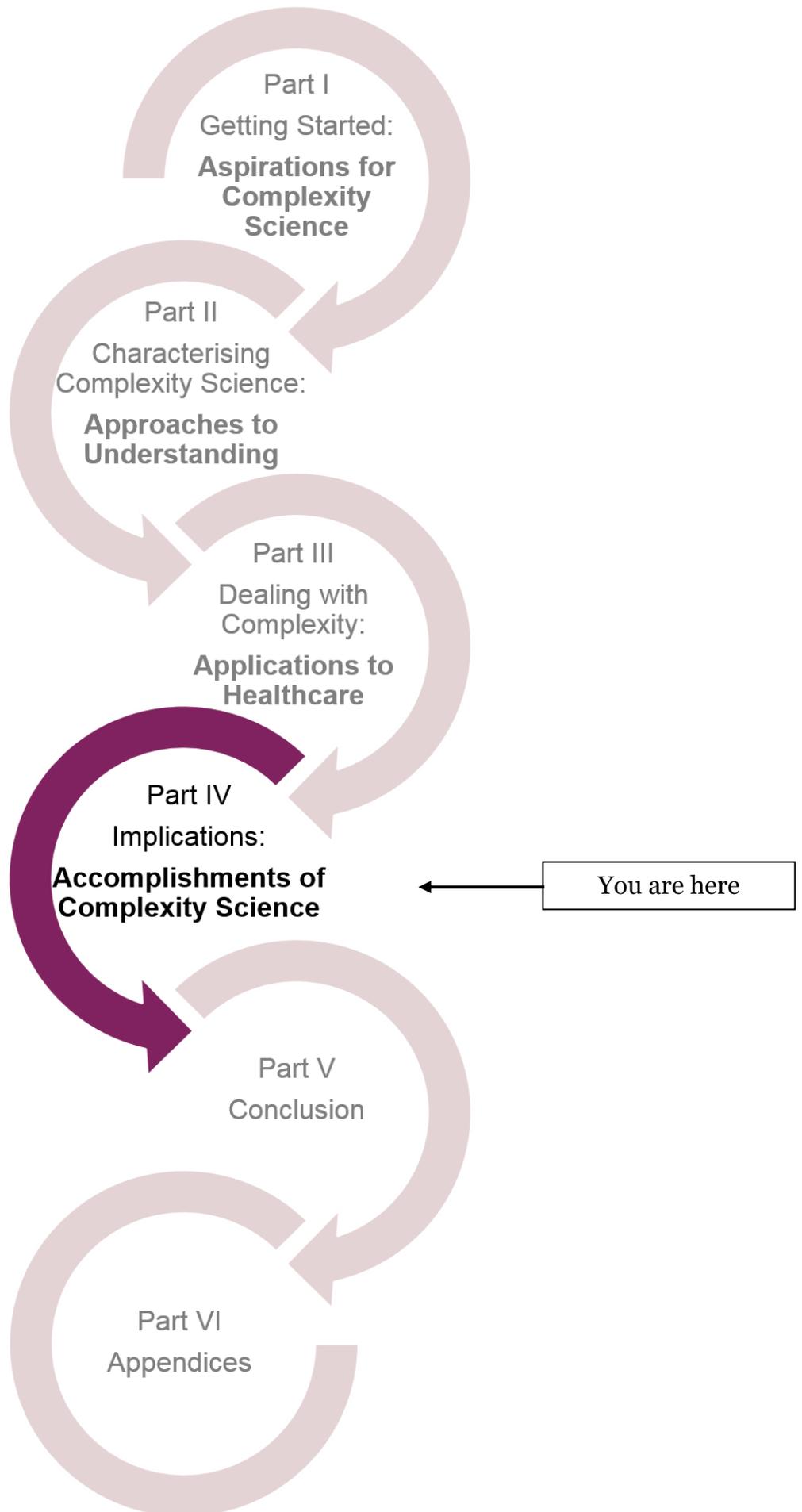
Part IV – Implications: Accomplishments of Complexity Science

WHAT HAVE WE ACCOMPLISHED WITH COMPLEXITY THEORY IN THE PAST?

In Part IV, we turn to the implications of our lines of reasoning and analyses about complexity. What, we ask, are the accomplishments of complexity science in healthcare? We look here at some of the evidence. Over the last twenty years, influential articles have promoted the use of complexity theory to improve healthcare systems and delivery (e.g., Plsek and Greenhalgh, 2001; Sterman, 2006). Though much of the published literature remains descriptive in nature, empirical studies incorporating complexity theory have increased in frequency in recent years (Brainard and Hunter, 2016), and the results, it has been argued, look promising (Thompson, Fazio, Kustra, Patrick and Stanley, 2016). The reasons for an increase in such research are clear: firstly, healthcare systems are rarely suited to simple linear interventions, nor are the problems to be solved suited to the so-called "gold standard" randomised controlled trial (see Box 10), due to the sheer complexity of inputs, their intricate processes, the ambiguity and uncertainty of outcomes, as well as the large number of confounders.

Complexity theory has thus been used to challenge commonly held assumptions, for example, that weight loss, and thereby the obesity crisis, can be easily rectified by people simply responding to admonitions to eat less and exercise more (See Figure 13). The focus should be on relationships rather than simple cause and effect models (Leykum, Lanham, Pugh, Parchman, Anderson, Crabtree, Nutting, Miller, Stange and McDaniel, 2014); be applicable in a variety of contexts; provide a framework for categorising knowledge and agents' behaviour; provide more nuanced analysis

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Box 10: Linear models and complexity

Linear models (e.g., the logical framework) still dominate. These models assume, wrongfully, that an intervention can work, and its impact assessed, without consideration of the context and connection. Similarly, the so-called "gold standard" randomised controlled trial attempting to "control" confounders, which are in fact the inextricable components of the system and its environment. Therefore, there is still too much naïve faith that we can evaluate the value of a complex initiative simply by reference to a small number of indicators. This is despite considerable evidence to the contrary, highlighting the multiple interacting activities and agents within a CAS.

Source: adapted from work in Reynolds, M., Forss, K., Hummelbrunner, R., Marra, M. and Perrin, B. (2012). Complexity, systems thinking and evaluation - an emerging relationship? *Evaluation Connections: The European Evaluation Society Newsletter, December*, 7-9.

Figure 13 – This system map highlights the enormous range of different and interconnected individual, social and economic systems that influence obesity. Source: Butland, B., Jebb, S., Kopelman, P., McPherson, K., Thomas, S., Mardell, J. and Parry, V. (2007). Tackling Obesities: Future Choices – Project Report. Retrieved from London, UK: https://pdfs.semanticscholar.org/b910/e21b81d6caa1d15040b2b69d62155471c692.pdf

of research evidence; suggest new possibilities or options for change; and provide a more complete picture of forces affecting change (The Health Foundation, 2010).

Although researchers and other stakeholders are applying complexity theory to healthcare more frequently than before, a key problem is that the appropriate or most feasible application of complexity theory to social contexts remains unknown (Thompson, Fazio, Kustra, Patrick and Stanley, 2016). Indeed, Thompson, Fazio, Kustra, Patrick and Stanley (2016), in their review of how complexity theory has been incorporated into health services research, identified that conceptual confusion and inconsistent application hinders the operationalisation of complexity theory, and therefore, generalisability from studies that incorporate complexity theory is difficult.

As we have seen, their review demonstrated considerable variation in how researchers define complexity, as well as in how they incorporate complexity theory into healthcare research (e.g., as a conceptual framework, for data analysis, or for interpreting findings). Nevertheless, what we are detecting is an increasing range of studies incorporating complexity theory using novel designs, the majority of which examine interactions or relationships between health professionals (Thompson, Fazio, Kustra, Patrick and Stanley, 2016). As we have seen, SNA has been the empirical method most frequently applied to examine structural relationships among healthcare agents (e.g., Cunningham, Ranmuthugala, Plumb, Georgiou, Westbrook and Braithwaite, 2012), and has been successfully used, for example, in examining patterns of networked communication and collaboration among healthcare professionals (e.g., Creswick, Westbrook and Braithwaite, 2009; Long, Cunningham, Carswell and Braithwaite, 2014) and leadership behaviour (Long, Cunningham, Carswell and Braithwaite, 2013).

Researchers have also used complexity theory, in a highly innovative and compelling approach, to take a retrospective look over their previous programs of research. For example, in a "look back" over their 15 year program of research in primary care practice Crabtree, Nutting, Miller, McDaniel, Stange, Jaén and Stewart (2011) highlighted the imperative to base quality improvement studies on a complexity systems perspective rather than via traditional linear, mechanistic approaches. More recently, Leykum, Lanham, Pugh, Parchman, Anderson, Crabtree, Nutting, Miller, Stange and McDaniel (2014), in a paradigm-breaking paper, took a look back at their program of research, and identified that system-level uncertainty, as a defining characteristic of the CAS, was useful in appreciating their previously unexplained mixed findings. Both of these look back pieces highlight the importance

of applying complexity theory for study design, data analysis and interpretation, as well as for continual refection and synergistic learning.

In the future, more adaptation and refinement of complexity science is needed by researchers and organisational agents seeking to improve organisational performance or patient outcomes. We think the next major conceptual shift is to move beyond exploratory and descriptive research to undertake more explanatory and intervention research grounded in complexity theory. This takes us to three exemplar bodies of work which has been grappling with how to do that.

COMPLEXITY SCIENCE IN ACTION: LEARNING FROM THEORY AND PRACTICE

For three evocative and purposeful ways of reaching into complexity theory and weighing up the accomplishments of complexity science ideas in health systems, we need look no further than the three scholars introducing this White Paper in the Preface above. We turn to an examination of some of the themes encapsulated in the work of groups led by Trisha Greenhalgh, Penny Hawe and Luci Leykum.

Social theory and complexity science

Over more than a decade and a half, Greenhalgh and colleagues have been theorising from a social science standpoint in order to give life to complex accounts of change in health systems. Amongst multiple others we could choose, three studies conducted by Greenhalgh's group show how an understanding of complexity theory can enrich analyses of health system interventions without necessarily explicitly documenting all the features of CASs well known to complexity science. One large-scale evaluation project that exemplifies this theoretically-rich approach to change was based on work to assess the introduction of large IT software systems at scale in the United Kingdom's NHS. In one study examining this multi-billion pound exercise, Greenhalgh and Stones (2010) illuminated aspects of complexity through a consideration of structuration theory and actor-network theory. Structuration theory, going back to its proponent Giddens (1986), allows reflection on the recursive and dynamic linkages between people and social structures that co-evolve over time. Actor-network theory draws attention to the relationships between people and their artefacts—their tools and technologies, in dynamic network configurations. The important dimensions Greenhalgh and Stones discerned in analysing the dynamic complexity of the NHS's IT intervention include the nature of the social structures which can make or break it, how this type of change relates to specific examples of human agency and how behaviours within the system are enabled or constrained, and alter across time. In short, their powerful question is to ask to what extent is the negotiated social order disturbed, perturbed or re-inscribed by big IT interventions of this kind. A theoretically-laden perspective like this is much more penetrative than simplistic or unidimensional evaluation methods, drawing out core features of what an at-scale intervention really means. This kind of approach takes issue with simplistic critiques arguing that the main challenges of new IT systems are to achieve "benefits realisation" or to understand instrumental policy pronouncements arguing that all we have to do is roll out the program and we will inevitably beget front line

change.

Going further, but staying with the big IT theme of e-Health programs and their implementation, Greenhalgh, Russell, Ashcroft and Parsons (2011) applied Wittgenstein's (2010) concept of "language games" to understand the discourse and stakeholder vantage points taken during the same unfolding IT program analysed in Greenhalgh and Stones (2010). They concluded that rolling out programs of this kind should not be thought of as some boiler plate design-and-introduction-plan or, as the public relations for the program suggested, for some kind of deterministic, technologically cutting-edge system. Instead, IT of this kind could be thought of as a cacophony of nested, contested, ambiguous and multi-layered language games. The situation produced is not the machine-like, unproblematic rollout of a fit-for-purpose IT solution, but a set of circumstances which is inherently uncertain, perennially emerging, and proceeds in punctuated fits and starts. Big IT systems implementation is confusing and paradoxical, and no-one in reality understands what's going on. However, policymakers often operate under conditions of bounded rationality, take normative positions, and do not for all sorts of reasons seek to uncover the subtle, deceptive processes and events, the messy politics and conditions of contestation and disagreement, that are integrally involved.

Changing tenor and voice, in current, ongoing work Greenhalgh, Shaw, Wherton, Hughes, Lynch, A'Court, Hinder, Fahy, Byrne, Finlayson, Sorell, Procter and Stones (2016) looked at the way assisted living technologies were researched. As they saw past research, it emerged historically from three generations of enquiry: an early stage that focused, initially, on technical design; then, a phase which privileged experimental trials; followed by an era of attempting to understand through qualitative studies the patient experience of these technologies. Greenhalgh and colleagues (2016) proposed that fourth generation studies were needed. These would engender understanding of dimensions of complexity including the rich tapestry of context, and factor in organisational, social and political aspects of change over time. They argued that "Fourth generation studies are necessarily organic and emergent; they view technology as part of a dynamic, networked and potentially unstable system. They use co-design methods to generate and stabilise local solutions, taking account of context." The Greenhalgh group saw five key characteristics in their new research paradigm: this approach, they proposed, is interdisciplinary, embraces complexity, is recursive, is ecological and critical.

Learning from public health interventions

Changing focus, Penny Hawe, an expert in public health and health promotion, who has worked in both Australia and Canada, has, with her colleagues, established a mission to reimagine how interventions work. This group's expressed concern is that traditional interventional models fail to appreciate the complexity of context (Hawe, Shiell and Riley, 2004). They also note how researchers often seek to overly-control or standardise the intervention in overly structured ways. In a complex system, this will not work as the proponents' hope.

Hawe and her colleagues are also interested in defining what is meant by terms used in complexity science, such as non-linear, universality, systems dynamics, path-dependency, self-organisation and feedback (Rickles, Hawe and Shiell, 2007). We have provided our definitions of these terms when we have used them, or in our glossary when we felt this was needed.

In a key paper in *The American Journal of Community Psychology,* Hawe, Shiell and Riley (2009) drew attention to how health promotion projects and public health initiatives had often failed. One reason, they suggested, was that researchers had all-too-often had recourse to theories at the individual level, but were aiming to influence communities. This might explain why historically many wellness-promoting interventions have fallen short. These weak prevention achievements may have eventuated from people focusing on individual behaviour change, hoping to aggregate these up and spread the modifications. But the complexity science model by way of contrast recognises that context matters, and although scaling is fractal, that does not mean the same strategies apply at different levels and across different parts of the environment, especially between the agent and ecological or systems domains.

Interventions instead should be seen as events designed to perturb the system over time. Often, they are large-scale and to be successful they must leave substantially re-etched, re-inscribed systems with differences apparent in the culture, politics and systems' characteristics, post the intervention. In regard to the characteristics of the intervention, Hawe and colleagues warn against thinking that everything must be standardised and controlled. Instead, the form of the intervention can differ across sites as long as the process and function of the intervention is standardised. So, on this view, methods of intervention can be customised and tailored to the context without losing the force of the intervention.

Turning from their contributions to theory to the empirical work of this group, Hawe and Riley (2005) took an ecological approach to understand the dynamics of a

community intervention designed to work with recent mothers to promote their health. The community development practitioners involved in the intervention kept diaries of their reflections during the course of the intervention and afterwards. They documented what happened, thinking especially of aspects such as who was most important in providing resources to the mothers, the interdependencies and interconnections of the ecosystems of support, how participants adapted over time, and what Hawe and Riley (2005) called "succession", how the intervention fitted in with the natural patterns of behaviour in the community. The researchers in this study documented many positive examples of how the system and participants improved over time.

Riley and Hawe (2009) looked further at the community development practitioners who had implemented the improvement program with the mothers participating in the Hawe and Riley (2005) study. In spite of each practitioner being given a set of uniform requirements for delivering the intervention, their study showed that community development workers exercise agency in the field and that they implemented according to a pattern. Within the pattern there were smaller stories about actions, causes, strategies and tradeoffs, all of which provided hitherto unrevealed insight into how agents in complex adaptive systems adapt.

Finally, in a review of the Gatehouse study (Bond, Patton, Glover, Carlin, Butler, Thomas and Bowes, 2004; Riley and Hawe, 2009) in Australia, which was subsequently replicated in Canada (Hawe, Bond, Ghali, Perry, Davison, Casey, Butler, Webster and Scholz, 2015), Hawe, Bond and Butler (2009) overlaid a complexity lens over knowledge theories. They found that complexity science can bring an understanding of the dynamics, contextual richness and systems fluidity to inform those who want to apply knowledge theories to healthcare.

The capstone for much of Hawe's work has been synthesised in her piece in the *Annual Review of Public Health*, entitled *Lessons from Complex Interventions to Improve Health* (Hawe, 2015). She argued that failing to understand complexity dimensions and the unpredictability of its effects "may blind us to the very mechanisms we seek to understand" (p. 307).

Investigating hospital-based studies

The third in our trio of profiles of accomplishment is the group led by Luci Leykum in San Antonio, Texas, United States of America. Leykum and colleagues have conducted advanced empirical work in hospital settings for over a decade, undergirding their studies with a deep respect for complexity science. Internationally,

health systems research of the type they do typically compartmentalises—breaking down the system in order to research or improve an individual component, such as by applying a checklist, introducing a standardised hand hygiene program, or an adverse event reporting system. In contrast, Leykum, Lanham, Provost, McDaniel and Pugh (2014) and McAllister, Leykum, Lanham, Reisinger, Kohn, Palmer, Pezzia, Agar, Parchman, Pugh and McDaniel (2014), and their related research, showed how a complexity science approach can broaden the focus by taking a systems-level perspective.

In one study, Leykum, Lanham, Provost, McDaniel and Pugh (2014) investigated the way inpatient teams did their rounds, using a multi-method research design. They examined 1,941 team discussions of 541 patients over 207 days. They showed a relationship between how teams were sense-making (using cognitive resources to elicit, assemble and use information in order to make decisions) and their clinical outcomes (Leykum, Lanham, Provost, McDaniel and Pugh, 2014). In this research, shared sense-making across the team, conducted in a purposeful or patient-driven manner, or both, was associated with better patient outcomes, measured by reduced length of stay, unnecessary length of stay, and complication rates.

In linked work, McAllister, Leykum, Lanham, Reisinger, Kohn, Palmer, Pezzia, Agar, Parchman, Pugh and McDaniel (2014) assessed the quality of relationships in those inpatient teams, categorising them against seven criteria following Lanham, McDaniel, Crabtree, Miller, Stange, Tallia and Nutting (2009): levels of trust, diversity of team members, respect, heedfulness, mindfulness, social relatedness, and appropriate use of rich communication. Medical inpatient teams with more positive relationships were more likely to have better patient outcomes, measured as before by reduced days of stay, unnecessary stay, and complications. In this work, levels of trust and the exercise of observable mindfulness had particular valency.

In other work applying a complexity frame, this research team proposed better ways to configure healthcare huddles so they exhibit richer, more effective relationships (Provost, Lanham, Leykum, McDaniel and Pugh, 2015), described a scale to support reciprocal learning in primary care (Leykum, Palmer, Lanham, Jordan, McDaniel, Noël and Parchman, 2011) and made available a tool to enhance the way medical teams did their rounds, encouraging them to relate more effectively, make sense of their patients and their conditions, and improvise under conditions of uncertainty (the PRISm intervention - Leykum, Lanham, Provost, McDaniel and Pugh, 2014). They have also examined the features of complexity which are associated

with improved chronic heart failure (Leykum, Parchman, Pugh, Lawrence, Noël and McDaniel, 2010) and type II diabetes (Leykum, Pugh, Lawrence, Parchman, Noël, Cornell and McDaniel, 2007).

Perhaps the most important contribution of this group has been to retrospectively review eight of their empirical studies, synthesising the collective learnings, adding depth to our understanding of an important and poorly understood characteristic of CASs—uncertainty (Leykum, Lanham, Pugh, Parchman, Anderson, Crabtree, Nutting, Miller, Stange and McDaniel, 2014). In this work, uncertainty arose in two ways—disease related uncertainty, and task-related uncertainty. Indeed, linear, mechanistic, unidimensional or accounts of health systems do not adequately appreciate the inherent unpredictable, vague, imprecise nature of health settings. That is perhaps the most telling and persistent message our highlighted trio of teams in complexity science are drawing to our attention.

COMPLEXITY IN LOW- AND MIDDLE-INCOME HEALTHCARE SYSTEMS

Until quite recently the application of CAS theory to healthcare systems, especially in informing improvement interventions, had occurred almost exclusively in high-income countries such as the United States, Canada, the United Kingdom, Western Europe and Australasia (Adam, Hsu, de Savigny, Lavis, Røttingen and Bennett, 2012; Thompson, Fazio, Kustra, Patrick and Stanley, 2016). Figure 14 highlights the unequal distribution of publication locations applying CAS theory worldwide, with much of the work that has been published in MEDLINE concentrated in North America and Western Europe.

This gap has left us with questions about the utility of CAS theory for healthcare systems in low- and middle-income countries (LMICs). How might CAS theory apply, and how useful is it for tackling the healthcare problems that countries face, with the kinds of systems that do not have the resources of more wealthy countries?
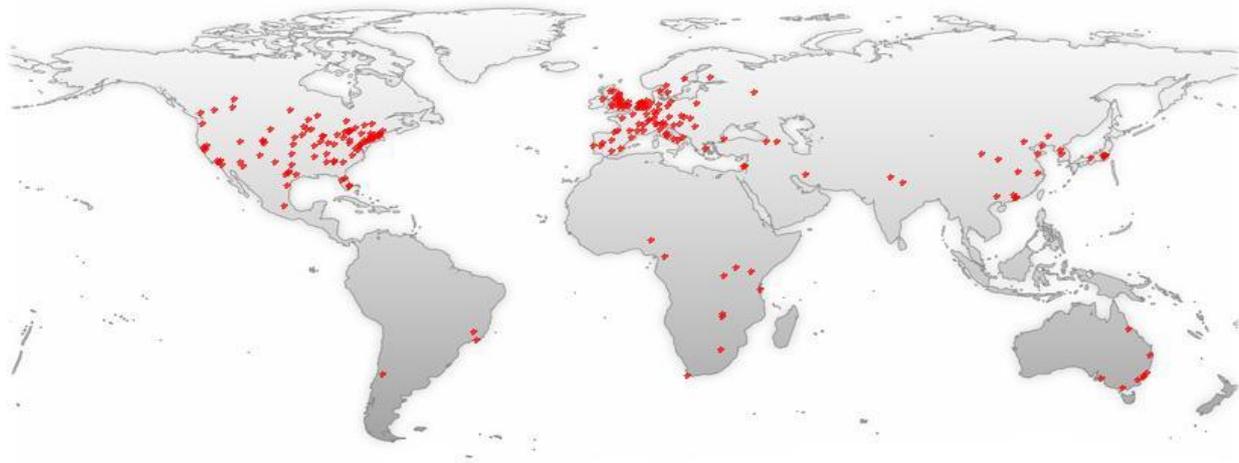
Figure 14 – A map of where people are publishing work using CAS theory (based on publications in MEDLINE using search terms "complexity science" OR "complex adaptive systems"). Source: generated through www.gopubmed.org on 24 March, 2017.

Healthcare systems in LMICs are not entirely different to those of high-income countries (Braithwaite, Mannion, Matsuyama, Shekelle, Whittaker and Al-Adawi, 2017; Braithwaite, Matsuyama, Mannion and Johnson, 2015). All health systems have key stakeholders (e.g., policymakers, managers, doctors, nurses) identifiable settings (e.g., hospitals, community-based, primary care organisations) and funding mechanisms (e.g., incentives, resource allocations to the point of delivery of care) to support care and its delivery to populations. Notwithstanding this, the influence of

certain agents, such as non-government organisations (NGOs), are typically larger in developing countries, the level of resources which they have available are tighter, and the kinds of healthcare problems they experience are often distinct. At a meso-level, hospitals in LMICs tend to differ in their organisational structures, operations, processes and target users (Barasa, Molyneux, English and Cleary, 2017). Often, because of poor resource levels, they are more streamlined and basic, but to compensate, they can correspondingly be less bureaucratic.

At the same time, because CAS theory is a way of thinking, the general principles still hold (e.g., the importance of organisational cultural history, feedback, perturbations, emergence, dynamics, and the diversity of agents), even if the attractors, agents, and landscape are distinctive. Therefore, there is reason to believe in the utility of complexity science for LMICs, and particularly with regard to health system strengthening, because it focuses not just upon the "building blocks" of the system, but the relationships between them (Adam and de Savigny, 2012; Willis, Riley, Best and Ongolo-Zogo, 2012).

Over the past decade, there have been a number supplements in international journals—such as *Health Research Policy and Systems* (2014, Volume 12) and *Health Policy and Planning* (2012, Volume 27)—with a theme centred on the application of CAS theory to LMICs. In addition, recent years have witnessed the formation of the Alliance for Health Policy and Systems Research within the World Health Organisation (De Savigny and Adam, 2009), which seeks to promote the use of systems research to improve health and health systems in LMICs. These trends point to the increasing interest in applying complexity theory to the healthcare problems of developing countries.

Thus far, when they have been applied, CAS theory and complexity science have manifested in a number of different ways to understand healthcare problems in LMICs. For example, Barasa, Molyneux, English and Cleary (2017) used a framework informed by CAS theory, applying an approach based on a causal loop diagram to understand relationships between various "hardware" (e.g., infrastructure, technology) and "software" (e.g., managerial skills, values and norms) that influence priority-setting activities in two Kenyan hospitals (see Box 11 for a related example of the CAS lens applied to hospitals in a LMIC). In a similar vein, Agyepong, Kodua, Adjei and Adam (2012) sought to examine the agents and connections that fed back into multiple health professional strikes related to the implementation of an additional duty hours allowance in Ghana. They surmised that a major perpetuator

Box 11: Hospitals as complex adaptive systems in the Democratic Republic of Congo

Recently, health system strengthening in the Democratic Republic of Congo (DRC) has begun to focus beyond primary care or disease-focused health programs, to the operation of first referral hospitals. Karemere, Ribesse, Kahindo and Macq (2015) use a CAS lens to understand how governance influenced "adaptation" within two first referral hospitals in the DCR, particularly focusing on two behaviours of the system: path dependency and phase transition.

The researchers used case study method with multiple sources of qualitative and quantitative data. Findings showed how the effects of implementing two governance improvement strategies—a hospital plan and performance-based financing— could vary considerably between the two hospitals because of their different context and initial conditions. For example, at the outset, there were weaker relationships among hospital management, staff and owners at one of the hospitals. Despite increases in 'outputs' at this site, the extent of improvement was highly questionable. Surgical service increases were often potentially unnecessary, even harmful (appendectomy, caesarean sections) and take up of the hospital plan was limited. On the other hand, the second hospital, which was originally classified as having a better 'atmosphere' of relationships among agents, had fairly stable outputs, but did not experience the unintended consequence of worker strikes, and had better staff involvement and reception to the hospital plan.

Source: adapted from work in Karemere, H., Ribesse, N., Kahindo, J.-B. and Macq, J. (2015). Referral hospitals in the Democratic Republic of Congo as complex adaptive systems: similar program, different dynamics. *Pan Afr Med J, 20*(281).

of these strikes was "crisis driven linear decision-making" of government. SNA, a complexity method for understanding the scale and strength of connections among agents that we have discussed above, has also been utilised to understand complexity issues in LMICs: for instance, why organisational structures for supervisory reporting bear little relationship to real-world advice-seeking behaviour among primary care physicians in Pakistan (Malik, Willis, Hamid, Ulikpan and Hill, 2014).

Other scholars of less wealthy health systems have adopted complexity methods to study multi-dimensional healthcare problems that particularly affect LMICs, such as those using systems dynamics modelling to examine the unintended consequences of a policy change in the resource allocation between disease prevention and cure, where different agents' (health professionals, government and NGOs) interests conflict (Bishai, Paina, Li, Peters and Hyder, 2014). CAS theory is also beginning to be applied in the evaluation of complex interventions, with Prashanth, Marchal, Devadasan, Kegels and Criel (2014) conducting a realist evaluation of a multi-modal capacity-building intervention implemented in the health management teams of a district in India. The evaluation component highlighted the importance of relationships of internal agents and the initial conditions, including norms, rules and shared

experiences, location and resources, in the success of the implemented intervention and the array of outcomes observed (Prashanth, Marchal, Devadasan, Kegels and Criel, 2014).

Despite these new lines of enquiry suggesting the value of CAS theory to LMICs, there are similar concerns about how to take complexity science from the abstract and conceptual to the practical and useful, as has been expressed in work on healthcare systems in high-income countries (Adam, 2014; Adam, Hsu, de Savigny, Lavis, Røttingen and Bennett, 2012; Brainard and Hunter, 2016; Thompson, Fazio, Kustra, Patrick and Stanley, 2016). No matter the category of country, the needs are shared across low-, middle- and high-income health systems, with the appropriate embedding of complexity in the design, implementation and evaluation of interventions often lacking. Further work is therefore needed to encourage and evaluate the application of CAS theory to LMICs. As Adam and de Savigny (2012) note, this cannot be achieved simply by conviction. It will require concerted effort among stakeholders, funding, and institutional support (see also Brainard and Hunter, 2016).

"Healthcare: an enterprise designed to produce incredible capability, despite the complexity"

Sir Liam Donaldson

Source: Donaldson, L (2017). *Global Perspectives on Patient Safety*. Faculty of Medicine and Health Sciences. Executive Dean's Lecture Series. Macquarie University, Sydney, Australia, 21 April

IMPLICATIONS

Implications for thinking and problem-solving

Having digested multiple perspectives on complexity as a paradigm, a way of thinking and an approach to understanding and improving health systems, in this penultimate section before we conclude, we want to look at the implications of our analysis. That's the task to which we now turn.

It seems to us that humans have a propensity to think in linear terms. This may be a fundamental aspect of the way our brains work. For some, perhaps even many challenges, this is both satisfactory and sufficient. Linearity gets us to work on time and gives us a way to solve simple problems in our lives; it supports efforts to build roads and bridges, fill in a form, design teaching curricula, draft a budget, hire a new staff member, write organisational and government policies, and help clinicians reach a diagnosis. The notion that many problems we encounter at least on the surface follow an input-process-output strategy, an "If I do X, Y will result, is true". As Robson (2015) explains, many processes in the everyday clinical work of healthcare are linear, such as medication order in a pharmacy, a process that follows clear rules and policies.

But we also want to recognise that linearity very often only gets us so far and sometimes misleads us into thinking that things are more simple than they really are. Furthermore, the open boundaries of human systems means that even simple processes are affected and disrupted by the external environment (Robson, 2015). We face many situations when it would be better to think about multiple dimensions of a problem or situation. We gave the earlier example of obesity: it looks like a unidimensional, linear problem on the surface, but Figure 13 shows that is palpably not so. This will be the case in other circumstances when we need to factor in the density of the interacting components in a system we are working in or on, or to take into account complex situations in which we find ourselves enmeshed.

That's when we need to put complexity science to work. In healthcare, the CAS features we have been describing mean that most times, rationalising in a linear way is too confining, too unidimensional. If we want to be inoculated against excessively straight-line rationalisations, Box 12 offers some suggestions. While we make these points for the benefit of anyone who wants to read or apply them, they could be especially useful for people with managerial or policymaking responsibilities, whose job is to lead complex organisations and solve high-level problems.

Implications for health system improvement

Health systems everywhere can benefit from concerted efforts to improve them. In support of such endeavours, approaches have emerged to enhance care quality, keep patients safe, re-engineer procedures, and implement new ways of working. Systems improvement strategies have proliferated over the last twenty years.

Many of these initiatives have helped people on-the-ground in healthcare to focus efforts and make tangible gains in providing better care for patients. Introducing rapid response systems, care bundles, hand hygiene projects, incident monitoring software and root cause analysis techniques (Braithwaite and Donaldson, 2016; Vincent and Amalberti, 2016) have created gains in some places, in some circumstances, some of which is well researched and documented. However, there is a case to be made that progress with such initiatives has been limited, or even constrained, because they have been treated overly prescriptively: as simplistic, linear "solutions" to complex problems situated in complex environments.

Box 12: Selected remedies for linear thinking

1. Resist the temptation to focus myopically on a problem, *per se*; instead, look for interconnections.

2. Consider that you can't actually see very far ahead. Things happen in response to active change when you least expect it.

3. Look for patterns in the system's behaviours, not just at events.

4. Be careful if attributing cause and effect. It's rarely that simple.

5. Generate new ideas beyond your own resources when tackling problems; ask someone, perhaps multiple people with a different perspective, including from outside your group, for an opinion.

6. Keep in mind the system is dynamic, and it doesn't necessarily respond to intended change as predicted; systems never change in a 1:1 relationship between what's intended and what actually eventuates.

7. If you have sufficient resources, model the system properties surrounding the problem you are trying to address.

8. Use systems tools at your disposal: these range from sociograms, to social network analyses, to systems diagrams, to soft systems methodology, to role plays, to simulation.

Source: Authors' conceptualisation.

From the foregoing, it is apparent that there are lessons to be learned from complexity science to help bolster such efforts. Attempts to improve or intervene in the healthcare systems could, as a start, be strengthened by describing the cultural features of the intended target for change. It is also useful to identify those key agents in the CAS, and leveraging their capacities within or between networks by enrolling them in improvement activities, or inviting these agents to support the uptake of new practices. In essence it is useful to identify those who matter (the brokers, bridge, boundary spanners and key influencers) in a CAS. These are the agents who will be instrumental in effecting improvement, that is, those who understand or give effect

to the interdependencies and influences, making use of them to ensure the uptake of any innovation. They can also de-rail needed change, of course, if they are ignored or feel isolated.

Complexity science also teaches us to be mindful of potential unintended consequences of any intervention (Brainard and Hunter, 2016). It's important to be on the lookout for inadvertencies, or unplanned outcomes. These are often the norm in CAS environments.

We should also not eliminate "contextual confounders" because they are typically the normal conditions of everyday clinical work into which interventions must be integrated (May, Johnson and Finch, 2016). Therefore, any intervention, for example, in one primary care setting, should not be mandated in precisely the same way to other contexts; it will need to be adapted, by taking into consideration the existing conditions, cultural features and dynamics of the local system, and the environment in which one is trying to intervene (Litaker, Tomolo, Liberatore, Stange and Aron, 2006).

Box 13: Advice to clinicians for making decisions in a complex system

1. Use your intuition – clinicians tend to make the best, but perhaps not the definite "right" decision, most of the time based on their own experience, evidence and knowledge of their patient.

2. Try experimenting – be empirical in your own clinical activities; use, for example, plan-do-study-act cycle (Taylor, McNicholas, Nicolay, Darzi, Bell and Reed, 2013) with patient recommendations.

3. Aim for minimum specification – give your patient broad goals, but try to leave some of the details to them; your solution might not fit their life

4. Chunk things together – not every problem is amenable to solution right away so try solving just one or two, answers to other issues may follow as a result.

5. Make use of metaphor – shared understanding can follow by using metaphor to communicate complex issues.

6. Ask the provocative questions – questions that might uncover some basic assumptions when stuck, such as when a patient disease management seems to stagnate.

Source: Plsek, P. E. and Greenhalgh, T. (2001). Complexity science: The challenge of complexity in health care. *Br Med J (Clin Res Ed), 323*(7313), 625-628.

The main group responsible for giving effect to improvement efforts are clinicians on the front lines of care. Plsek and Greenhalgh (2001) have provided the best advice we know to clinicians making decisions in complex settings (Box 13).

In a key paper published at the same time, McDaniel and Driebe (2001) suggested that people in healthcare (both clinicians and managers) might try sense-making rather than decision-making, by which they meant that understanding complex problems was at least

as important, and in many cases more important, than making decisions when under the challenging conditions of uncertainty and ambiguity.

Implications for research

We turn to the lessons learnt from the White Paper for researchers (McDaniel, Lanham and Anderson, 2009). It seems to us that researchers of complex health settings cannot simply rely on RCTs or routinely implemented interventions, mirroring the way drug trials are conducted, as their model for research. Whatever improvement strategy or intervention is envisaged, researchers will need to factor in uncertainty, context, culture, and the features of complexity we have articulated above. Researchers need not only do the studies they envisage, but also should seek to apprehend how the actors in the system work in it now, traverse it, and how they navigate the complexities that are integral to their leadership and clinical activities.

This means that researchers examining complex systems would be well served to delineate at a minimum what they mean by complexity, how they will factor that into their study designs, and then develop strategies for studying it, in-depth. Ignoring complexity, or wishing it would go away, is not an option. It follows that conventional methods in healthcare research, especially the reliance on linear research designs or simplistic statistical associations must be supported by the use of observation, simulation and modelling. Indeed, linear statistical models are not appropriate for understanding complexity because of fundamental assumptions made, of independence, "control" groups, and procedures of averaging to the mean. These belie complexity's recognition of the interdependence of agents, unpredictability, unforeseen consequences, and the importance of local context.

It is very hard to do, but it also behoves researchers to accept that there will always be high degrees of uncertainty *in situ* for healthcare participants, and for researchers in their studies. Acknowledging, rather than failing to recognise, such uncertainty is an important endeavor (Han, Klein and Arora, 2011). We may not be able to manage or tame complexity, but we can learn how to cope with the types of uncertainty that complexity gives rise to (Hamui-Sutton, Vives-Varela, Gutierrez-Barreto, Leenen and Sanchez-Mendiola, 2015). That is what Greenhalgh, Hawe and Leykum have tried to do.

We must all remember that healthcare systems are ambiguous, deceptive and unpredictable, and any activities to influence, nudge or shape them will not be achieved in a 1:1 correspondence with what is intended. Unforeseen consequences will always emerge. The best lessons are to go with the complexity flow, look at both the formal and informal dynamics, be alert for unintended outcomes, play a long game, and take advantage of emerging opportunities.

Part I

Getting Started:

Aspirations for Complexity Science

Part II

Characterising Complexity Science:

Approaches to Understanding

Part III

Dealing with Complexity:

Applications to Healthcare

Part IV

Implications:

Accomplishments of Complexity Science

Part V
Conclusion

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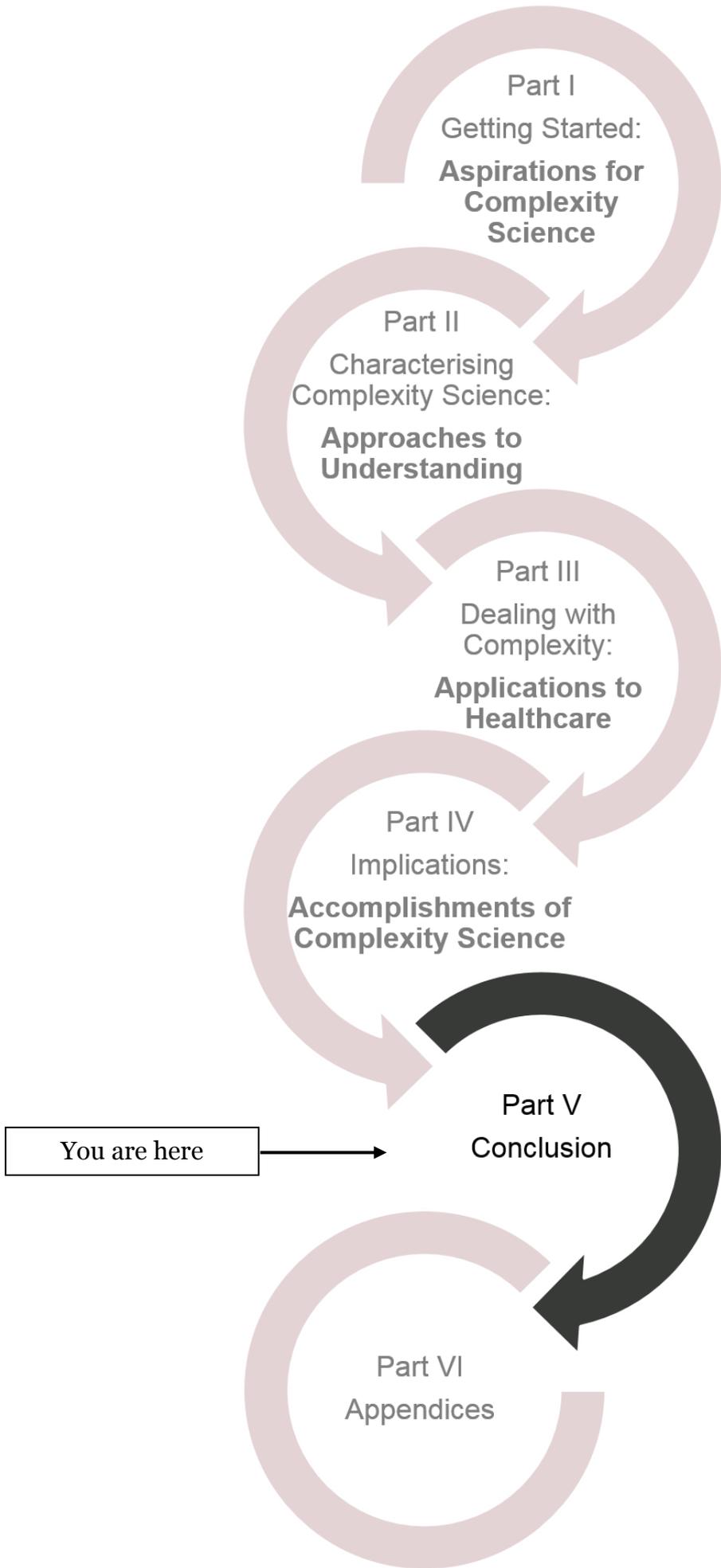
Part VI
Appendices

Part V – Conclusion

Across the pages of this White Paper, we have attempted to grapple with a challenging basket of ideas under the rubric of complexity science. This is a challenging endeavour. No one ever said that complexity science was unidimensional. Nor is it trivial to understand the characteristics of complexity, how CASs operate, and how they can be better understood.

But understand them we must. The world is not simple, and we can't ignore complexity or wish it away. Taking a linear approach to problems, which is common, and perhaps ubiquitous, is not a solution to many of the problems we encounter in healthcare today. Learning to embrace complexity thinking rather than continue along the line, as we have in the past, of thinking that traditional approaches will work in an increasingly complex future, is a key lesson for us all. Those who do understand more than others about complexity, who delve deep and embrace complexity thinking, applying a complexity lens to their work, are likely to be rewarded. They will produce better solutions to the problems they face than those who don't. That's perhaps the key message of this White Paper, and the one with which we will end.

References

Adam, T. (2014). Advancing the application of systems thinking in health. *Health Research Policy and Systems, 12*(1), 50. doi:10.1186/1478-4505-12-50

Adam, T. and de Savigny, D. (2012). Systems thinking for strengthening health systems in LMICs: Need for a paradigm shift. *Health Policy and Planning, 27*(Suppl. 4), iv1-iv3. doi:10.1093/heapol/czs084

Adam, T., Hsu, J., de Savigny, D., Lavis, J. N., Røttingen, J.-A. and Bennett, S. (2012). Evaluating health systems strengthening interventions in low-income and middle-income countries: Are we asking the right questions? *Health Policy and Planning, 27*(Suppl. 4), iv9-iv19. doi:10.1093/heapol/czs086

Agyepong, I. A., Kodua, A., Adjei, S. and Adam, T. (2012). When "solutions of yesterday become problems of today": Crisis-ridden decision making in a complex adaptive system (CAS)—the Additional Duty Hours Allowance in Ghana. *Health Policy and Planning, 27*(Suppl. 4), iv20-iv31. doi:10.1093/heapol/czs083

Aronson, J. (2016). "Collaborative care" is preferable to "patient centred care". *British Medical Journal (Online), 353*. doi:10.1136/bmj.i2926

Bar-Yam, Y. (2002). Complexity rising: From human beings to human civilization, a complexity profile. In UNESCO (Ed.), *Encyclopedia of Life Support Systems*. Oxford, UK: UNESCO Publishers.

Bar-Yam, Y. (2004). *System Care: Multiscale Analysis of Medical Errors-Eliminating Errors and Improving Organizational Capabilities*. Retrieved from Boston, MA: http://www.necsi.edu/projects/yaneer/NECSITechnicalReport2004-09.pdf

Bar-Yam, Y. (2006). Improving the effectiveness of health care and public health: A multiscale complex systems analysis. *American Journal of Public Health, 96*(3), 459-466. doi:10.2105/AJPH.2005.064444

Bárabasi, A.-L. (2002). *Linked: The New Science of Networks*. Boulder, CO: Perseus Books Group.

Barasa, E. W., Molyneux, S., English, M. and Cleary, S. (2017). Hospitals as complex adaptive systems: A case study of factors influencing priority setting practices at the hospital level in Kenya. *Social Science & Medicine, 174*, 104-112. doi:10.1016/j.socscimed.2016.12.026

Bastian, H., Glasziou, P. and Chalmers, I. (2010). Seventy-five trials and eleven systematic reviews a day: How will we ever keep up? *PLOS Medicine, 7*(9), e1000326. doi:10.1371/journal.pmed.1000326

Begun, J. W. and Kaissi, A. (2004). Uncertainty in health care environments: Myth or reality? *Health Care Management Review, 29*(1), 31-39. doi:10.1097/00004010-200401000-00005

Begun, J. W., Zimmerman, B. and Dooley, K. (2003). Health care organizations as complex adaptive systems. In S. Mick & M. Wyltenbach (Eds.), *Advances in Health Care Organization Theory* (Vol. 253-288, pp. 288). San Francisco, CA: Jossey-Bass.

Benham-Hutchins, M. M. and Effken, J. A. (2010). Multiprofessional patterns and methods of communication during patient handoffs. *International Journal of Medical Informatics, 79*(4), 252-267.

Best, A., Greenhalgh, T., Lewis, S., Saul, J. E., Carroll, S. and Bitz, J. (2012). Large-system transformation in health care: A realist review. *Milbank Quarterly, 90*, 421–456. doi:10.1111/j.1468-0009.2012.00670.x

Bishai, D., Paina, L., Li, Q., Peters, D. H. and Hyder, A. A. (2014). Advancing the application of systems thinking in health: Why cure crowds out prevention. *Health Research Policy and Systems, 12*(1), 28. doi:10.1186/1478-4505-12-28

Bond, L., Patton, G., Glover, S., Carlin, J. B., Butler, H., Thomas, L. and Bowes, G. (2004). The Gatehouse Project: Can a multilevel school intervention affect emotional wellbeing and health risk behaviours? *Journal of Epidemiology and Community Health, 58*(12), 997-1003. doi:10.1136/jech.2003.009449

Boustani, M. A., Sachs, G. A., Alder, C. A., Munger, S., Schubert, C. C., Guerriero Austrom, M., . . . Callahan, C. M. (2011). Implementing innovative models of dementia care: The

Healthy Aging Brain Center. *Aging & Mental Health, 15*(1), 13-22. doi:10.1080/13607863.2010.496445

Brainard, J. and Hunter, P. R. (2016). Do complexity-informed health interventions work? A scoping review. *Implementation Science, 11*(1), 127. doi:10.1186/s13012-016-0492-5

Braithwaite, J. (2010). Between-group behaviour in health care: Gaps, edges, boundaries, disconnections, weak ties, spaces and holes. A systematic review. *BMC Health Services Research, 10*(1), 330. doi:10.1186/1472-6963-10-330

Braithwaite, J. (2011). A lasting legacy from Tony Blair? NHS culture change. *Journal of the Royal Society of Medicine, 104*(2), 87-89. doi:10.1258/jrsm.2010.100364

Braithwaite, J. (2015). Bridging gaps to promote networked care between teams and groups in health delivery systems: a systematic review of non-health literature. *BMJ Open, 5*(9), e006567. doi:10.1136/bmjopen-2014-006567

Braithwaite, J., Clay-Williams, R., Hunt, G. and Wears, R. L. (2015). Understanding resilient clinical practices in Emergency Department ecosystems. In J. Braithwaite, R. Wears, & E. Hollnagel (Eds.), *Resilient Health Care: Reconciling Work-As-Imagined and Work-As-Done* (pp. 89-102). Boca Raton, FL: Taylor & Francis.

Braithwaite, J., Clay-Williams, R., Nugus, P. and Plumb, J. (2013). Health care as a complex adaptive system. In E. Hollnagel, J. Braithwaite, & R. L. Wears (Eds.), *Resilient Health Care* (pp. 57-73). Farnham, Surrey, UK: Ashgate Publishing, Ltd.

Braithwaite, J., Clay-Williams, R., Vecellio, E., Marks, D., Hooper, T., Westbrook, M., . . . Ludlow, K. (2016). The basis of clinical tribalism, hierarchy and stereotyping: A laboratory-controlled teamwork experiment. *BMJ Open, 6*(7). doi:10.1136/bmjopen-2016-012467

Braithwaite, J. and Donaldson, L. (2016). Patient safety and quality. In E. Ferlie, K. Montgomery, & A. Reff (Eds.), *The Oxford Handbook of Health Care Management* (pp. 325-351). Oxford, UK: Oxford University Press.

Braithwaite, J., Herkes, J., Ludlow, K., Lamprell, G. and Testa, L. (2016). Association between organisational and workplace cultures, and patient outcomes: Systematic review protocol. *BMJ Open, 6*(e013758). doi:10.1136/bmjopen-2016-013758

Braithwaite, J., Hyde, P. and Pope, C. (2010). *Culture and Climate in Health Care Organizations*. Basingstoke, London, UK: Palgrave Macmillan.

Braithwaite, J., Mannion, R., Matsuyama, Y., Shekelle, P., Whittaker, S. and Al-Adawi, S. (Eds.). (2017). *Health Systems Improvement Across the Globe: Success Stories from 60 Countries*. Abingdon, UK: Taylor & Francis.

Braithwaite, J., Matsuyama, Y., Mannion, R. and Johnson, J. (2015). *Healthcare Reform, Quality and Safety: Perspectives, Participants, Partnerships and Prospects in 30 Countries*. Farnham, Surrey, UK: Ashgate Publishing, Ltd.

Braithwaite, J., Runciman, W. B. and Merry, A. F. (2009). Towards safer, better healthcare: Harnessing the natural properties of complex sociotechnical systems. *Quality and Safety in Health Care, 18*(1), 37-41. doi:10.1136/qshc.2007.023317

Braithwaite, J., Wears, R. L. and Hollnagel, E. (2015). Resilient health care: Turning patient safety on its head. *International Journal for Quality in Health Care, 27*(5), 418-420. doi:10.1093/intqhc/mzv063

Braithwaite, J., Wears, R. L. and Hollnagel, E. (Eds.). (2017). *Resilient Health Care: Reconciling Work-as-Imagined and Work-as-Done* (Vol. III). Boca Raton, FL: Taylor & Francis.

Braithwaite, J., Westbrook, M. T., Hindle, D., Iedema, R. A. and Black, D. A. (2006). Does restructuring hospitals result in greater efficiency - an empirical test using diachronic data. *Health Services Management Research, 19*(1), 1-12. doi:10.1258/095148406775322016

Bratianu, C. (2007). *Thinking patterns and knowledge dynamics*. Paper presented at the European Conference on Knowledge Management, Barcelona, ESP.

Burt, R. S. (1995). *Structural Holes: The Social Structure of Competition*. Cambridge, MA: Harvard University Press

Byng, R., Norman, I. and Redfern, S. (2005). Using realistic evaluation to evaluate a practice-level intervention to improve primary healthcare for patients with long-term mental illness. *Evaluation, 11*(1), 69-93. doi:10.1177/1356389005053198

Cable, D. and DeRue, D. (2002). The convergent and discriminant validity of subjective fit perceptions. *Journal of Applied Psychology, 87*(5), 875-884. doi:10.1037/0021-9010.87.5.875

Callen, J. L., Braithwaite, J. and Westbrook, J. I. (2007). Cultures in hospitals and their influence on attitudes to, and satisfaction with, the use of clinical information systems. *Social Science & Medicine, 65*, 635-639. doi:10.1016/j.socscimed.2007.03.053

Carmi, S., Havlin, S., Kirkpatrick, S., Shavitt, Y. and Shir, E. (2007). A model of Internet topology using k-shell decomposition. *Proceedings of the National Academy of Sciences, 104*(27), 11150-11154. doi:10.1073/pnas.0701175104

Chan, B., Reeve, E., Matthews, S., Carroll, P., Long, J. C., Held, F., . . . Hilmer, S. N. (2017). Medicine information exchange networks among health care professionals and prescribing in geriatric medicine wards. *British Journal of Clinical Pharmacology 83*(6), 1185-1196. doi:10.1111/bcp.13222

Clay-Williams, R. (2013). Restructuring and the resilient organisation: Implications for health care. In E. Hollnagel, J. Braithwaite, & R. L. Wears (Eds.), *Resilient Health Care* (pp. 123-134). Farnham, Surrey, UK: Ashgate Publishing, Ltd.

Coiera, E. (2009). Building a national health IT system from the middle out. *Journal of the American Medical Informatics Association, 16*(3), 271-273.

Coiera, E. (2011). Why system inertia makes health reform so difficult. *British Medical Journal (Online), 342*. doi:10.1136/bmj.d3693

Coiera, E. and Hovenga, E. (2007). Building a sustainable health system. In A. Geissbuhler, R. Haux, & C. Kulikowski (Eds.), *IMIA Yearbook of Medical Informatics* (Vol. II, pp. 11-18). Stuttgart, DEU: Schattauer Publishers.

Crabtree, B. F., Nutting, P. A., Miller, W. L., McDaniel, R. R., Stange, K. C., Jaén, C. R. and Stewart, E. (2011). Primary care practice transformation is hard work: Insights from a 15-year developmental program of research. *Medical Care, 49*(Suppl.), S28-S35. doi:10.1097/MLR.0b013e3181cad65c

Craig, P., Dieppe, P., Macintyre, S., Michie, S., Nazareth, I. and Petticrew, M. (2008). Developing and evaluating complex interventions: The new Medical Research Council guidance. *British Medical Journal, 337*, a1655. doi:10.1136/bmj.a1655

Creswick, N. and Westbrook, J. I. (2007). The medication advice-seeking network of staff in an Australian hospital renal ward. *Information Technology in Health Care, 130*, 217-231.

Creswick, N. and Westbrook, J. I. (2010). Social network analysis of medication advice-seeking interactions among staff in an Australian hospital. *International Journal of Medical Informatics, 79*, e116-e125.

Creswick, N., Westbrook, J. I. and Braithwaite, J. (2009). Understanding communication networks in the emergency department. *BMC Health Services Research, 9*(1), 247. doi:10.1186/1472-6963-9-247

Cunningham, F. C., Ranmuthugala, G., Plumb, J., Georgiou, A., Westbrook, J. I. and Braithwaite, J. (2012). Health professional networks as a vector for improving healthcare quality and safety: A systematic review. *BMJ Quality & Safety, 21*(3), 239-249. doi:10.1136/bmjqs-2011-000187

Damschroder, L. J., Aron, D. C., Keith, R. E., Kirsh, S. R., Alexander, J. A. and Lowery, J. C. (2009). Fostering implementation of health services research findings into practice: A consolidated framework for advancing implementation science. *Implementation Science, 4*(1), 50. doi:10.1186/1748-5908-4-50

Das, H., Panda, G. S., Muduli, B. and Rath, P. K. (2014). *The complex network analysis of power grid: A case study of the west Bengal power network.* Paper presented at the Intelligent Computing, Networking, and Informatics: Proceedings of the International Conference on Advanced Computing, Networking, and Informatics, New Delhi, India.

Datta, J. and Petticrew, M. (2013). Challenges to evaluating complex interventions: A content analysis of published papers. *BMC Public Health, 13*, 568. doi:10.1186/1471-2458-13-568

De Savigny, D. and Adam, T. (2009). *Systems Thinking for Heath Systems sStrengthening*. Retrieved from Geneva, SUI: http://apps.who.int/iris/bitstream/10665/44204/1/9789241563895_eng.pdf?ua=1

Debono, D., Greenfield, D., Black, D. and Braithwaite, J. (2012). Achieving and resisting change: Workarounds straddling and widening gaps in health care. *The Reform of Health Care*, 177-192.

Deutsch, E., Fairbanks, T. and Patterson, M. (Forthcoming). Simulation as a tool to study systems and enhance resilience. In E. Hollnagel, J. Braithwaite, & R. L. Wears (Eds.), *Resilient Health Care: A Field Guide* (Vol. IV): Taylor & Francis.

Dopson, S., Locock, L., Gabbay, J., Ferlie, E. and Fitzgerald, L. (2003). Evidence-based medicine and the implementation gap. *Health: An Interdisciplinary Journal for the Social Study of Health, Illness and Medicine, 7*(3), 311-330. doi:10.1177/1363459303007003004

Emirbayer, M. and Goodwin, J. (1994). Network analysis, culture, and the problem of agency. *American Journal of Sociology, 99*(6), 1411-1454.

Fitzgerald, L., Ferlie, E., McGivern, G. and Buchanan, D. (2013). Distributed leadership patterns and service improvement: Evidence and argument from English healthcare. *The Leadership Quarterly, 24*(1), 227-239. doi:10.1016/j.leaqua.2012.10.012

Freeman, L. C. (2004). *The Development of Social Network Analysis: A Study in the Sociology of Science*. Vancouver, CA: Empirical Press.

Giddens, A. (1986). *The Constitution of Society: Outline of the Theory of Structuration*. Berkeley, CA: University of California Press.

Gordon, G., Joos, S. and Byrne, J. (2000). Physician expressions of uncertainty during patient encounters. *Patient Education and Counseling, 40*(1), 59-65. doi:10.1016/S0738-3991(99)00069-5

Greenfield, D., Braithwaite, J., Pawsey, M., Johnson, B. and Robinson, M. (2009). Distributed leadership to mobilise capacity for accreditation research. *Journal of Health Organization and Management, 23*(2), 255-267. doi:10.1108/14777260910960975

Greenhalgh, T. (2000). Change and complexity-the rich picture. *British Journal of General Practice, 50*(455), 514-515.

Greenhalgh, T., Plsek, P., Wilson, T., Fraser, S. and Holt, T. (2010). Response to "The appropriation of complexity theory in health care". *Journal of Health Services Research & Policy, 15*(2), 115-117. doi:10.1258/jhsrp.2010.009158

Greenhalgh, T., Robert, G., Macfarlane, F., Bate, P. and Kyriakidou, O. (2004). Diffusion of innovations in service organizations: Systematic review and recommendations. *Milbank Quarterly, 82*(4), 581-629. doi:10.1111/j.0887-378X.2004.00325.x

Greenhalgh, T., Russell, J., Ashcroft, R. E. and Parsons, W. (2011). Why national eHealth programs need dead philosophers: Wittgensteinian reflections on policymakers' reluctance to learn from history. *Milbank Quarterly, 89*(4), 533-563. doi:10.1111/j.1468-0009.2011.00642.x

Greenhalgh, T., Shaw, S., Wherton, J., Hughes, G., Lynch, J., A'Court, C., . . . Stones, R. (2016). SCALS: A fourth-generation study of assisted living technologies in their organisational, social, political and policy context. *BMJ Open, 6*(2). doi:10.1136/bmjopen-2015-010208

Greenhalgh, T. and Stones, R. (2010). Theorising big IT programmes in healthcare: Strong structuration theory meets actor-network theory. *Social Science & Medicine, 70*(9), 1285-1294. doi:10.1016/j.socscimed.2009.12.034

Grimshaw, J. M., Eccles, M. P., Lavis, J. N., Hill, S. J. and Squires, J. E. (2012). Knowledge translation of research findings. *Implementation Science, 7*(1), 50. doi:10.1186/1748-5908-7-50

Hamui-Sutton, A., Vives-Varela, T., Gutierrez-Barreto, S., Leenen, I. and Sanchez-Mendiola, M. (2015). A typology of uncertainty derived from an analysis of critical incidents in medical residents: A mixed methods study. *BMC Medical Education, 15,* 198. doi:10.1186/s12909-015-0459-2

Han, P., Klein, W. and Arora, N. (2011). Varieties of uncertainty in health care: A conceptual taxonomy. *Medical Decision Making, 31*(6), 828-838. doi:10.1177/0272989X11393976

Hawe, P. (2015). Lessons from complex interventions to improve health. *Annual Review of Public Health, 36*, 307-323. doi:10.1146/annurev-publhealth-031912-114421

Hawe, P., Bond, L. and Butler, H. (2009). Knowledge theories can inform evaluation practice: What can a complexity lens add? *New Directions for Evaluation, 2009*(124), 89-100. doi:10.1002/ev.316

Hawe, P., Bond, L., Ghali, L. M., Perry, R., Davison, C. M., Casey, D. M., . . . Scholz, B. (2015). Replication of a whole school ethos-changing intervention: Different context, similar effects, additional insights. *BMC Public Health, 15*(1), 265. doi:10.1186/s12889-015-1538-3

Hawe, P. and Riley, T. (2005). Ecological theory in practice: Illustrations from a community-based intervention to promote the health of recent mothers. *Prevention Science, 6*(3), 227-236. doi:10.1007/s11121-005-0008-z

Hawe, P., Shiell, A. and Riley, T. (2004). Complex interventions: How "out of control" can a randomised controlled trial be? *British Medical Journal, 328*(7455), 1561-1563. doi:10.1136/bmj.328.7455.1561

Hawe, P., Shiell, A. and Riley, T. (2009). Theorising interventions as events in systems. *American Journal of Community Psychology, 43*(3-4), 267-276. doi:10.1007/s10464-009-9229-9

Hollnagel, E. (2011). Epilogue: RAG - the Resilience Analysis Grid. In E. Hollnagel, J. Pariès, D. D. Woods, & J. Wreathall (Eds.), *Resilience Engineering in Practice: A Guidebook*. Farnham, Surrey, UK: Ashgate Publishing, Ltd.

Hollnagel, E., Braithwaite, J. and Wears, R. L. (Eds.). (2013). *Resilient Health Care*. Farnham, Surrey, England: Ashgate Publishing, Ltd.

Hollnagel, E., Wears, R. L. and Braithwaite, J. (2015). From Safety-I to Safety-II: A white paper. *The Resilient Health Care Net: Published simultaneously by the University of Southern Denmark, University of Florida, USA, and Macquarie University, Australia.*

Janssen, M. (2010). Complex adaptive systems. Introduction to Agent-Based Modeling. Tempe, AZ: OpenABM. Retrieved from https://www.openabm.org/book/33102/1-complex-adaptive-systems.

Johnson, S. (2002). *Emergence: The Connected Lives of Ants, Brains, Cities, and Software*. New York, NY: Simon and Schuster.

Jones, W. and Hughes, S. H. (2003). Complexity, conflict resolution, and how the mind works. *Conflict Resolution Quarterly, 20*(4), 485-494. doi:10.1002/crq.42

Kannampallil, T. G., Schauer, G. F., Cohen, T. and Patel, V. L. (2011). Considering complexity in healthcare systems. *Journal of Biomedical Informatics, 44*(6), 943-947. doi:http://doi.org/10.1016/j.jbi.2011.06.006

Karemere, H., Ribesse, N., Kahindo, J.-B. and Macq, J. (2015). Referral hospitals in the Democratic Republic of Congo as complex adaptive systems: Similar program, different dynamics. *The Pan African Medical Journal, 20*(281). doi:10.11604/pamj.2015.20.281.4266

Kitson, A. L., Rycroft-Malone, J., Harvey, G., McCormack, B., Seers, K. and Titchen, A. (2008). Evaluating the successful implementation of evidence into practice using the PARiHS framework: Theoretical and practical challenges. *Implementation Science, 3*(1), 1. doi:10.1186/1748-5908-3-1

Kottke, T. E. (2013). Simple rules that reduce hospital readmission. *The Permanente Journal, 17*(3), 91-93. doi:10.7812/TPP/13-024

Kristof, A. (1996). Person-organization fit: An integrative review of its conceptualizations, measurement, and implications. *Personnel Psychology, 49*(1), 1-49.

Lanfranco, A. R., Castellanos, A. E., Desai, J. P. and Meyers, W. C. (2004). Robotic surgery: A current perspective. *Annals of Surgery, 239*(1), 14-21. doi:10.1097/01.sla.0000103020.19595.7d

Lanham, H. J., Leykum, L. K., Taylor, B. S., McCannon, C. J., Lindberg, C. and Lester, R. T. (2013). How complexity science can inform scale-up and spread in health care: Understanding the role of self-organization in variation across local contexts. *Social Science & Medicine, 93*, 194-202. doi:10.1016/j.socscimed.2012.05.040

Lanham, H. J., McDaniel, R. R., Crabtree, B. F., Miller, W. L., Stange, K. C., Tallia, A. F. and Nutting, P. A. (2009). How improving practice relationships among clinicians and

nonclinicians can improve quality in primary care. *The Joint Commission Journal on Quality and Patient Safety, 35*(9), 457-AP452. doi:10.1016/S1553-7250(09)35064-3

Lanham, H. J., Palmer, R. F., Leykum, L. K., McDaniel, R. R., Jr., Nutting, P. A., Stange, K. C., . . . Jaén, C. R. (2016). Trust and reflection in primary care practice redesign. *Health Services Research, 51*(4), 1489-1514. doi:10.1111/1475-6773.12415

Leykum, L., Kumar, P., Parchman, M., McDaniel, R. R., Lanham, H. and Agar, M. (2012). Use of an agent-based model to understand clinical systems. *Journal of Artificial Societies and Social Simulation, 15*(3), 2. doi:10.18564/jasss.1905

Leykum, L. K., Chesser, H., Lanham, H. J., Carla, P., Palmer, R., Ratcliffe, T., . . . Pugh, J. (2015). The association between sensemaking during physician team rounds and hospitalized patients' outcomes. *Journal of General Internal Medicine, 30*(12), 1821-1827. doi:10.1007/s11606-015-3377-4

Leykum, L. K., Lanham, H. J., Provost, S. M., McDaniel, R. R. and Pugh, J. (2014). Improving outcomes of hospitalized patients: The Physician Relationships, Improvising, and Sensemaking intervention protocol. *Implementation Science, 9*(1), 171. doi:10.1186/s13012-014-0171-3

Leykum, L. K., Lanham, H. J., Pugh, J. A., Parchman, M., Anderson, R. A., Crabtree, B. F., . . . McDaniel, R. R. (2014). Manifestations and implications of uncertainty for improving healthcare systems: An analysis of observational and interventional studies grounded in complexity science. *Implementation Science, 9*, 165. doi:10.1186/s13012-014-0165-1

Leykum, L. K., Palmer, R., Lanham, H., Jordan, M., McDaniel, R. R., Noël, P. H. and Parchman, M. (2011). Reciprocal learning and chronic care model implementation in primary care: Results from a new scale of learning in primary care. *BMC Health Services Research, 11*(1), 44. doi:10.1186/1472-6963-11-44

Leykum, L. K., Parchman, M., Pugh, J., Lawrence, V., Noël, P. H. and McDaniel, R. R. (2010). The importance of organizational characteristics for improving outcomes in patients with chronic disease: A systematic review of congestive heart failure. *Implementation Science, 5*(1), 66. doi:10.1186/1748-5908-5-66

Leykum, L. K., Pugh, J., Lawrence, V., Parchman, M., Noël, P. H., Cornell, J. and McDaniel, R. R. (2007). Organizational interventions employing principles of complexity science have improved outcomes for patients with Type II diabetes. *Implementation Science, 2*(1), 1-8. doi:10.1186/1748-5908-2-28

Litaker, D., Tomolo, A., Liberatore, V., Stange, K. C. and Aron, D. (2006). Using complexity theory to build interventions that improve health care delivery in primary care. *Journal of General Internal Medicine, 21*(S2), S30-S34. doi:10.1111/j.1525-1497.2006.00360.x

Locock, L. (2003). Healthcare redesign: Meaning, origins and application. *Quality and Safety in Health Care, 12*(1), 53-57. doi:10.1136/qhc.12.1.53

Long, J. C., Cunningham, F. C. and Braithwaite, J. (2013). Bridges, brokers and boundary spanners in collaborative networks: A systematic review. *BMC Health Services Research, 13*(1), 158. doi:10.1186/1472-6963-13-158

Long, J. C., Cunningham, F. C., Carswell, P. and Braithwaite, J. (2013). Who are the key players in a new translational research network? *BMC Health Services Research, 13*, 338-338. doi:10.1186/1472-6963-13-338

Long, J. C., Cunningham, F. C., Carswell, P. and Braithwaite, J. (2014). Patterns of collaboration in complex networks: The example of a translational research network. *BMC Health Services Research, 14*(1), 225. doi:10.1186/1472-6963-14-225

Long, J. C., Hibbert, P. and Braithwaite, J. (2016). Structuring successful collaboration: A longitudinal social network analysis of a translational research network. *Implementation Science, 11*(1), 19. doi:10.1186/s13012-016-0381-y

MacDavitt, K., Chou, S. and Stone, P. (2007). Organizational climate and health care outcomes. *The Joint Commission Journal on Quality and Patient Safety, 33*, 45-56. doi:10.1016/S1553-7250(07)33112-7

Mainzer, K. (2007). *Thinking in Complexity: The Computational Dynamics of Matter, Mind, and Mankind*. New York, NY: Springer-Verlag.

Malik, A. U., Willis, C. D., Hamid, S., Ulikpan, A. and Hill, P. S. (2014). Advancing the application of systems thinking in health: Advice seeking behavior among primary

health care physicians in Pakistan. *Health Research Policy and Systems, 12*(1), 43. doi:10.1186/1478-4505-12-43

Mann, S. and Cowburn, J. (2005). Emotional labour and stress within mental health nursing. *Journal of Psychiatric and Mental Health Nursing, 12*(2), 154-162. doi:10.1111/j.1365-2850.2004.00807.x

Martin, J. (2002). *Organizational Culture: Mapping the Terrain*. Thousand Oaks, CA: SAGE Publications.

Mataric, M. J. (1993). *Designing emergent behaviors: From local interactions to collective intelligence*. Paper presented at the Second International Conference on Simulation of Adaptive Behavior, Honolulu, HI.

May, C. R., Johnson, M. and Finch, T. (2016). Implementation, context and complexity. *Implementation Science, 11*(1), 141. doi:10.1186/s13012-016-0506-3

McAllister, C., Leykum, L. K., Lanham, H., Reisinger, H. S., Kohn, J. L., Palmer, R., . . . McDaniel, R. R., Jr. (2014). Relationships within inpatient physician housestaff teams and their association with hospitalized patient outcomes. *Journal Of Hospital Medicine, 9*(12), 764-771. doi:10.1002/jhm.2274

McCallin, A. (2001). Interdisciplinary practice – a matter of teamwork: An integrated literature review. *Journal of Clinical Nursing, 10*(4), 419-428. doi:10.1046/j.1365-2702.2001.00495.x

McDaniel, R. R. and Driebe, D. J. (2001). Complexity science and health care management. In L. H. Friedman, J. Goes, & G. T. Savage (Eds.), *Advances in Health Care Management* (Vol. 2, pp. 11-36). Bingley, UK: Emerald Group Publishing Limited.

McDaniel, R. R., Lanham, H. J. and Anderson, R. A. (2009). Implications of complex adaptive systems theory for the design of research on health care organizations. *Health Care Management Review, 34*(2), 191-199. doi:10.1097/HMR.0b013e31819c8b38

Mohr, J., Batalden, P. and Barach, P. (2004). Integrating patient safety into the clinical microsystem. *Quality and Safety in Health Care, 13*(Suppl. 2), ii34. doi:10.1136/qshc.2003.009571

Morita, S., Oshio, K., Osana, Y., Funabashi, Y., Oka, K. and Kawamura, K. (2001). Geometrical structure of the neuronal network of *Caenorhabditis elegans*. *Physica A: Statistical Mechanics and its Applications, 298*(3-4), 553-561. doi:10.1016/S0378-4371(01)00266-7

Morris, A., Bloom, J. R. and Kang, S. (2007). Organizational and individual factors affecting consumer outcomes of care in mental health services. *Administration and Policy in Mental Health and Mental Health Services Research, 34*(3), 243-253. doi:10.1007/s10488-006-0104-9

Nakajima, K. (2015). Blood transfusion with health information technology in emergency settins from a Safety-II perspective. In R. L. Wears, E. Hollnagel, & J. Braithwaite (Eds.), *Resilient Health Care: The Resilience of Everyday Clinical Work* (Vol. III, pp. 99-113). Farnham, Surrey, UK: Ashgate Publishing, Ltd.

Nyssen, A. S. and Berastegui, P. (2017). Is system resilience maintained at the expense of individual resilience? In J. Braithwaite, R. L. Wears, & E. Hollnagel (Eds.), *Resilient Health Care: Reconciling Work-As-Imagined and Work-As-Done* (Vol. III, pp. 37-46). Boca Raton, FL: Taylor & Francis.

Obstfeld, D. (2005). Social networks, the tertius iungens orientation, and involvement in innovation. *Administrative Science Quarterly, 50*(1), 100-130. doi:10.2189/asqu.2005.50.1.100

Parmelli, E., Flodgren, G., Beyer, F., Baillie, N., Schaafsma, M. E. and Eccles, M. P. (2011). The effectiveness of strategies to change organisational culture to improve healthcare performance: A systematic review. *Implementation Science, 6*(1), 1-8. doi:10.1186/1748-5908-6-33

Patterson, M., Deutsch, E. and Jacobson, L. (2017). Simulation: Closing the gap between work-as-imagined and work-as-done. In J. Braithwaite, R. L. Wears, & E. Hollnagel (Eds.), *Resilient Health Care: Reconciling Work-As-Imagined and Work-As-Done* (Vol. III, pp. 143-152). Boca Raton, FL: Taylor & Francis.

Patterson, P. D., Pfeiffer, A. J., Weaver, M. D., Krackhardt, D., Arnold, R. M., Yealy, D. M. and Lave, J. R. (2013). Network analysis of team communication in a busy emergency

department. *BMC Health Services Research, 13*(1), 109. doi:10.1186/1472-6963-13-109

Peters, D. H. (2014). The application of systems thinking in health: Why use systems thinking? *Health Research Policy and Systems, 12*(1), 51. doi:10.1186/1478-4505-12-51

Petticrew, M. (2011). When are complex interventions 'complex'? When are simple interventions 'simple'? *European Journal of Public Health, 21*(4), 397-398. doi:10.1093/eurpub/ckr084

Piasentin, K. and Chapman, D. (2006). Subjective person–organization fit: Bridging the gap between conceptualization and measurement. *Journal of Vocational Behaviour, 69*, 202-221.

Plsek, P. E. (2001). Appendix B. Redesigning Health Care with Insights from the Science of Complex Adaptive Systems. In Institute of Medicine (US) Committee on Quality of Health Care in America (Ed.), *Crossing the Quality Chasm. A New Health System for the 21st Century* (pp. 309-322). Washington, DC: National Academies Press.

Plsek, P. E. and Greenhalgh, T. (2001). The challenge of complexity in health care. *British Medical Journal, 323*, 625. doi:10.1136/bmj.323.7313.625

Plsek, P. E. and Wilson, T. (2001). Complexity, leadership, and management in healthcare organisations. *British Medical Journal, 323*(7315), 746-749. doi:10.1136/bmj.323.7315.746

Prashanth, N. S., Marchal, B., Devadasan, N., Kegels, G. and Criel, B. (2014). Advancing the application of systems thinking in health: A realist evaluation of a capacity building programme for district managers in Tumkur, India. *Health Research Policy and Systems, 12*(1), 42. doi:10.1186/1478-4505-12-42

Provost, S. M., Lanham, H. J., Leykum, L. K., McDaniel, R. R. and Pugh, J. (2015). Health care huddles: Managing complexity to achieve high reliability. *Health Care Management Review, 40*(1), 2-12. doi:10.1097/HMR.0000000000000009

Ranmuthugala, G., Plumb, J. J., Cunningham, F. C., Georgiou, A., Westbrook, J. I. and Braithwaite, J. (2011). How and why are communities of practice established in the healthcare sector? A systematic review of the literature. *BMC Health Services Research, 11*(1), 273. doi:10.1186/1472-6963-11-273

Rapport, F., Clay-Williams, R., Churruca, K., Shih, P., Hogden, A. and Braithwaite, J. (2017). The struggle of translating science into action: Foundational concepts of implementation science. *Journal of Evaluation in Clinical Practice,* (First Published Online 31 March 2017). doi:10.1111/jep.12741

Reynolds, M., Forss, K., Hummelbrunner, R., Marra, M. and Perrin, B. (2012). Complexity, systems thinking and evaluation - an emerging relationship? *Evaluation Connections: The European Evaluation Society Newsletter, December*, 7-9.

Rickles, D., Hawe, P. and Shiell, A. (2007). A simple guide to chaos and complexity. *Journal of Epidemiology and Community Health, 61*(11), 933-937. doi:10.1136/jech.2006.054254

Riley, T. and Hawe, P. (2009). A typology of practice narratives during the implementation of a preventive, community intervention trial. *Implementation Science, 4*(1), 80. doi:10.1186/1748-5908-4-80

Robson, R. (2015). Everyday Clinical Work (ECW) in Complex Adaptive Systems. In R. L. Wears, E. Hollnagel, & J. Braithwaite (Eds.), *Resilient Health Care: The Resilience of Everyday Clinical Work* (Vol. III, pp. 177-188). Farnham, Surrey, UK: Ashgate Publishing, Ltd.

Rose, J., Riolo, R., Hovmand, P., Cherng, S., Ferrer, R., Katerndahl, D. A., . . . Stange, K. C. (2013). Modeling the paradox of primary care In J. P. Sturmberg & C. Martin (Eds.), *Handbook of Systems and Complexity in Health* (pp. 815-825). New York, NY: Springer Science & Business Media.

Rouse, W. B. (2008). Health care as a complex adaptive system: Implications for design and management. *The Bridge, 38*(1), 17-25.

Rychetnik, L., Frommer, M., Hawe, P. and Shiell, A. (2002). Criteria for evaluating evidence on public health interventions. *Journal of Epidemiology and Community Health, 56*(2), 119-127. doi:10.1136/jech.56.2.119

Sackmann, S. A. (1991). Uncovering Culture in Organizations. *The Journal of Applied Behavioral Science, 27*(3), 295-317. doi:10.1177/0021886391273005

Senge, P. M. (2006). *The Fifth Discipline: The Art and Practice of the Learning Organization*. London, UK: Crown Pub.

Sheps, S., Cardiff, K., Pelletier, R. and Robson, R. (2015). Revealing resilience through critical incident narratives: A way to move from Safety-I to Safety-II. In R. L. Wears, E. Hollnagel, & J. Braithwaite (Eds.), *Resilient Health Care: The Resilience of Everyday Clinical Work* (Vol. III, pp. 189-206). Farnham, Surrey, UK: Ashgate Publishing, Ltd.

Shiell, A., Hawe, P. and Gold, L. (2008). Complex interventions or complex systems? Implications for health economic evaluation. *British Medical Journal, 336*(7656), 1281-1283. doi:10.1136/bmj.39569.510521.AD

Simmel, G. (1950). *The Sociology of Georg Simmel*. New York, NY: Free Press.

Simpson, K. M., Porter, K., McConnell, E. S., Colón-Emeric, C., Daily, K. A., Stalzer, A. and Anderson, R. A. (2013). Tool for evaluating research implementation challenges: A sense-making protocol for addressing implementation challenges in complex research settings. *Implementation Science, 8*(1), 2. doi:10.1186/1748-5908-8-2

Solberg, L. I., Klevan, D. H. and Asche, S. E. (2007). Crossing the quality chasm for diabetes care: The power of one physician, his team, and systems thinking. *The Journal of the American Board of Family Medicine, 20*(3), 299-306. doi:10.3122/jabfm.2007.03.060132

Spector, L., Klein, J., Perry, C. and Feinstein, M. (2003). Emergence of Collective Behavior in Evolving Populations of Flying Agents. In E. Cantú-Paz, J. A. Foster, K. Deb, L. D. Davis, R. Roy, U.-M. O'Reilly, H.-G. Beyer, R. Standish, G. Kendall, S. Wilson, M. Harman, J. Wegener, D. Dasgupta, M. A. Potter, A. C. Schultz, K. A. Dowsland, N. Jonoska, & J. Miller (Eds.), *GECCO 2003: Genetic and Evolutionary Computation Conference Chicago, IL, USA, July 12–16, 2003 Proceedings, Part I* (pp. 61-73). Berlin, Heidelberg: Springer Berlin Heidelberg.

Sterman, J. D. (2006). Learning from evidence in a complex world. *American Journal of Public Health, 96*(3), 505-514. doi:10.2105/ajph.2005.066043

Tan, J., Wen, J. and Awad, N. (2005). Health care and services delivery systems as complex adaptive systems. *Communications of the ACM, 48*(5), 36-44. doi:10.1145/1060710.1060737

Taylor, M. J., McNicholas, C., Nicolay, C., Darzi, A., Bell, D. and Reed, J. E. (2013). Systematic review of the application of the plan–do–study–act method to improve quality in healthcare. *BMJ Quality & Safety, 23*, 290-298.

The Health Foundation. (2010). *Complex adaptive systems*. Retrieved from London, UK: http://www.health.org.uk/sites/health/files/ComplexAdaptiveSystems.pdf

Thompson, D. S., Fazio, X., Kustra, E., Patrick, L. and Stanley, D. (2016). Scoping review of complexity theory in health services research. *BMC Health Services Research, 16*(1), 1-16. doi:10.1186/s12913-016-1343-4

Turing, A. M. (1952). The chemical basis of morphogenesis. *Philosophical Transactions of the Royal Society of London 237*(641), 37-72. doi:10.1098/rstb.1952.0012

US National Library of Medicine. (2017). PubMed. *National Institute of Health.* Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/

Vincent, C. and Amalberti, R. (2016). *Safer healthcare: Strategies for the real world*. New York, NY: Springer International Publishing.

Wears, R. L. (2010). Exploring the dynamics of resilience. *Proceedings of Human Factors and Ergonomics Society 54th Annual Meeting, 54*(4), 394-398.

Wears, R. L., Hollnagel, E. and Braithwaite, J. (Eds.). (2015). *Resilient Health Care: The Resilience of Everyday Clinical Work* (Vol. II). Farnham, Surrey, UK: Ashgate Publishing, Ltd.

Weaver, T. D. and Patterson, S. (2009). The myth of complexity. *British Medical Journal, 339*. doi:10.1136/bmj.b3505

Weick, K. E. (1995). *Sensemaking in Organizations* (Vol. 3). Thousand Oaks, CA: SAGE Publication.

Wellman, B. (2007). Social network analysis. In G. Ritzer (Ed.), *The Blackwell Encyclopaedia of Sociology* (Vol. IX). Malden, MA: Wiley-Blackwell.

Williams, A. and Sibbald, B. (1999). Changing roles and identities in primary health care: Exploring a culture of uncertainty. *Journal of Advanced Nursing, 29*(3), 737-745. doi:10.1046/j.1365-2648.1999.00946.x

Willis, C. D., Riley, B. L., Best, A. and Ongolo-Zogo, P. (2012). Strengthening health systems through networks: The need for measurement and feedback. *Health Policy and Planning, 27*(suppl_4), iv62-iv66. doi:10.1093/heapol/czs089

Wilson, T. and Holt, T. (2001). Complexity and clinical care. *British Medical Journal, 323*(7314), 685-688.

Wittgenstein, L. (2010). *Philosophical Investigations*. Oxford, UK: Wiley-Blackwell.

Part I

Getting Started:

Aspirations for Complexity Science

Part II

Characterising Complexity Science:

Approaches to Understanding

Part III

Dealing with Complexity:

Applications to Healthcare

Part IV

Implications:

Accomplishments of Complexity Science

Part V

Conclusion

Part VI

Appendices

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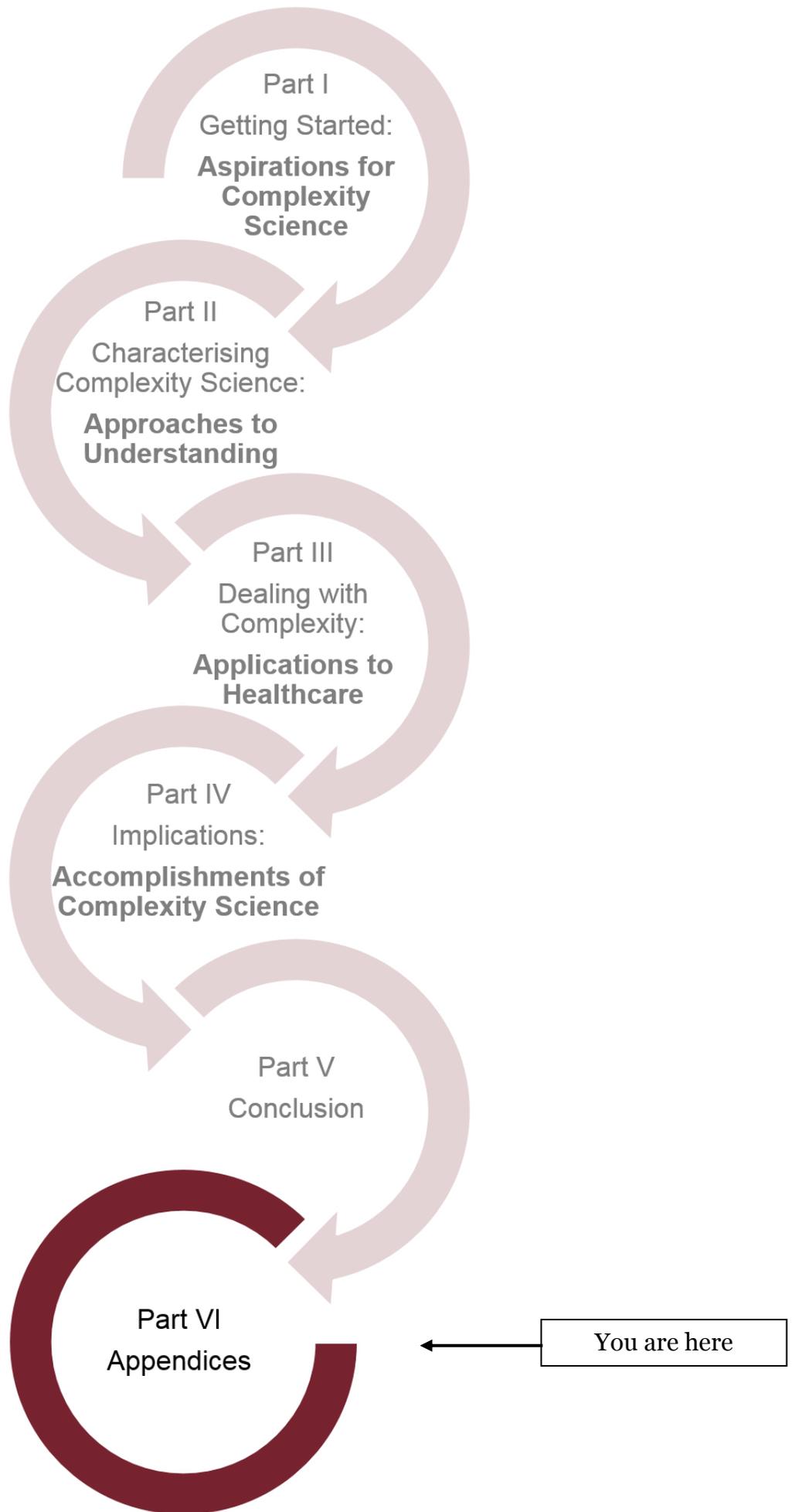
Part VI - Appendices

APPENDIX A: IMAGES OF COMPLEXITY

1) What are complex adaptive systems?

http://www.trojanmice.com/articles/complexadaptivesystems.htm
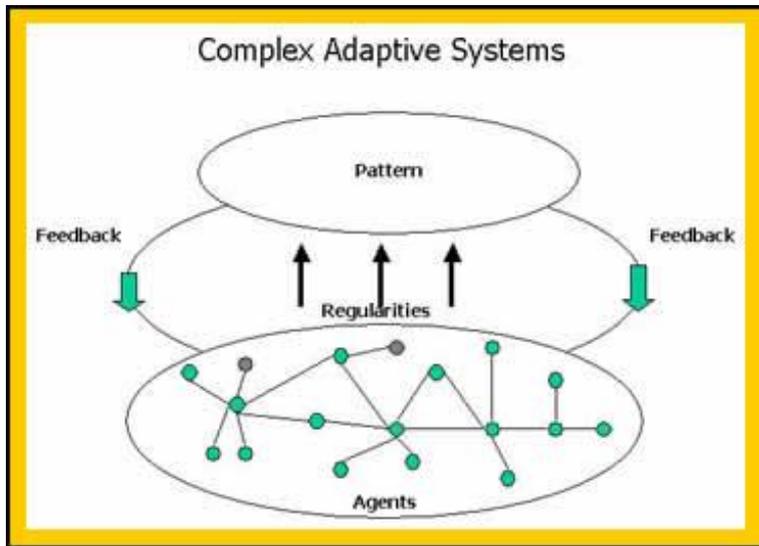
2) The strategic decision-making as a complex adaptive system: a conceptual scientific model[1]
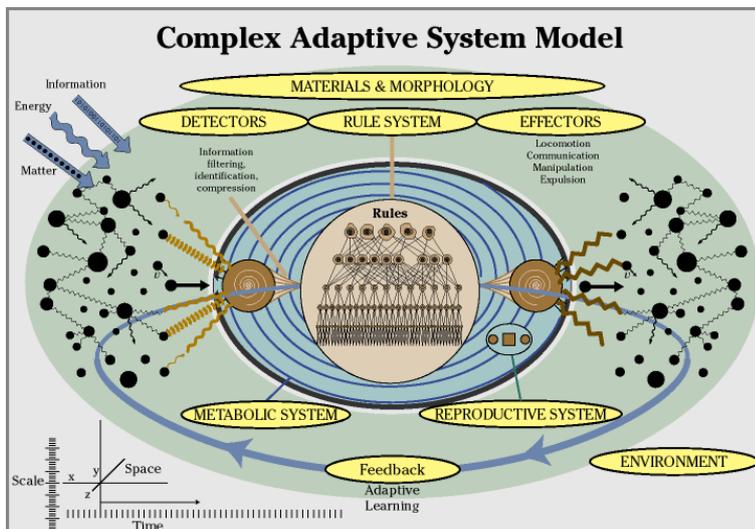
http://www.necsi.edu/projects/mclemens/casmodel.gif

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[1] Adaptated or duplicate images in the search were removed from Appendix A in order to provide the first 50 "unique" images. Adapted or duplicate versions can be found at: https://au.pinterest.com/pin/369998925606900166; https://basreus.nl/tag/complex-adaptive-systems/; http://www.nrsum.org/complex-adaptive-systems.html

3) Complex adaptive system[2]
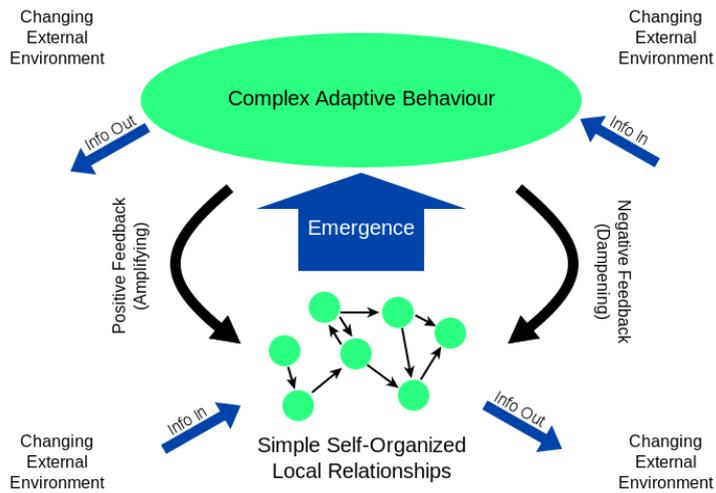
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4) Complex adaptive system
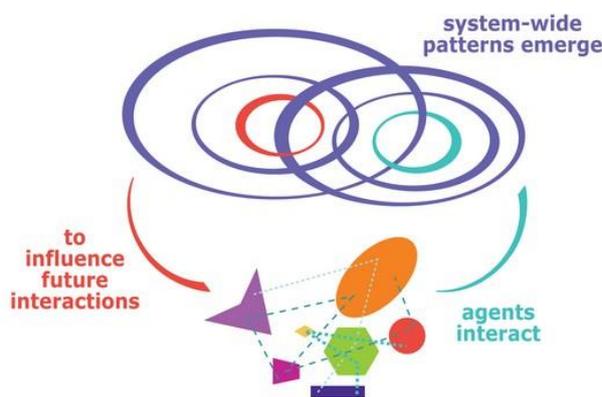
http://www.hsdinstitute.org/resources/complex-adaptive-system.html

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[2] Adapted or duplicate images in the search were removed from Appendix A in order to provide the first 50 "unique" images. Adapted or duplicate versions can be found at: https://blogs.msdn.microsoft.com/zen/2010/08/10/the-new-world-of-emergent-architecture-and-complex-adaptive-systems/; https://basreus.nl/tag/complex-adaptive-systems/; http://www.liteea.com/wordpress/holisticarchitecture/enterprise-is-a-complex-adaptive-system/; https://en.wikipedia.org/wiki/Complex_systems

5) Complex adaptive system
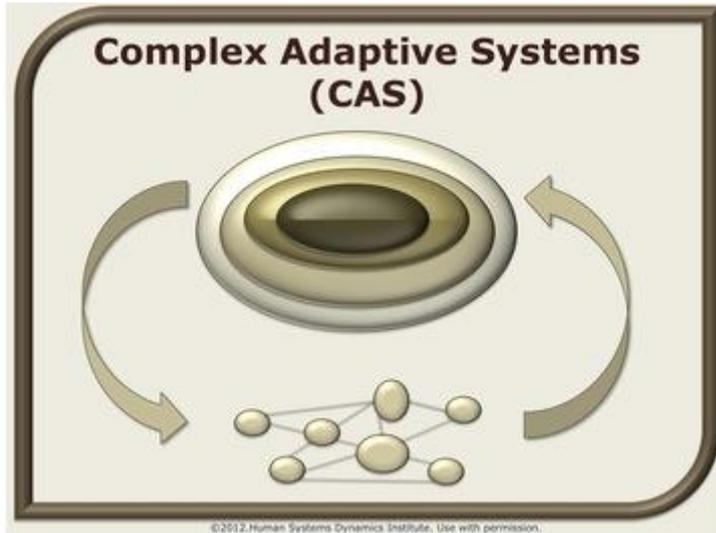
http://wiki.hsdinstitute.org/complex_adaptive_system

6) Understanding supply networks for complex adaptive systems
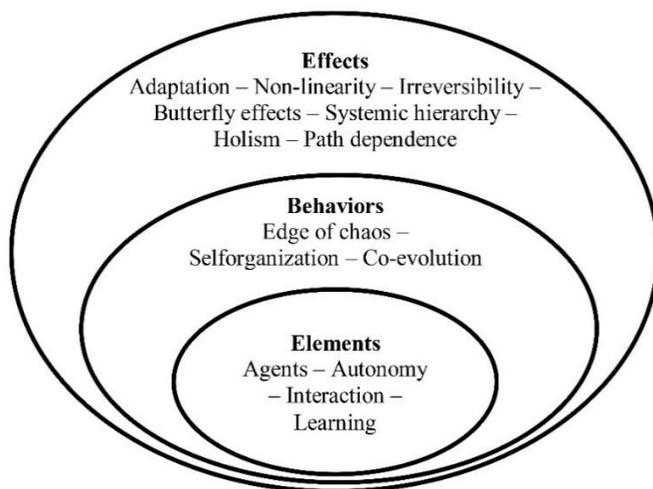
http://www.scielo.br/scielo.php?script=sci_arttext&pid=S1807-76922014000400441

7) Complex adaptive systems—Future health systems

http://www.futurehealthsystems.org/complex-adaptive-systems/
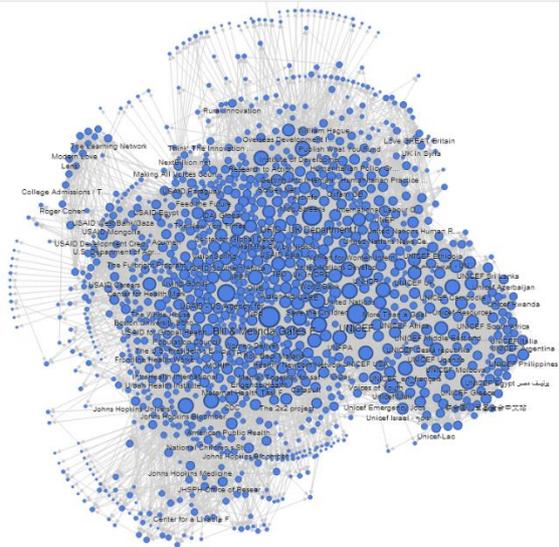
8) A model of nursing as a complex adaptive system[3]
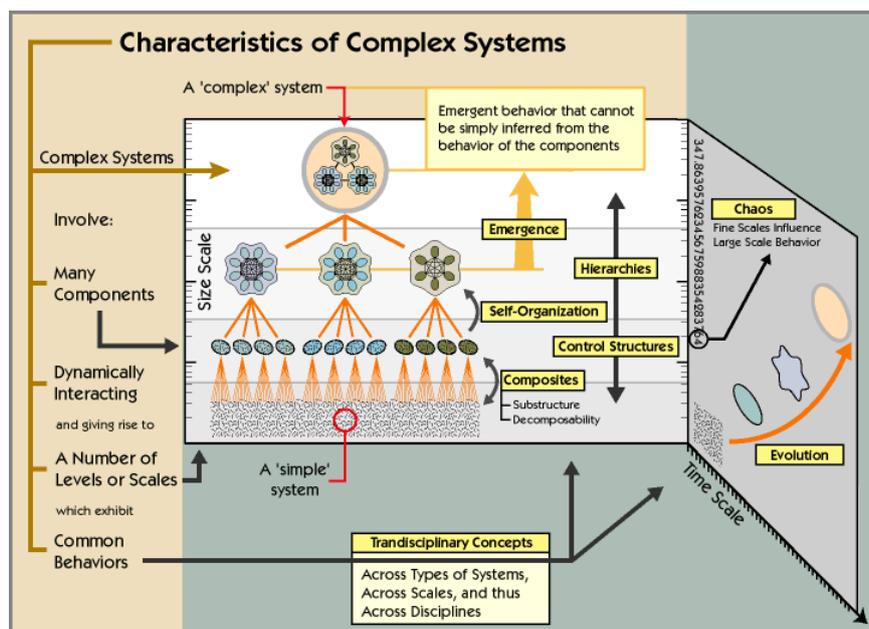
http://www.nursingoutlook.org/article/S0029-6554(07)00100-5/abstract

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[3] Adapted or duplicate images in the search were removed from Appendix A in order to provide the first 50 "unique" images. Adapted or duplicate version can be found at: http://vinodwadhawan.blogspot.com.au/2013/05/78-modelling-of-adaptation-and-learning.html

9) 3 Quarks Daily: the pathology of stabilisation in complex adaptive systems

http://www.3quarksdaily.com/3quarksdaily/2012/02/the-pathology-of-stabilisation-in-complex-adaptive-systems.html
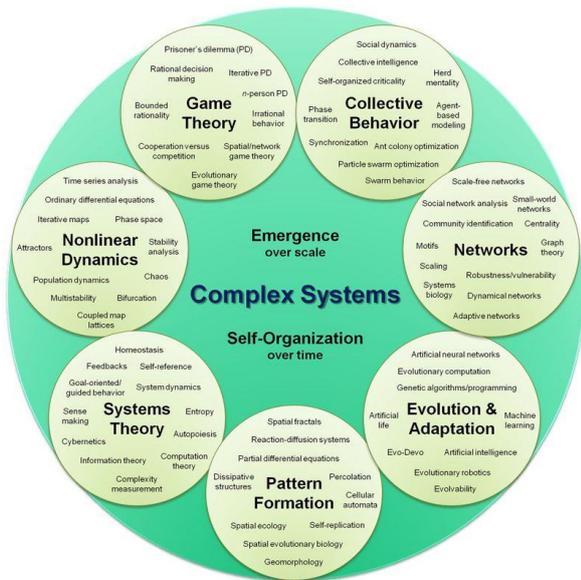
10) NAE Website - Health care as a complex adaptive system: implications for design and management

https://www.nae.edu/Publications/Bridge/EngineeringandtheHealthCareDeliverySystem/HealthCareasaComplexAdaptiveSystemImplicationsforDesignandManagement.aspx
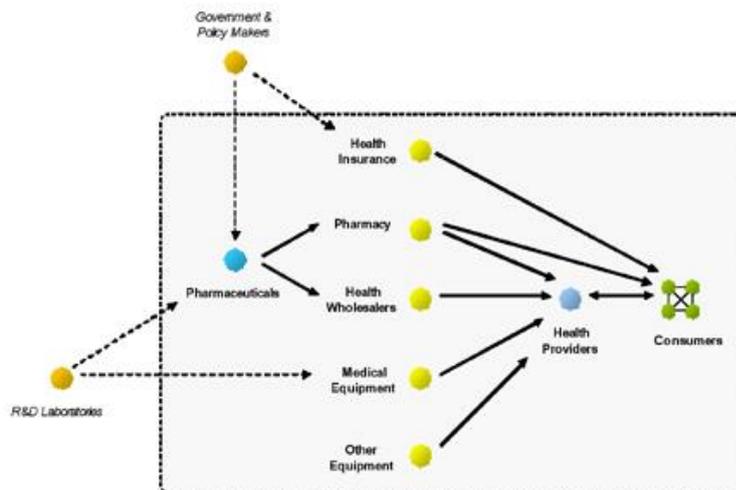
11) Maverick and Boutique: complex adaptive systems and the myth of control

http://maverickandboutique.com/complex-adaptive-systems/

12) Classrooms as complex adaptive systems: a relational model[4]
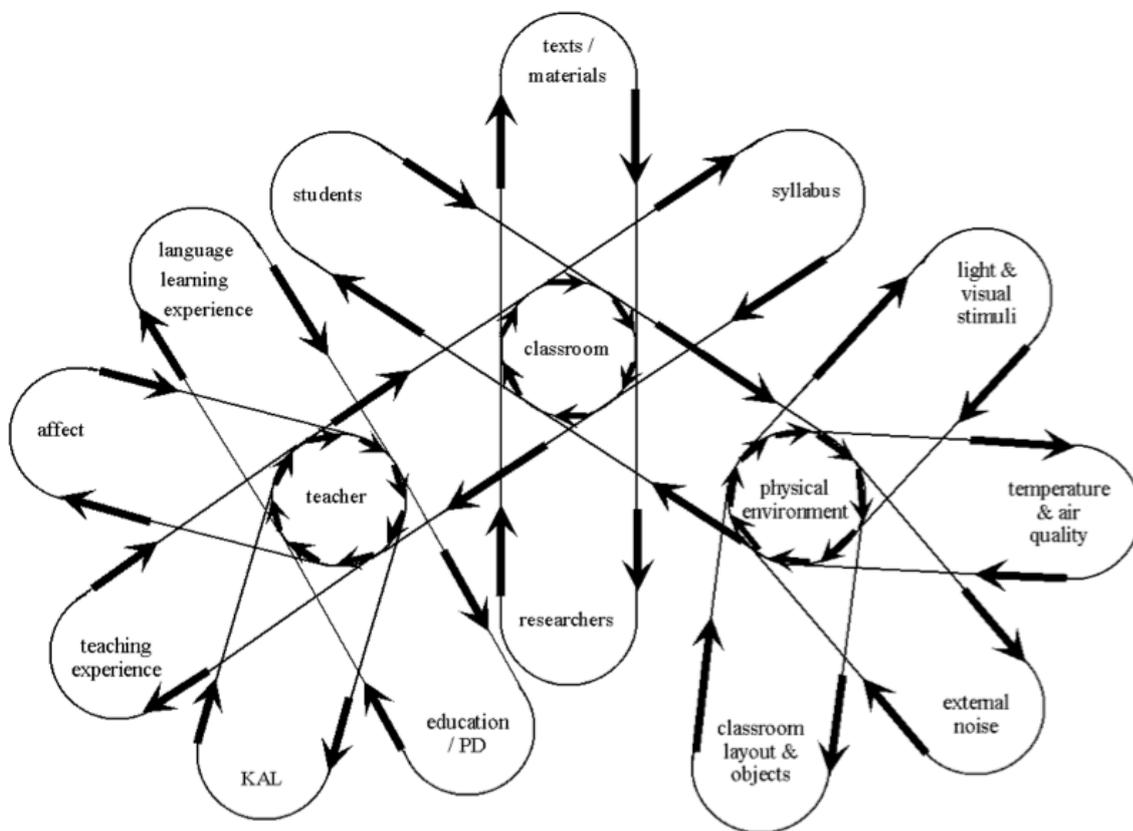
http://www.tesl-ej.org/wordpress/issues/volume15/ej57/ej57a1/

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[4] Adapted or duplicate images in the search were removed from Appendix A in order to provide the first 50 "unique" images. Adapted or duplicate version can be found at: http://www.tesl-ej.org/wordpress/issues/volume15/ej57/ej57a1/

13) Complex adaptive systems in health

https://www.slideshare.net/FHScomms/complex-adaptive-systems-in-health
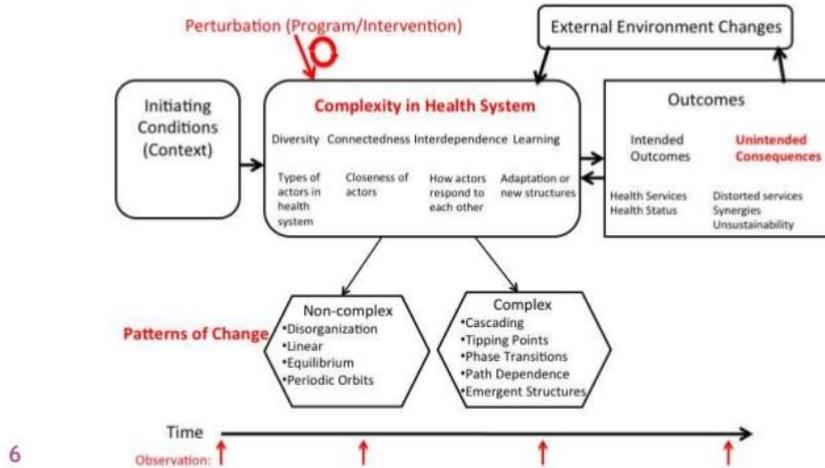
14) Interdisciplinary complex adaptive networks and systems @ KCL

https://sites.google.com/site/cnskcl/home
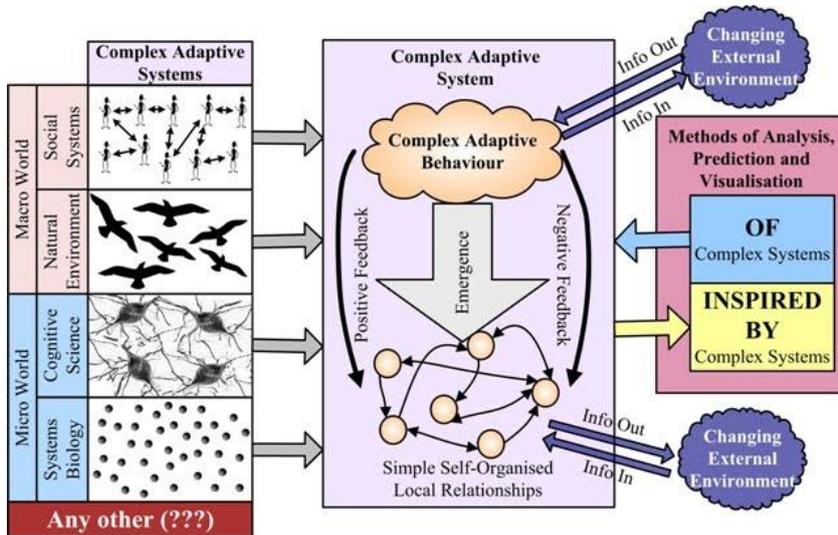
15) Word cloud for complex adaptive system
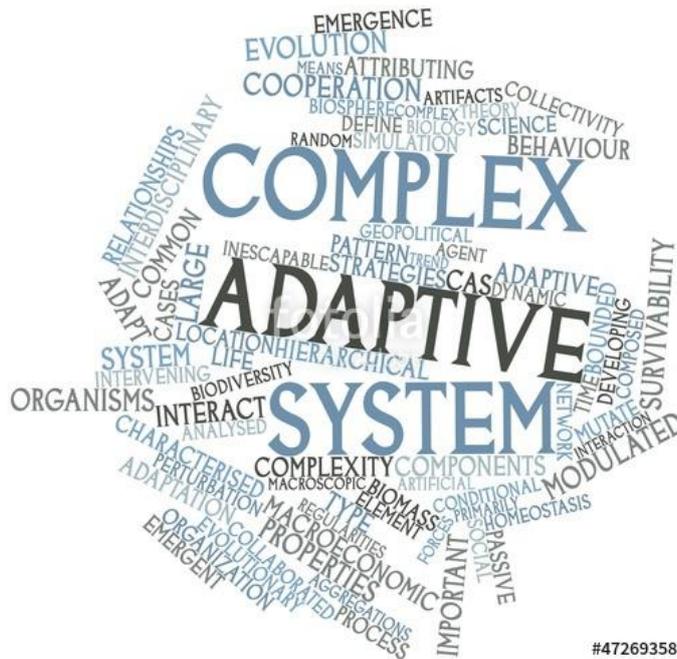
https://www.fotolia.com/id/47269358#

16) The organization as a complex adaptive system

https://hollypendleton.wordpress.com/2011/11/11/the-organization-as-a-complex-adaptive-system/

17) Democracy as a complex adaptive system

https://medium.com/dark-mountain/democracy-as-a-complex-adaptive-system-c6d81f450b92

18) Complex adaptive systems
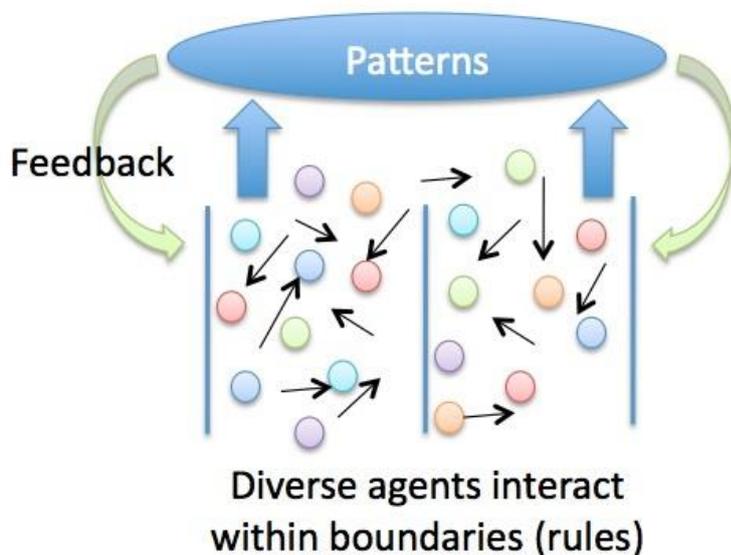
http://www.beyondintractability.org/essay/complex-adaptive-systems
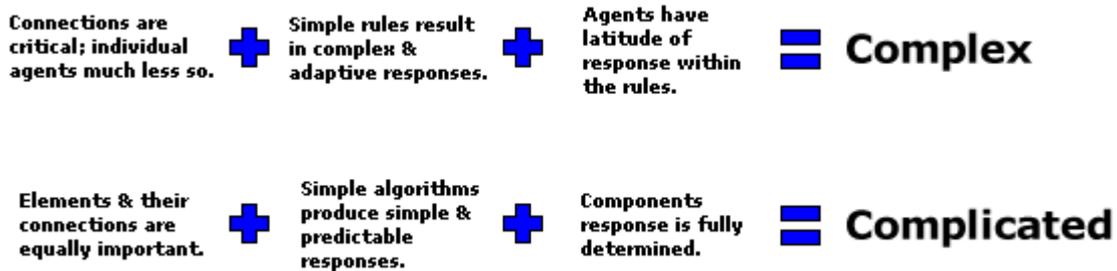
19) Abstract word cloud for complex adaptive system with related tags and terms

https://www.123rf.com/photo_16579254_abstract-word-cloud-for-complex-adaptive-system-
with-related-tags-and-terms.html

20) Complex adaptive systems

https://manoftheword.com/tag/complex-adaptive-systems/
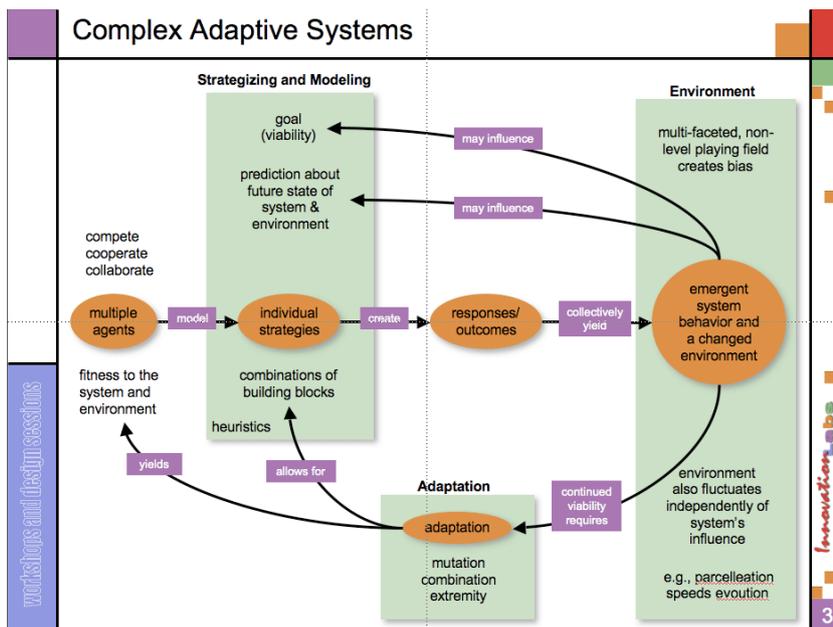
21) Complex adaptive systems - different scales cheat sheet by Davidpol

https://www.cheatography.com/davidpol/cheat-sheets/complex-adaptive-systems-different-scales/
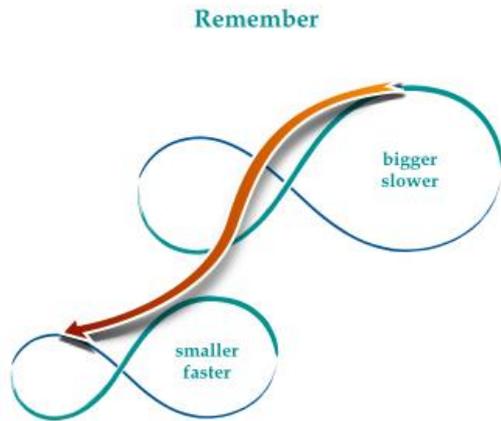
22) Complex adaptive systems: 3 overview

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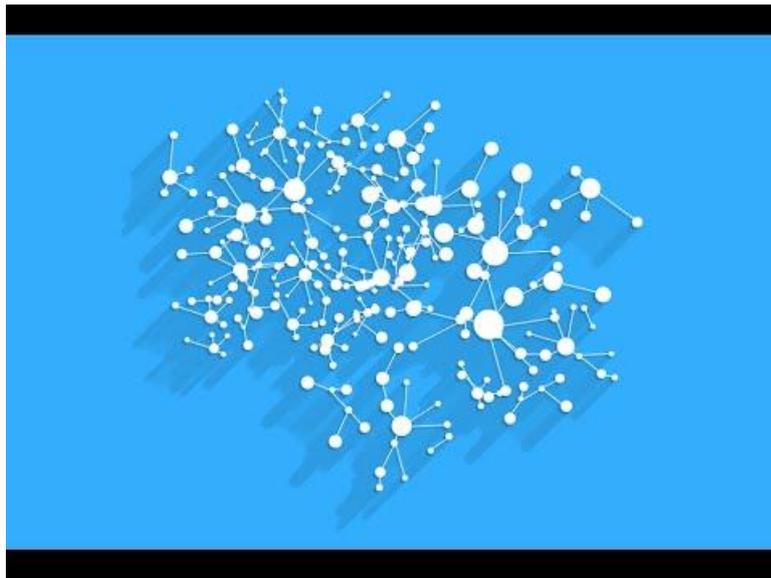
23) The Vinod Wadhawan Blog: 78. Modelling of adaptation and learning in complex adaptive
    systems

http://vinodwadhawan.blogspot.com.au/2013/05/78-modelling-of-adaptation-and-
    learning.html

24) Learning to handle complexity in social systems
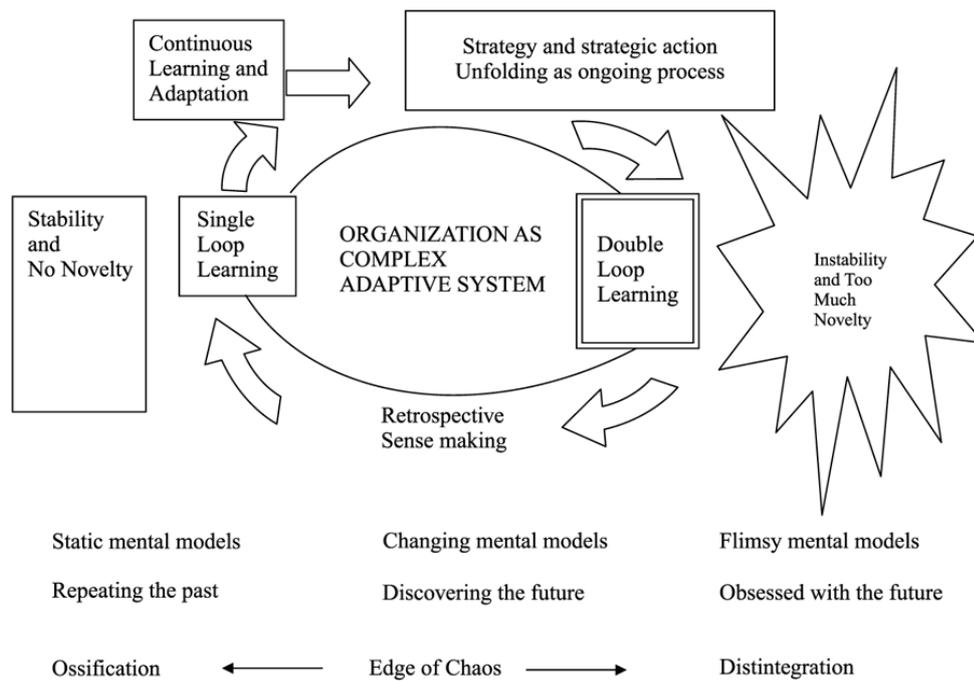
http://www.kmpc.nl/learning-to-handle-complexity-in-social-systems/

25) Complex adaptive systems

https://www.openabm.org/book/export/html/3445
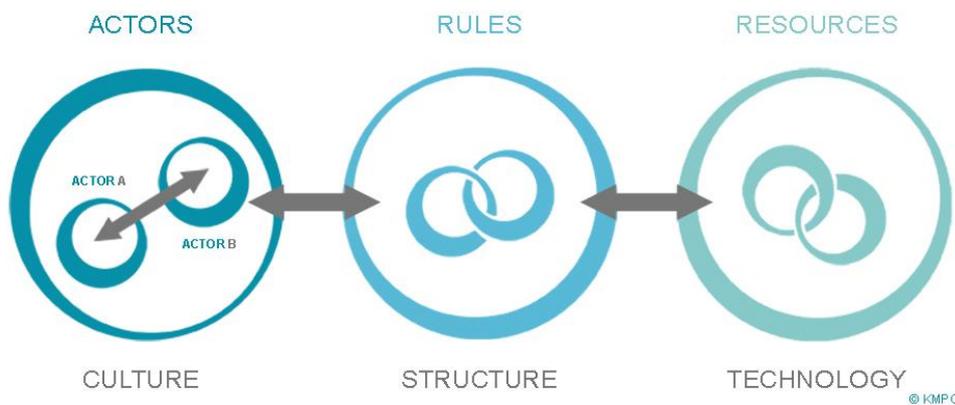
26) RedStateElectic: science sick from too much bad politics
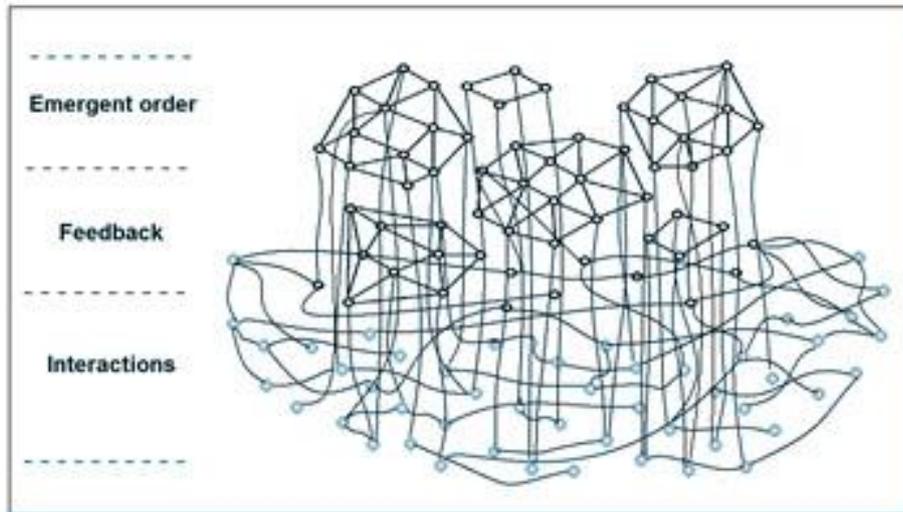
http://redstateeclectic.typepad.com/redstate_commentary/2014/02/fabricated-facts.html

27) Software applications as complex adaptive systems

https://hackernoon.com/complex-adaptive-systems-and-the-future-of-app-development-2bb0288f05e0
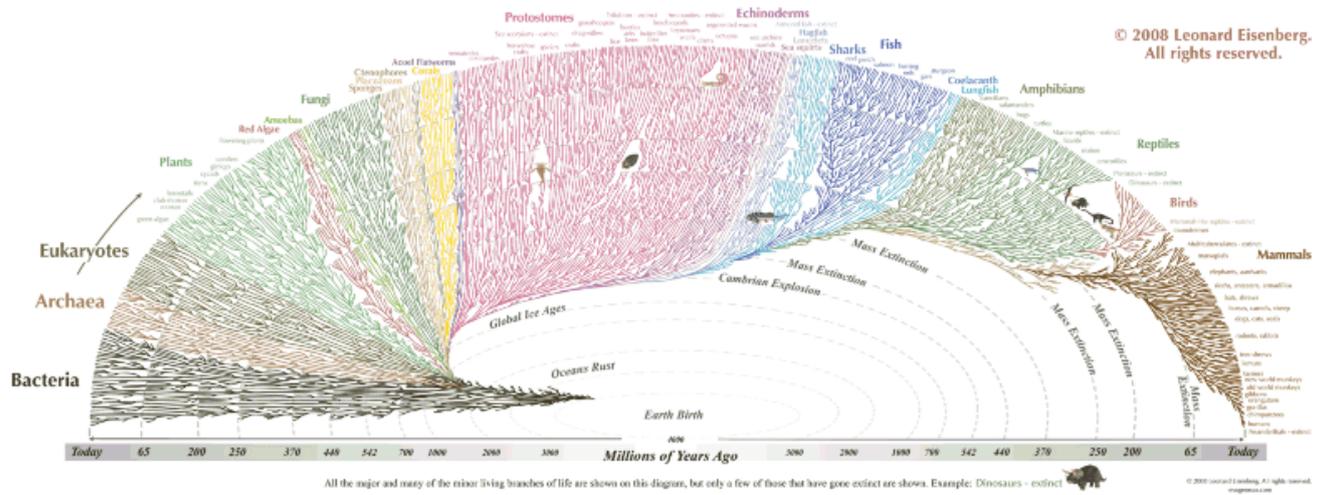
28) Electricity Market Complex Adaptive System (EMCAS)

http://ceeesa.es.anl.gov/projects/emcas.html

29) The Internet Analyzed as a Complex Adaptive System
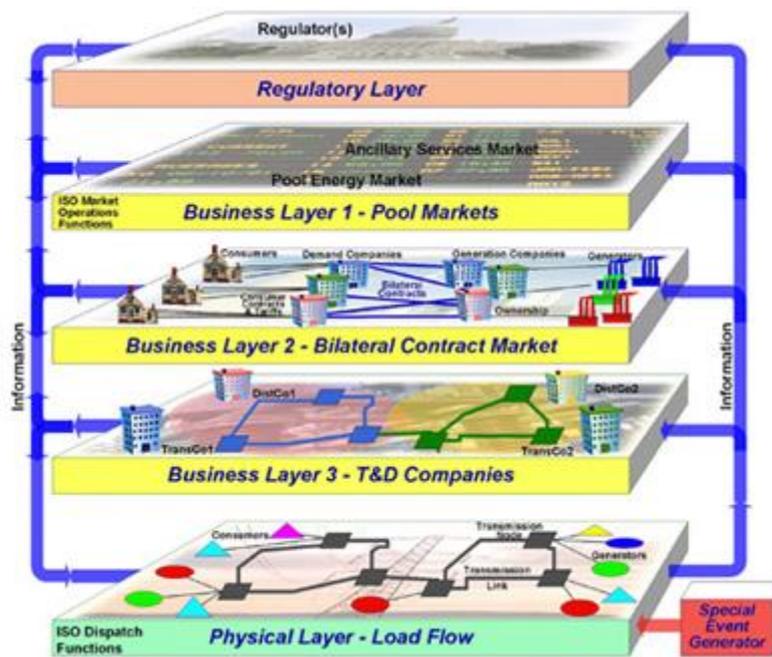
http://spacecollective.org/aloksubbarao/5730/the-internet-analyzed-as-a-complex-adaptive-system

30) Complex adaptive systems
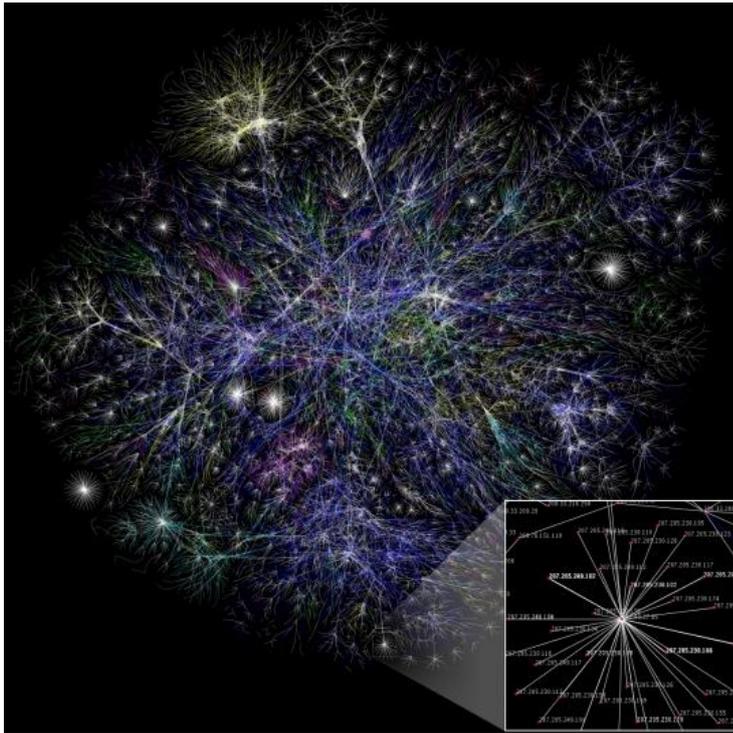
http://www.kristenzelenka.com/portfolio/2016/4/22/complex-adaptive-systems

31) Complex adaptive systems and communities
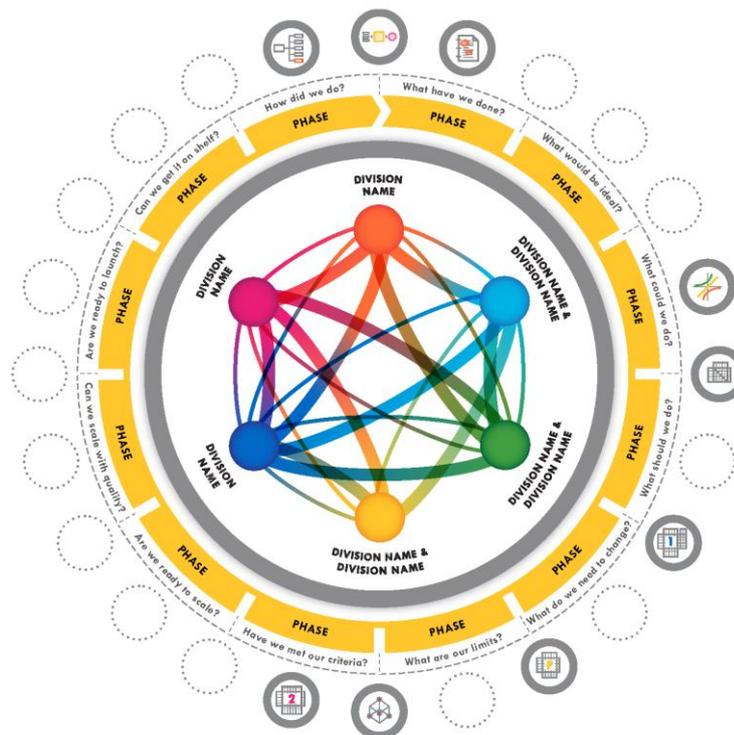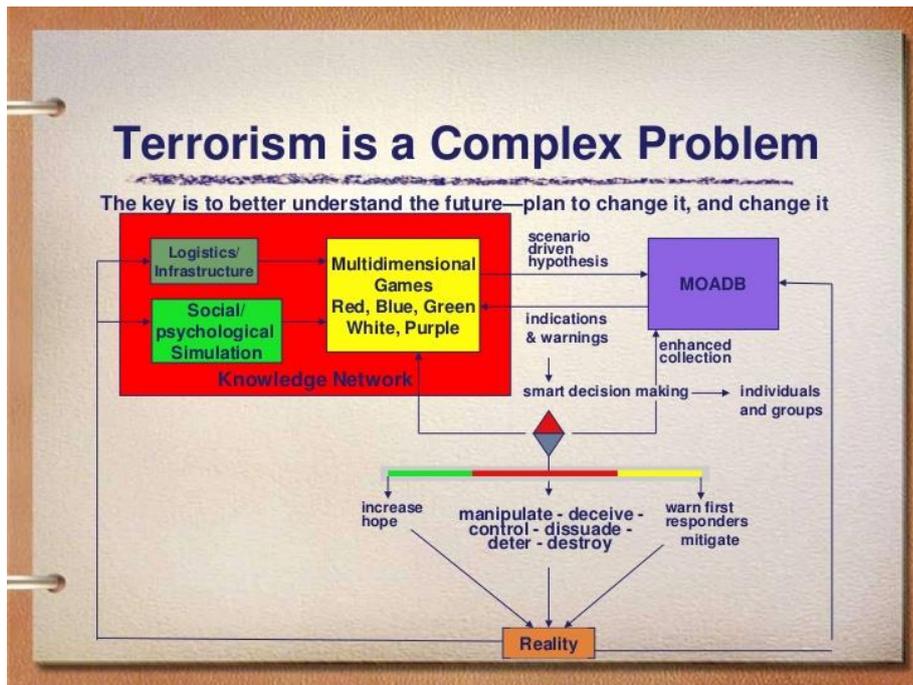
https://www.slideshare.net/NKHAYDEN/complex-adaptive-systems-and-communities

32) Complex adaptive system mechanisms, adaptive management practices, and firm product innovativeness
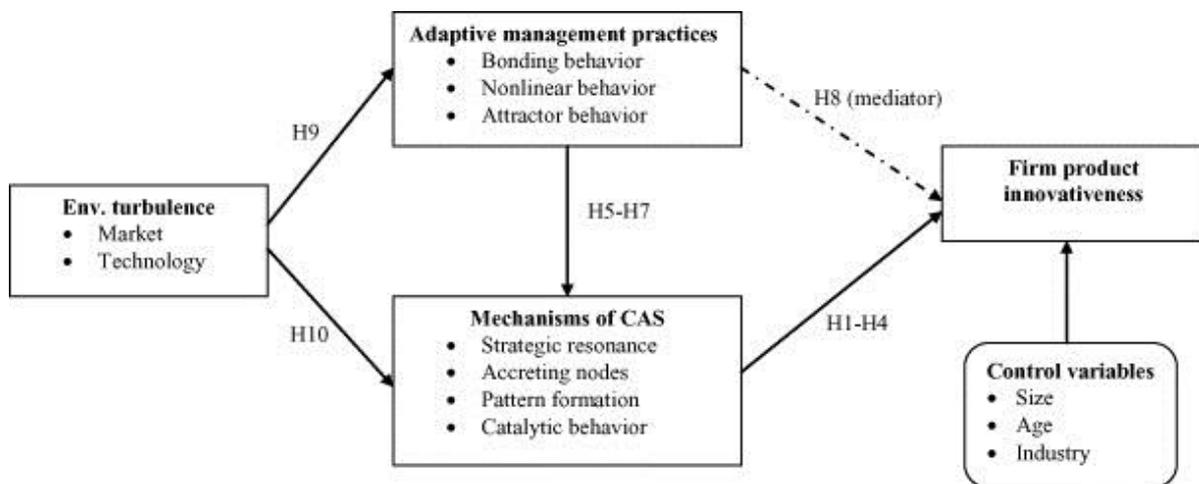
https://www.researchgate.net/publication/259555462_Complex_adaptive_system_mechanisms_adaptive_management_practices_and_firm_product_innovativeness/figures?lo=1

33) Interactive and visual representations: visualizing Complex Systems Science (CSS)

http://www.necsi.edu/visual/systems.html
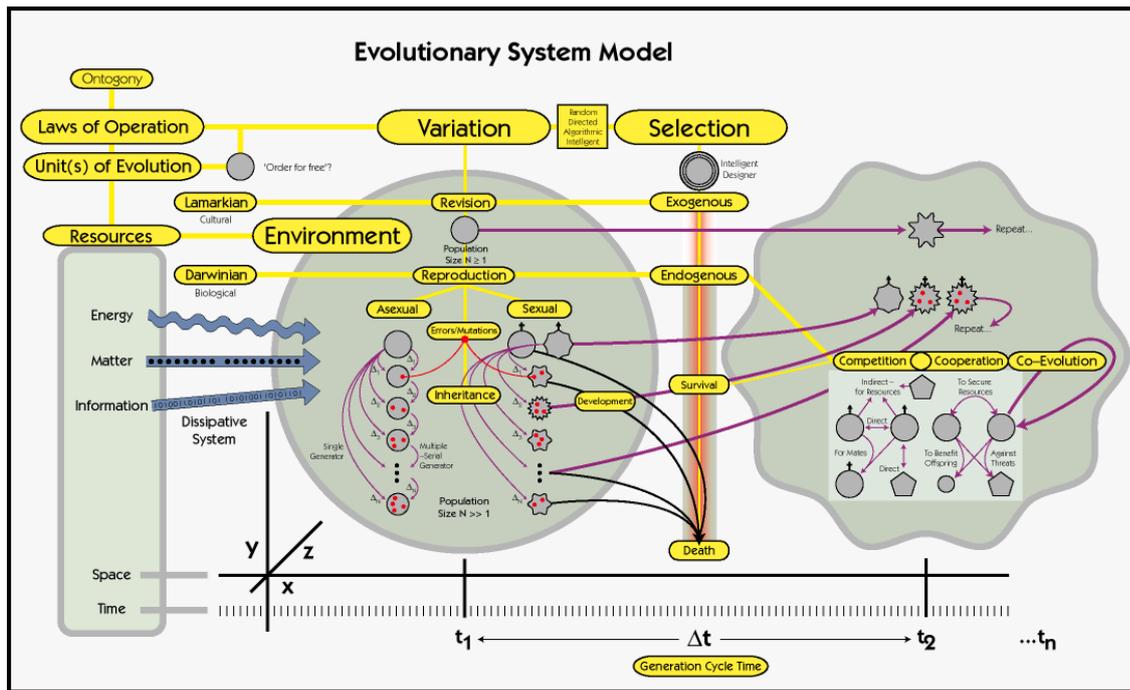
34) Emergence and complex adaptive systems:

https://www.openabm.org/book/export/html/1929
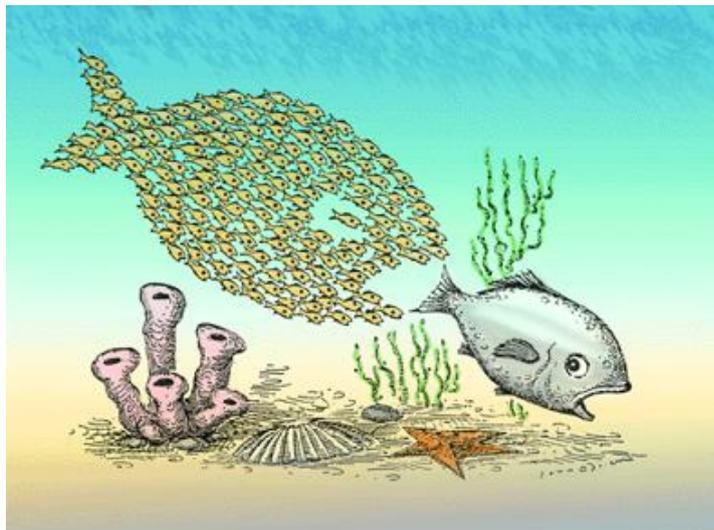
35) Complex adaptive systems healthcare images[5, 6]

Figure 5.2: The full obesity system map with thematic clusters (see main text 5.1.2 for discussion)[17,18] Variables are represented by boxes, positive causal relationships are represented by solid arrows and negative relationships by dotted lines. The central engine is highlighted in orange at the centre of the map.
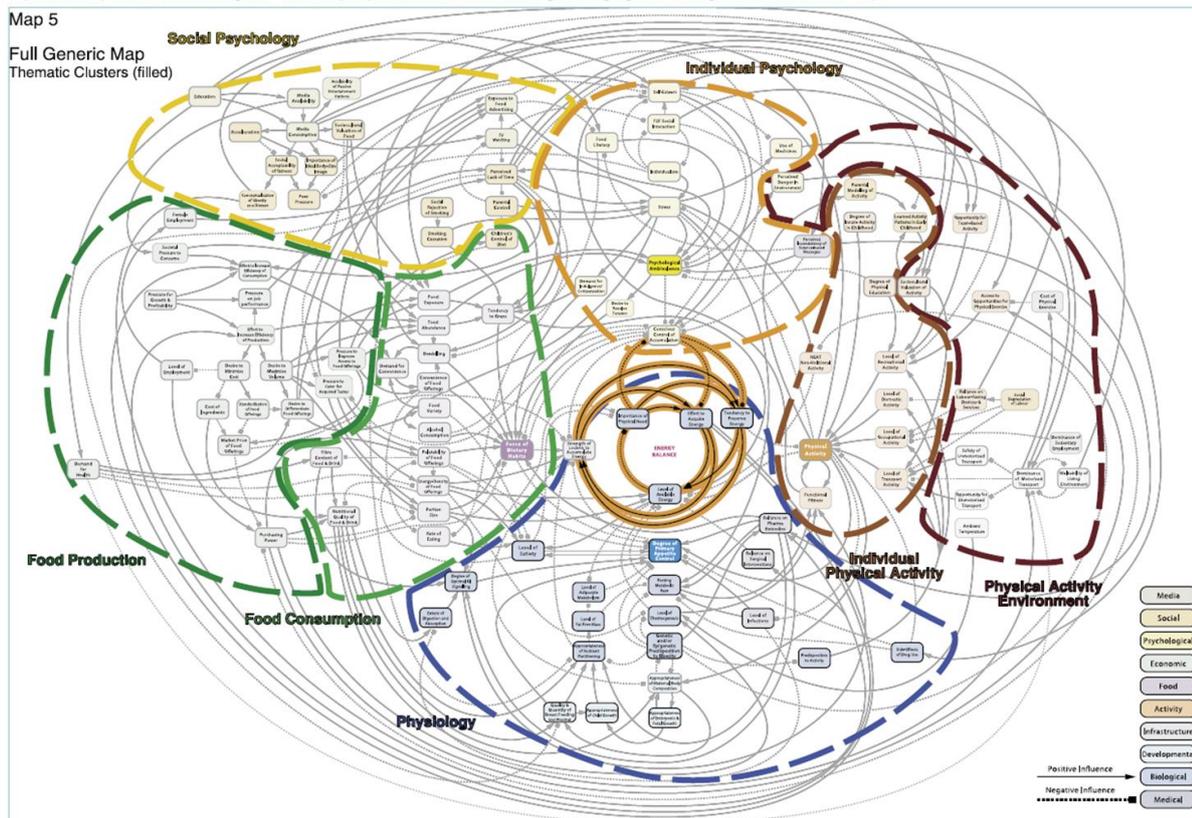
36) The Vinod Wadhawan Blog: 38. Complex adaptive systems

http://vinodwadhawan.blogspot.com.au/2012/07/38-complex-adaptive-systems.html

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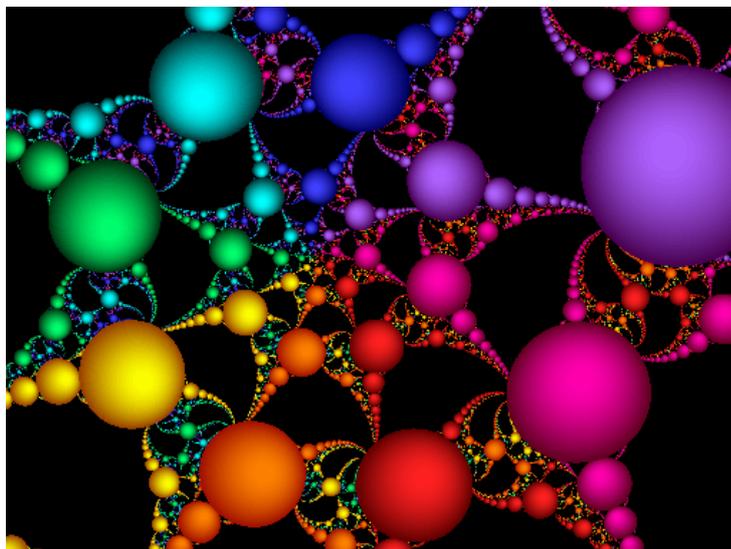
[5] Web link is withheld for this image due to browser security concerns

[6] Adapted or duplicate images in the search were removed from Appendix A in order to provide the first 50 "unique" images. Adapted or duplicate version can be found at: https://steps-centre.org/blog/complex-adaptive-systems/

37) Complex adaptive systems group at Iowa State University


http://web.cs.iastate.edu/~honavar/cas.html
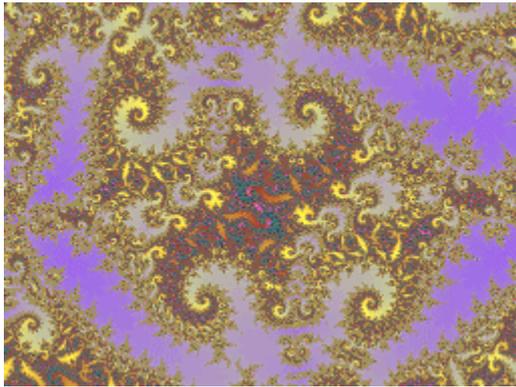
38) Introduction to complex adaptive systems

https://www.youtube.com/watch?v=o3RlqQjuIhM
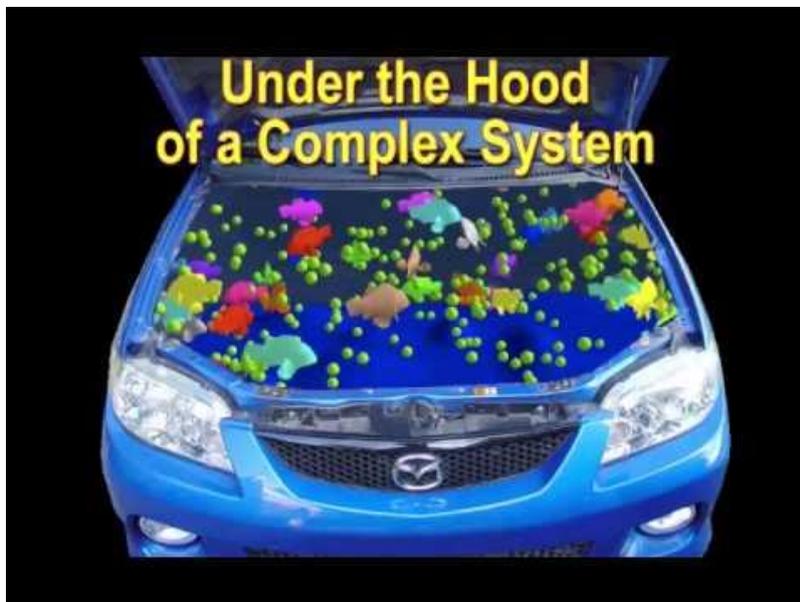
39) Researching language as a complex adaptive system
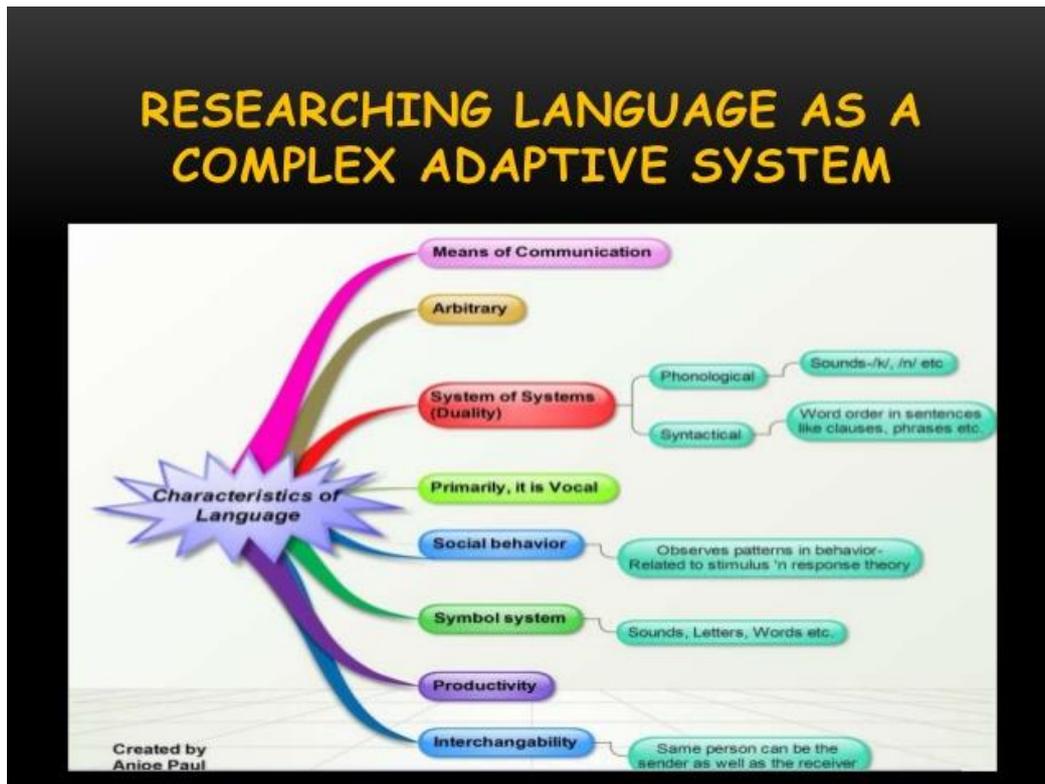
40) Peter Fryer - A brief description of complex adaptive systems and complexity theory
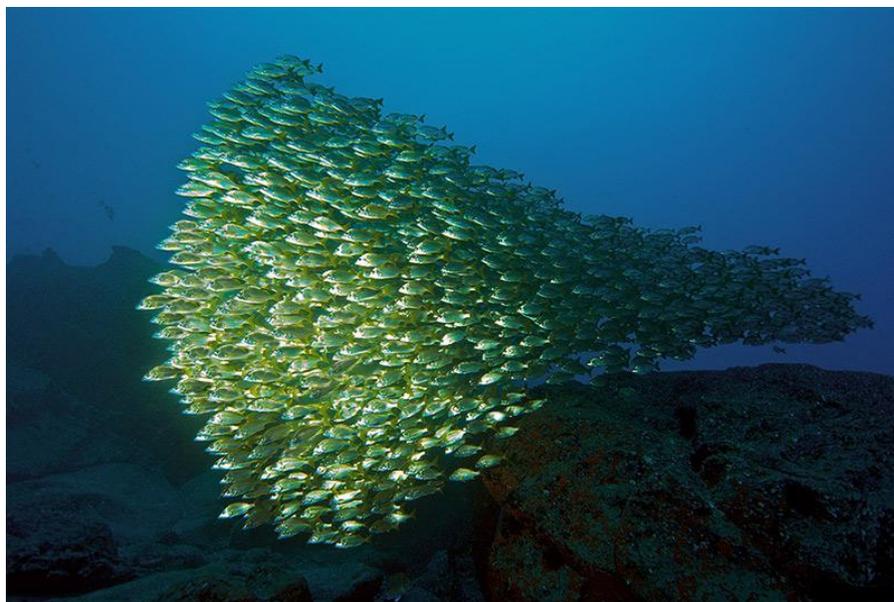
41) Complex adaptive system
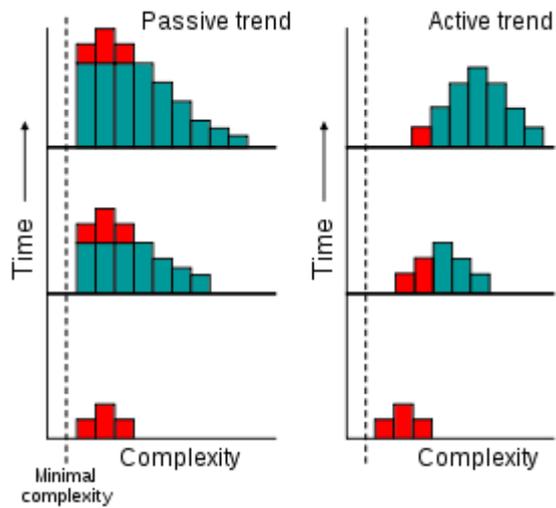
https://en.wikipedia.org/wiki/Complex_adaptive_system

42) Complicated or complex - knowing the difference is important

43) Welcome: Complex adaptive systems initiative
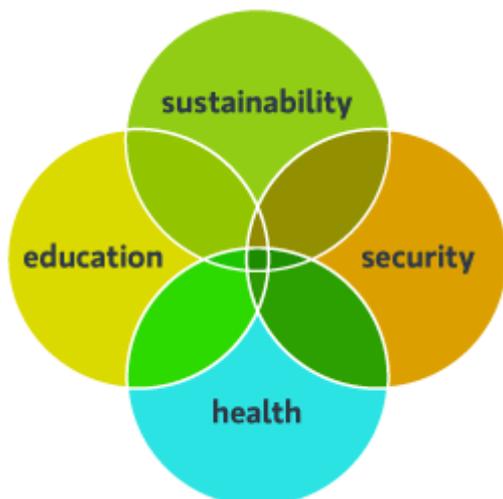
44) Conference papers: Complex Adaptive Systems Engineering (CASE)


http://cau-ses.net/papers/

45) Complex adaptive systems

http://www.wur.nl/en/About-Wageningen/Strategic-Plan/Strategic-plan-2011-2014/CAS.htm
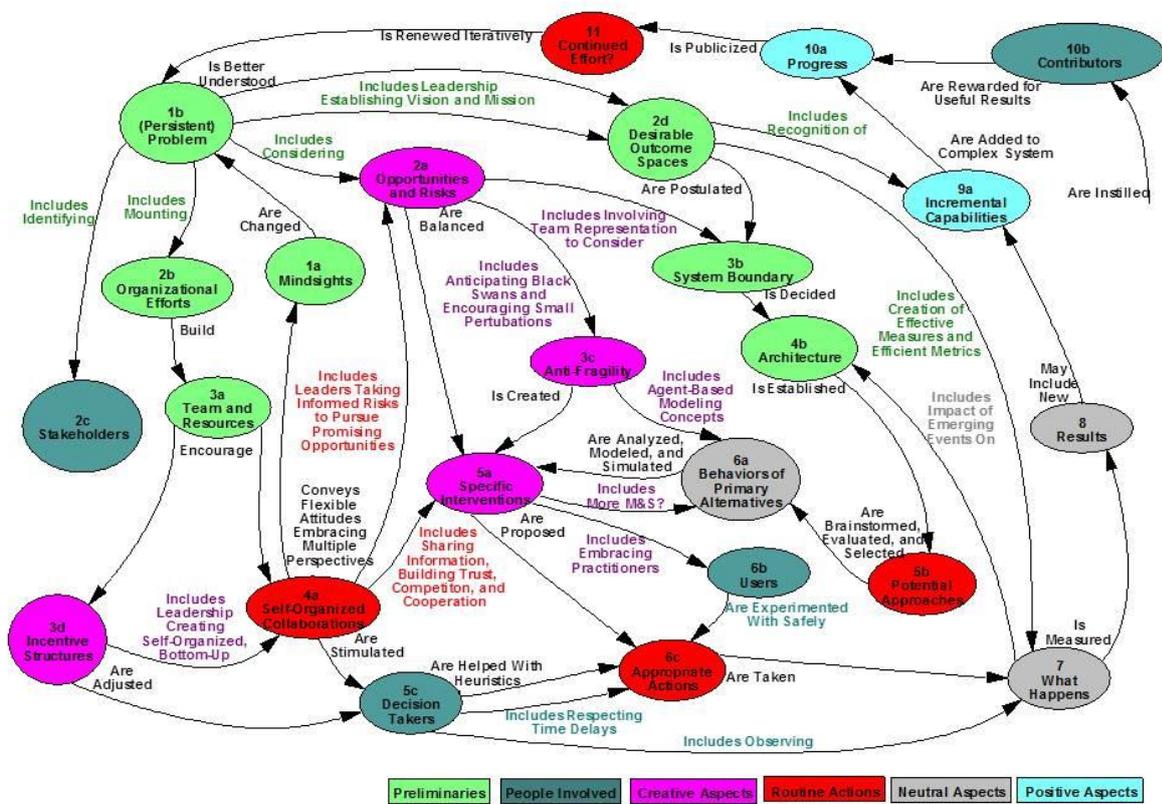
46) Complex adaptive systems laboratory

http://www.ece.uc.edu/~casl/welcome.html

47) Science for designers: how complex adaptive systems work

http://www.metropolismag.com/ideas/science-for-designers-complex-adaptive-systems/
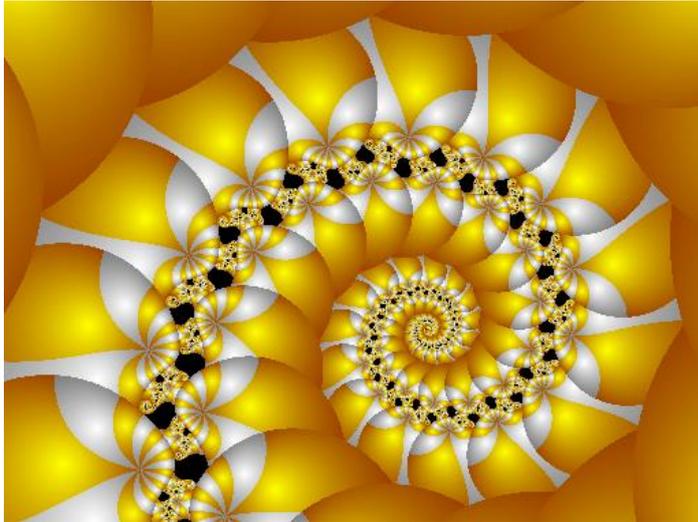
48) Mary Corrigan. Tracking the wisdom: dialogue on complex adaptive systems
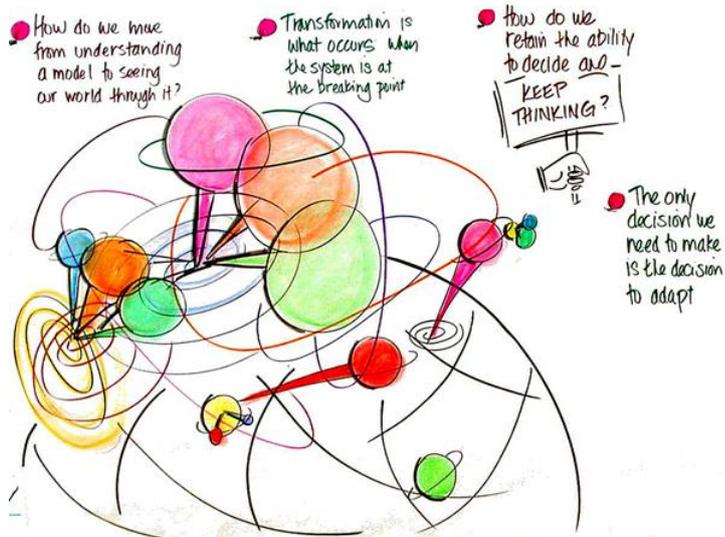
http://www.trackingthewisdom.com/what_weve_done/kaiser/

49) Complex adaptive systems principles

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97efa73e6cf9ec76e45a2cefb0995de

50) Science for Designers: How Complex Adaptive Systems Work

http://www.metropolismag.com/ideas/science-for-designers-complex-adaptive-systems/
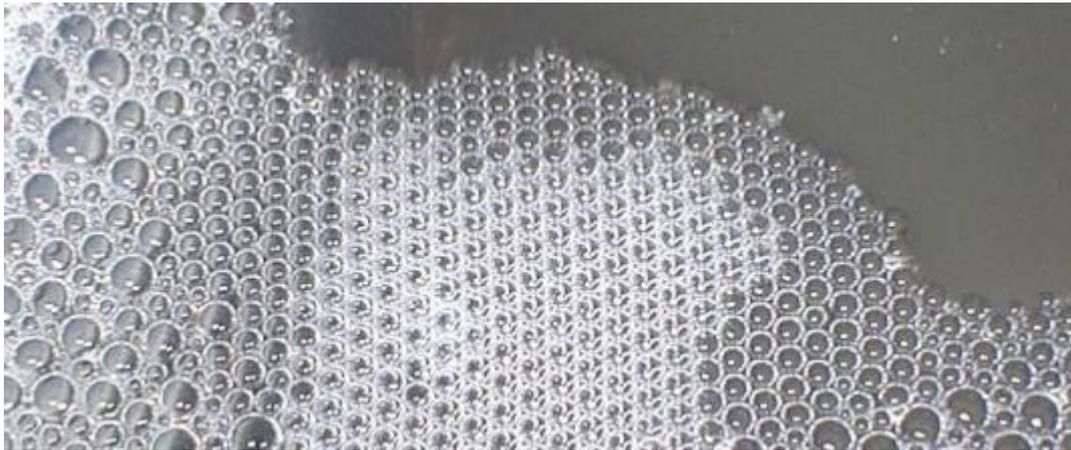
APPENDIX B: VOICES ON COMPLEXITY

"The complexity of things - the things within things - just seems to be endless. I mean nothing is easy, nothing is simple."

— **Alice Munro**

"From time immemorial, man has desired to comprehend the complexity of nature in terms of as few elementary concepts as possible."

— **Abdus Salam**

"Stop trying to change reality by eliminating complexity."

— **David Whyte**

"Any intelligent fool can make things bigger, more complex, and more violent. It takes a touch of genius — and a lot of courage to move in the opposite direction."

— **Ernst F. Schumacher**

"Complexity is the prodigy of the world. Simplicity is the sensation of the universe. Behind complexity, there is always simplicity to be revealed. Inside simplicity, there is always complexity to be discovered."

— **Gang Yu**

"The only simple truth is that there is nothing simple in this complex universe. Everything relates. Everything connects."

— **Johnny Rich, The Human Script**

"The ideal art, the noblest of art: working with the complexities of life, refusing to simplify, to "overcome" doubt."

— **Joyce Carol Oates, The Journal of Joyce Carol Oates: 1973-1982**

"Complexity has the propensity to overload systems, making the relevance of a particular piece of information not statistically significant. And when an array of mind-numbing factors is added into the equation, theory and models rarely conform to reality."

— **L.K. Samuels, In Defense of Chaos: The Chaology of Politics, Economics and Human Action**

"Abandon the urge to simplify everything, to look for formulas and easy answers, and to begin to think multidimensionally, to glory in the mystery and paradoxes of life,

not to be dismayed by the multitude of causes and consequences that are inherent in each experience—to appreciate the fact that life is complex.”

— M. Scott Peck

 “Today the network of relationships linking the human race to itself and to the rest of the biosphere is so complex that all aspects affect all others to an extraordinary degree. Someone should be studying the whole system, however crudely that has to be done, because no gluing together of partial studies of a complex nonlinear system can give a good idea of the behavior of the whole.”

— Murray Gell-Mann

“Complexity Thinking is best thought of as a way of continually generating multiple perspectives on issues.”

— Pearl Zhu, Thinkingaire: 100 Game Changing Digital Mindsets to Compete for the Future

“Let us keep the discoveries and indisputable measurements of physics. But … A more complete study of the movements of the world will oblige us, little by little, to turn it upside down; in other words, to discover that if things hold and hold together, it is only by reason of complexity, from above.”

— Pierre Teilhard de Charin, The Phenomenon of Man

“Simple is never that simple.”

— Philip Roth, American Pastoral

“We are glorious accidents of an unpredictable process with no drive to complexity, not the expected results of evolutionary principles that yearn to produce a creature capable of understanding the mode of its own necessary construction.”

— Stephen Jay Gould, Evolution and the Common Law

“I think the next [21st] century will be the century of complexity. We have already discovered the basic laws that govern matter and understand all the normal situations. We don’t know how the laws fit together, and what happens under extreme conditions. But I expect we will find a complete unified theory sometime this century. There is no limit to the complexity that we can build using those basic laws.”

— Stephen W. Hawking

"Complexity theory is really a movement of the sciences. Standard sciences tend to see the world as mechanistic. That sort of science puts things under a finer and finer microscope. In biology the investigations go from classifying organisms to functions of organisms, then organs themselves, then cells, and then organelles, right down to protein and enzymes, metabolic pathways, and DNA. This is finer and finer reductionist thinking. The movement that started complexity looks in the other direction. It's asking, how do things assemble themselves? How do patterns emerge from these interacting elements? Complexity is looking at interacting elements and asking how they form patterns and how the patterns unfold. It's important to point out that the patterns may never be finished. They're open-ended. In standard science this hit some things that most scientists have a negative reaction to. Science doesn't like perpetual novelty."

> — **W. Brian Arthur, Coming from Your Inner Self, Conversation with W. Brian Arthur**

"I actually enjoy complexity that's empowering. If it challenges me, the complexity is very pleasant. But sometimes I must deal with complexity that's disempowering. The effort I invest to understand that complexity is tedious work. It doesn't add anything to my abilities."

> — **Ward Cunningham, The Simplest Thing that Could Possibly Work: A Conversation with Ward Cunningham**

APPENDIX C: GLOSSARY OF ABBREVIATIONS

CAS	Complex adaptive system
ED	Emergency department
EHR	Electronic Health Record
LMIC	Low- and middle-income country
NGO	Non-government organisations
NHS	National Health Service
PARiHS	Promoting Action on Research Implementation in Health Services
P-G	Person-group
P-O	Person-organisation
RCT	Randomised controlled trial
$SI = \int(e, c, f)$	Successful Implementation = function of evidence, context and facilitations
SNA	Social network analysis

APPENDIX D: GLOSSARY OF TERMS

Adaptation: The capacity to adjust to internal and external circumstances; usually thought of in terms of modifying behaviours over time.

Agents: The individual components of a complex system, whose capacity for sense-making means they can learn and adapt their behaviours across time.

Attractor: The structure or behaviour of a complex system that make it consistently pull, usually toward some stable state; in CASs, a tension that draws things together.

Bridge: Someone who spans two clusters, teams, networks, or other formal or informal organisational entity.

Broker: A network role; someone who acts as an intermediary between unlinked actors or clusters.

Coevolution: Individual and organisational entities influence others and their environment, and adapt in response to others and environmental conditions in mutually-affecting ways.

Complexity: The behaviour embedded in highly composite systems or models of systems with large numbers of interacting components (e.g., agents, artefacts and groups); their ongoing, repeated interactions create local rules and rich, collective behaviours.

Emergence: Behaviours that are built from smaller or simpler entities, the characteristics or properties of which arise through the interactions of those smaller or simpler entities; the larger entities are one level up in scale, and manifest as structures, patterns or properties.

Feedback loop: A recursive mechanism creating reciprocal behaviours which "feed back" in on of themselves. A positive (self-reinforcing) feedback loop increases the rate of change of a factor, creating more of its own output. In a negative (self-correcting) feedback loop, the output creates input to dampen the change or modulate its direction.

Gatekeeper: An individual within a network fulfilling the role of bridging a formal or informal organisational divide. He or she controls what information passes between the bridged entities.

Network: An interlocking web of relationships at varying levels of scale in a system; the agents or artefacts are the nodes and the relationships between them are lines or vectors, which together describe the structure of the interactions of the network's membership.

Organisational culture: The sum of the shared values, attitudes and beliefs across an organisation (e.g., across a hospital).

Path dependence: Current events and circumstances are influenced by, and sometimes determined by, prior events and circumstances, harking back to the origins of the entity or system; path dependence underpins the fact that "history matters".

Person-group (P-G) fit: The compatibility between an individual and their work group or groups. The exact proponents of this "group" will depend on the job and the nature of the individual's work.

Person-organisation (P-O) fit: The compatibility of a person (e.g., employee, intern or volunteer) and his or her organisation. It occurs when an entity fulfils the needs of the other; or they share similar characteristics; or both.

Perturbation: An internal or external disruption or unexpected event which affects normal patterned behaviours, structures or processes; often thought of as an external disturbance or interruption to the current state-of-affairs.

Phase transition: The rapid transition of a system's state to another state; this manifests as a discontinuity, with the new state exhibiting different characteristics from the prior state.

Scale-free: This describes systems that follows a power law, and its parts, consequently have scale-invariant correlations between them, meaning that events of all magnitudes can occur and there is no characteristics scale for the system.

Self-organisation: The way in which agents interact relatively independently to coordinate their circumstances, workplaces, processes and procedures, such that they order their work and they autonomously, or semi-autonomously, organise their localised behaviour. This can occur passively or actively.

Sense-making: Methods by which individuals figure out what's going on around them; a social process among agents in which they come to a shared meaning of their experience.

Social network: A set of people who have relationships, communications, ties or interactions which connect them.

System dynamics: An analytical modelling methodology used for problem solving, which combines qualitative and quantitative data and identifies the fundamental elements of a system, and how they influence one another over time.

Universality: The fact that very different systems (human social systems, cells, neural networks) can display similar patterns of behaviours and properties.

***Tertius gaudens*:** The "third who enjoys"; this is a broker in a network who keeps others apart, typically to increase his or her own place in the system and social capital.

***Tertius iungens*:** The "third who joins"; this is a broker in a network whose strategy is to join others together to improve the performance of the network.

Workplace culture: The sum of the shared values, attitudes and beliefs across a part of an organisation (e.g., across division of a hospital).

A note on contributions

JB led the project and drafted the front and back-end sections of the manuscript and edited or developed the other sections in conjunction with KC. He co-wrote the sections *Toward a framework for complexity in healthcare, Conceptual fuzziness in applying research findings in CASs* and *Implications*, and wrote the *Introduction, Conclusion,* and sections *Complexity and linearity, Complexity and emergence, Complexity and implementation science,* and *Complexity science in action: Learning from theory and practice.* KC researched much of the document, supported its development, co-wrote sections *Toward a framework for complexity in healthcare, Conceptual fuzziness in applying research findings in CASs*, and *Implications,* and wrote *Complexity in low- and middle-income countries* and *Distributed control and organisational complexity in healthcare.* LE co-wrote the *Implications*, and then contributed the section asking *What have we accomplished with complexity theory in the past?* JL co-wrote the *Implications*, and developed the section on *Complexity and networks.* RCW contributed the section on *Complexity and resilience.* ND contributed the section discussing *The actors who matter in a complex adaptive system.* JH developed the section on *Complexity and culture*, while CP drafted the section *Complexity and uncertainty.* KL performed the searches to extract images and voices of complexity (Appendices A and B), synthesising their common themes in *Images and words of complexity.* All authors contributed to revisions of the manuscript and agreed upon the final version.

About the authors

The Complexity Science Team in the Centre for Healthcare Resilience and Implementation Science at the Australian Institute of Health Innovation, Faculty of Medicine and Health Science at Macquarie University is examining how complexity science can be applied to healthcare settings.

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Dr Louise Ellis, BPsych (Hons), PhD is a Research Fellow in the Centre for Healthcare Resilience and Implementation Science, Australian Institute of Health Innovation, Macquarie University, Australia. Her current research interests are primarily in the application of complexity science to healthcare and using social-psychological theories to understand hospital organisational culture. Originally qualified as a registered Psychologist, Dr Ellis started her career in clinical roles, with a particular focus on youth mental health. From 2007 to 2016, Dr Ellis worked on innovative projects at The University of Sydney aimed at improving mental health services for young people. Specific areas of interest include: mixed-methods research, innovative technologies, peer support, youth mental health, health systems improvement and resilient health care. Dr Ellis has published in leading international journals, has been successful in attracting research funding, and has presented at international conferences in her field.

Dr Janet Long, BSc (Hons), MN (Ed), CertOpthNurs, PhD, **FISQua** originally qualified as a registered nurse before studying Biological Sciences at Macquarie University. She completed a Masters of Nursing (Education) at UTS, and her last clinical role was Clinical Nurse Consultant at Sydney Hospital and Sydney Eye Hospital. In 2014, she moved into health services research, undertaking a PhD that used social network analysis to evaluate how a new translational research network increased collaborative links across hospital and university silos. Dr Long is working on several projects in implementation science and complexity, including used a behaviour change approach to improve management of people flagged at high risk of Lynch syndrome, a hereditary cancer. She is working with the Australian Genomic Health Alliance, on multiple projects, including using a social network lens to quantify and analyse the Alliance as a complex adaptive system. Dr Long is a member of the Cognitive Decline Partnership Centre and has completed three projects with this group using her expertise in social network analysis.

Dr Robyn Clay-Williams, BEng, PhD is a specialist in health systems research and resilient healthcare, working as a Research Fellow in the Centre for Healthcare Resilience and Implementation Science, Australian Institute of Health Innovation. Prior to her work in health services research, she was a military test pilot, an electronics engineer, and flight instructor. Dr Clay-Williams transitioned to healthcare seven years ago through a PhD, which in internationally recognised work, translated aviation teamwork concepts to healthcare via a randomised controlled trial evaluating a Crew Resource Management based training intervention. She has produced over 80 peer-reviewed research outputs. Her current research fellowship is in the field of human factors and resilience in healthcare, where she is investigating methods for improving productive safety in hospital ED. Specific areas of interest include teams and teamwork, decision-making, leadership, simulation, resilience engineering, and usability test and evaluation of medical devices and IT systems.

Dr Nikki Damen, PhD is a Visiting Postdoctoral Research Fellow in the Centre for Health Care Resilience and Implementation Science, in the Australian Institute of Health Innovation, Macquarie University, Australia. Dr Damen was visiting from the Netherlands, at the time of the publication of the White Paper. Previously, she worked as a postdoctoral research fellow at the Dutch Institute for Health Services Research. Her research is primarily focused on medication safety, and specifically the organisation and quality of care around anticoagulation medication. She is involved in research on the development and implementation of guidelines for medication care, and the application of innovative methods (such as 'FRAM') to examine work-as-done in everyday medical practice. The research involves both quantitative and qualitative research methods, including surveys, focus groups, and semi-structured interviews. She is also involved in the supervision of PhD-students in the Netherlands. Dr Damen undertook her PhD between 2010 and 2014; her thesis focused on the psychological wellbeing of patients who underwent coronary stenting procedures, utilising large-scale surveys.

Ms Jessica Herkes, BSc (Adv) is a Master of Research Candidate and Research Assistant in the Centre for Healthcare Resilience and Implementation Science, in the Australian Institute of Health Innovation, Macquarie University, Australia. Her research interests include health system sustainability, organisational culture, organisational psychology, person-environment fit, and complexity and implementation science. Her Master of Research project includes qualitative and quantitative methods to examine the perceptions of compatibility of employees with their environment, and how this impacts patient outcomes. She has published in journals such as *BMJ Open*, and her work has been presented at international conferences.

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