Complex Systems

Complexity theory is a branch of science that investigates the rich, collective properties and dynamics of complex systems. Such a system is characterised as consisting of many sub-units that interact in such a way that they produce macro-level patterns, structures and properties that cannot be inferred from an understanding of these individual parts alone. Emergence is the process by which these features arise (Goldstein, 1999) and the spontaneous order that emerges is said to be self-organising (De Wolf and Holvoet, 2004). For an exploration of how simple rules can create rich behaviour see Wolfram's work on Cellular Automata (1984, 2002). Because the formation of order is distributed throughout the system and is a product of its constituent parts and their logic, these systems are robust to perturbations as they are able to dynamically adapt to a changing environment (Kitano, 2004). A key mechanism that facilitates this is feedback: where output is re-used as input by the system that produces it (Franklin et al., 2001). It can be reinforcing or inhibiting and can even occur between different levels of organisation. That is to say that it is possible for sub-units to generate emergent behaviour that they then react to; this type of macro to micro feedback is called co-evolution (Kallis, 2007).

This paradigm was a response to the insufficiencies of reductionism to account for the non-linearity of dynamic systems. The traditional approach to inaccuracies in scientific models was to study smaller spatial and temporal scales, in the belief that faults lay in the impreciseness of measurement, and later that inherent stochasticity was to blame. The mathematical-physicist Lord Kelvin claimed in 1900 that, "There is nothing new to be discovered in physics now. All that remains is more and more precise measurement" (Weinberg, 1987). It was not until the second half of the 20th century that the study of non-linear dynamic systems and chaos theory began in earnest (Lorenz, 1972; Gleick, 1987). While the two fields are not to be equated, we should note that over time it has come to be accepted that focusing on sub-unit functionality is insufficient for understanding behaviour. Instead we must look to the dynamics and interactions of a system for insight.

Arguably we should see complexity theory as offering an alternative perspective, it being a scientific technique for explaining the dynamics of systems we do not comprehensively understand. However, it is a useful and underappreciated one that has started to gain traction in the field of theoretical neuroscience over the last 20 years.

Ordered, Critical, and Chaotic Regimes

Complex systems can be described as operating in three different regimes: ordered, critical and chaotic (Gershenson, 2004). Each has unique global features that can be altered by parameters, which may be externally input or internally generated by part of the system (Haken, 2004). These states exist as a continuum, such that, as the parameters of an ordered system are adjusted, it reaches a critical point at which it undergoes a phase transition before becoming chaotic. This phase transition is the critical regime, otherwise known as the “edge of chaos”, which can be seen as an area of state-space between order and disorder. The criticality hypothesis postulates that the critical region provides the right balance between adaptability and robustness while maximising computational effectiveness (Langton, 1990; Bertschinger and Natschläger, 2004; Roli et al., 2017). In particular, the ability for a system to store, modify and transmit information. Previous work supports the claim that dynamical systems evolve to this point through their self-organising properties and feedback mechanics, such that the critical point operates as an attractor in biological systems (Kauffman, 1993; Mora and Bialek, 2011).

Characteristics of these phases are as follows (Gershenson, 2004; Roli et al., 2017):

Order: While in this regime, the system is stable and resilient to outside perturbations, meaning that similar states tend to converge, and changes are eradicated swiftly. Individual components tend to stay in the same state resulting in poor information flow and slow computational operations. Ordered systems tend to be highly segregated meaning that different areas are capable of performing specialised functions.

Chaos: In this phase, the system is incredibly sensitive to stochastic noise and perturbations; small changes can spread throughout the whole system leading to divergent state space trajectories (Shinbrot et al., 1992). Information transfer is fast but there is little coherence, as information is frequently corrupted. While this phase can hypothetically compute quickly, redundancies must be built in to deal with this instability. Chaotic systems tend to be highly integrated, meaning that different parts of the system are exposed to each other, allowing for functional synthesis.

Edge of Chaos: In this regime we have a compromise between the two previous regimes and their properties, where certain regions are more aptly described as chaotic and others as ordered. This creates the ideal conditions for effective transfer, modification and storage of information, as well as, system robustness and flexibility. The criticality hypothesis states that in this phase the system can optimally balance “mutational robustness and phenotypic innovation” making it more evolvable (Roli et al., 2017, page 14). The balancing of segregation and integration that occurs is central to functional connectivity (Sporns and Tonoshi, 2007).