Graceful Collapse – Part 3: Dynamic Reconfigurability and Resilience in Complex Systems

1. TRADITIONAL DEFENCES AND SYSTEM RECONFIGURABILITY

In Part 1 and Part 2 of this blog series I have looked at the potential contribution of traditional 'predict and withstand' defences in technical systems to resilient performance. If you haven't stumbled across these defences in the other parts yet, they are:

- Redundancy – having more than one system that can perform the same function
- Segregation – splitting a system up
- Diversity – having more than one system that performs the same function, but are different from one another
- Resistance – the inherent capacity of a system to withstand whatever is thrown at it

Parts 1 and 2 explain that we can be surprised by the performance of traditional defences to deliver measure of resilience, even when situation is outside what the system was originally designed to cope with. Also, that traditional defences can even provide some relief in the face of the pernicious, cascading effects of common mode failures. So the good news is that despite some clear limitations, traditional defences can offer some protection from complex and unforeseen disturbances.

The ability to reorganise a system on the fly in response to a changed situation is critical to provide this capability to respond to unforeseen events. The resilient capabilities afforded by traditional redundancy, segregation and diversity strategies lies in their potential for reconfiguration of system elements and to change the way they are connected. So, while limited, traditional systems can let us reorganise them by the activation or deactivation of system elements, or by enabling choices over which connections to use. Resistance as a defence works a little differently to provide a resilient capability, by changing the inherent strength of elements. Still, this is a form of reconfiguration.

All good – but in exploring this logic we can see that the limited capability typically offered by traditional defences to support resilient performance is really only an accident of design that can be exploited when the going gets tough. Unfortunately, traditional defences will readily become overwhelmed by unforeseen events without a good deal of luck. And when I look to the future to a world of ever increasing complexity, I'm not convinced that luck is the weapon of choice to deliver any semblance of a future utopia.

So what happens if we take this logic of reconfigurability of defences to the extreme? Could we imagine a system where we design in the capability to dynamically increase or decrease each type of defence? Could this type of system plasticity be advantageous for responding to unforeseen disturbances in complex systems and environments? And what are the inevitable downsides?

I think we need to start with a basic assumption underpinning the ideas discussed here. Here goes:

1. ***Brittleness is bad***. Any system that is fundamentally brittle is fragile. When it is exposed to a stressor it won't yield and return to its original form, or remould itself into something new – it will break. As disturbances are a type of stressor, fragile systems are not capable of resilient performance as they fail when stressed beyond their design limit.

2. ***Plasticity is good***. I'm not just talking about the common garden variety of plasticity being able to yield and recover to its old form when stressed (although that's part of it). I'm also talking a deeper, more fundamental ability to temporarily or permanently reorganise and reconfigure the underlying architecture on which a system is based, and the elements within it, in order to preserve function. Let's call this **deep plasticity**.

In this discussion, it is still useful to think of systems very simply as a series of inputs, processes, and outputs. This brings our focus to the mechanics of how systems do what they do to achieve their goal. It all comes down to the functionality of the parts that together deliver the objective of the whole. This way of thinking is useful at micro, meso and macro scales, and also to explore links in between scales as well.

This perspective on systems helps us understand the effects of disruption and how systems can respond, i.e. how they:

- Adapt to varying levels of input – famine or feast
- Retain an ability to utilise inputs, perform processes, and generate outputs when needed
- Adapt to varying demand or capacity to store outputs

So in terms of what systems do, when any of the input, process, or output phases are disrupted, the ability of that system to completely and reliably deliver its function is usually diminished. What traditional defences do in this context is to provide protected or alternate means to preserve system functionality in the face of disruption. E.g. more engines on an aircraft, more resistant bridge designs, and so on.

2. DEEP PLASTICITY FOR RESILIENT PERFORMANCE

So let's explore how deep plasticity (i.e. dynamically reconfiguring the quantity of each the traditional defences) could be useful in terms of preserving the capability to respond to disruptions in input, process, or output, and retaining system functionality.

In the Table 1, I explain what it means to add to or remove redundancy, segregation, diversity, and resistance, what effect on resilient performance might be achieved, and provide real world examples from a number of domains. Figure 1 shows a pictorial representation of what deep plasticity could look like in an actual system. It illustrates the result of changing the amount (i.e. more or less) of each traditional defence as a result of reconfiguration of system elements and their connections.

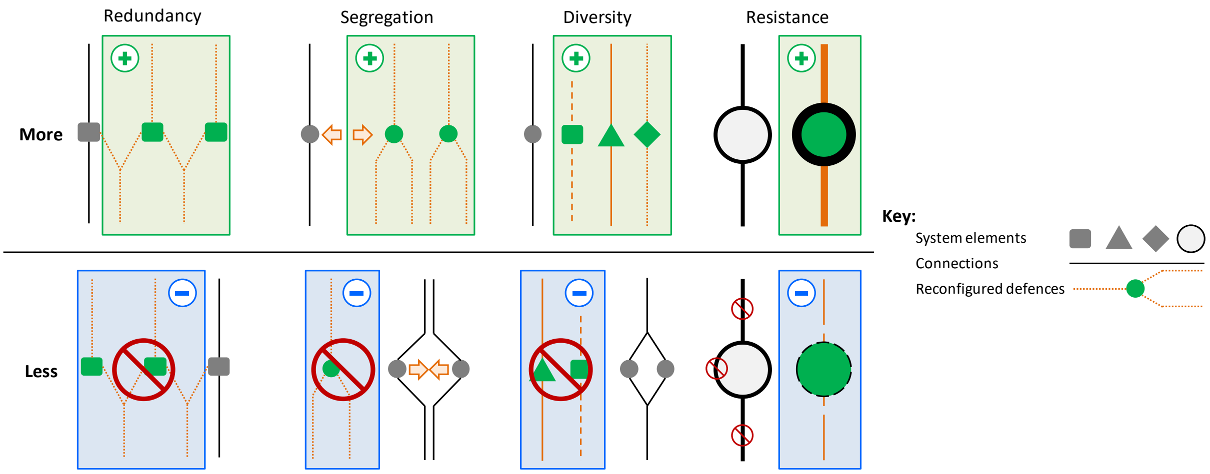

Figure 1. Reconfiguration of traditional defences in systems for resilient performance

Table 1. Summary of dynamic reconfigurability of traditional defences, the potential resilient effect, and examples

Defence	Dynamic Reconfigurability	Resilience Effect	Examples
REDUNDANCY: The capability to add or remove elements of the system to maintain, increase or reduce system function or capacity			
More	• *Physically add / bring on-line new elements to increase system capacity (i.e. 'plug and play')*	• Spread load / wear over more elements • Swap out damaged, malfunctioning, under-performing elements (while system is operating) • Extend operational envelope by increasing input, processing and output capacity	• Add production modules to keep up with spike in demand • Add coolers to keep up with increased heat load (e.g. nuclear power plant reactor cooling with warm intake water) • Add medical treatment centres to respond to a pandemic
Less	• *Take components off-line / physically remove elements from the system*	• Reduce the throughput by reducing number of systems operating in response to reduced availability of inputs or demand for outputs – Effective if the system's tempo / throughput cannot be sped up / slowed down (i.e. throttle-able) • Concentrate load / wear on some elements while leaving some in reserve (i.e. sacrifice some to protect later performance) • Effective where the disturbance affects functional pathways that can be quarantined and isolated from the rest of the system • Ineffective for a common mode failure affecting all elements in the system that provide a function	• Switch off aircraft engines in volcanic ash cloud to prevent wear • Take reactors off-line due to over warm cooling water
SEGREGATION: The capability to introduce / increase or eliminate / decrease separation of system elements physically or functionally			
More	• *Physically relocate system elements* • *Functionally disconnect or change the connection pathway of elements from inputs / outputs to a system*	• Retain system functionality by removing elements from areas affected or contaminated by a disruption and still have them functionally contributing to the system • Retain system functionality by changing connection to inputs / outputs that have been affected or contaminated by a disruption (i.e. Isolate / quarantine elements) and still have them functionally contributing to the system	• Move generators to higher ground to power pumps during flooding • Redistribute organisational functions to offices in other geographical areas outside of areas affected by an earthquake

Defence	Dynamic Reconfigurability	Resilience Effect	Examples
Less	• *Physically relocate distributed system elements to concentrate them in one geographical location (i.e. co-location)* • *Functionally connect elements to a single input / output or reduce the number of connection pathways (and still have them functionally contributing to the system)*	• Reduce physical distribution for more efficient to operation / maintenance • Enhance situational awareness of system operation and state for operators / maintainers by increasing physical proximity • Simplify connectivity of system elements	• Co-locate team members to enable verbal communication without reliance communication equipment • Run electrical equipment from a single large generator rather than numerous smaller generators to reduce cabling, fuel monitoring, maintenance burden from multiple units
DIVERSITY: The capability to increase or reduce the difference of elements within the system whilst maintain system function or capacity			
More	• *Introduce or increase heterogeneity of system elements (e.g. elements that operate differently from one-another, are designed and manufactured by different organisations, and/or use different inputs / outputs)*	• Reduces impact of common mode failures through increasing difference within the system – maintain operation in the face of a disruption affecting one type of input (e.g. temperature versus pressure)	• Add multiple power generation types to an electricity generation network to reduce impact of input scarcity (e.g. water for hydro power, coal, wind, etc.) • Use multi-disciplinary teams to aid problem solving in complex and novel situations • Permit the manufacture of generic drugs to increase and distribute manufacturing capacity in the case of pandemic • Use phone chargers that can operate on both 120 V and 240 V electrical networks eliminating the need for multiple chargers • Use on-site additive manufacturing to reduce reliance on single supply chains for spare parts

Defence	Dynamic Reconfigurability	Resilience Effect	Examples
Less	- *Eliminate or reduce the heterogeneity of system elements (e.g. elements that operate similarly or identically to one-another, are designed and manufactured a single organisations, and/or use common inputs / outputs)*	- Provides systems where knowledge can be reliably generalised to other identical / similar systems - Enhance operating simplicity - Reduces total systems complexity and competence requirements for different systems	- Operate an airline fleet of a single aircraft type to simplify operation, maintenance, spares management and reduce human errors from similar but different design philosophies
RESISTANCE: The capability to increase or reduce the inherent capacity of a system to withstand exposure to stressors and disturbances			
More	- *Strengthen / reinforce / protect elements against a stressor beyond the design basis of the system element*	- Strengthen systems to retain functionality during exposure to greater energy (e.g. weight, pressure, speed, temperature, etc.) - Provide resistance to a new type threat not considered or integrated during design	- Add sandbags to heighten flood banks extending their operational envelop to prevent overtopping - Cover equipment to prevent damage by contaminants (e.g. volcanic ash)
Less	- *Weaken / eliminate elements against a stressor below the design basis of the system element*	- Remove functionality of a system component by destroying it (sometimes temporarily) in response to conditions unanticipated during design	- Break though flood defences to allow water to drain from inundated areas

3. FIGHTING FIRE WITH DEEP PLASTICITY

In a complex problem space, I think it would be foolhardy to presume by just adopting any one single approach from the table above to promote deep plasticity would be sufficient to pave the way for significant gains in resilient performance. Maybe, maybe not. It would depend on the system and the context in which it operates.

By introducing deep plasticity by extending the application of traditional defences, there is an opportunity under our noses to address complex problems with positive effect using approaches we actually know a lot about, but haven't used in this way before. Traditional defences do this by providing people the opportunity to work innovatively within much less constrictive technological bounds to more effectively respond to unforeseen and extreme events to achieve better outcomes.

In a way, deep plasticity is fighting fire with fire. Complexity and uncertainty present very big and slippery challenges. But if our systems afford just a little more reconfigurability that outpaces the rate of change demanded by a disturbance, we might just be able to outmanoeuvre it get ahead of the flames.

The changes needed to reorganise a system effectively might not be pretty – perhaps nothing more than a bodge[1]. But if by building systems with inherent bodge-ability we are better able to sustain functionality to minimise harm or maximise performance, then they have done their job in contributing to resilient performance.

You never know, we may even find that integrating reconfigurability into system defences may also enable different, more flexible ways of working day to day. This could have benefits in itself, but this needs to be demonstrated.

4. NO SUCH THING AS A SILVER BULLET

It is always important in a discussion like this to remind ourselves what our real socio-technical systems look like. System functionality is delivered by actual people and stuff working together. The stuff of systems these days can be all sorts of things like the hardware of technological systems, the software they run on, regulations, and organisational processes, policies, and procedures that govern and direct the human interaction with them. Also, our systems exist in a context where all their elements and the environment in which they sit co-evolve together over time[2].

With this reality check in mind, I want to highlight a couple of significant potential implications for the usability of reconfigurable systems. While developing deep plasticity in systems presents a significant and new technological challenge, it also presents significant human factors challenges, especially in terms of competence requirements and maintaining situation awareness. Greater complexity and changing system configurations, especially in the aftermath of a disruption, could be difficult for people to keep up with. This could provide opportunities for decision errors, and make retaining a cohesive response with mutually understood objectives increasingly difficult.

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[1] To make or repair something badly because you do not have enough time or the right materials to do it properly (Macmillan Dictionary; http://www.macmillandictionary.com/dictionary/british/bodge)

[2] For more on the concept of co-evolution of engineered systems see 'Mirce Functionalbility Equation' by Dr Jezdimir KNEZEVIC Int. Journal of Engineering Research and Applications ISSN : 2248-9622, Vol. 4, Issue 8 (Version 7), August 2014, pp.93-100

So it would be naive to assume that introducing dynamic reconfigurability to hardware systems is a silver bullet with no penalties. Life is never that simple. Deep complexity comes with the penalty of greater complexity that could have profound effects on the global usability of the system if not carefully managed. Fortunately, we know how to do that! The application of human factors to guide design, operation and maintenance over the entire lifecycle of the system is absolutely essential to provide that reality check. At least in part, the human factors of systems capable of resilient performance is the human factors of bodge-ability.