Complex Systems Overview

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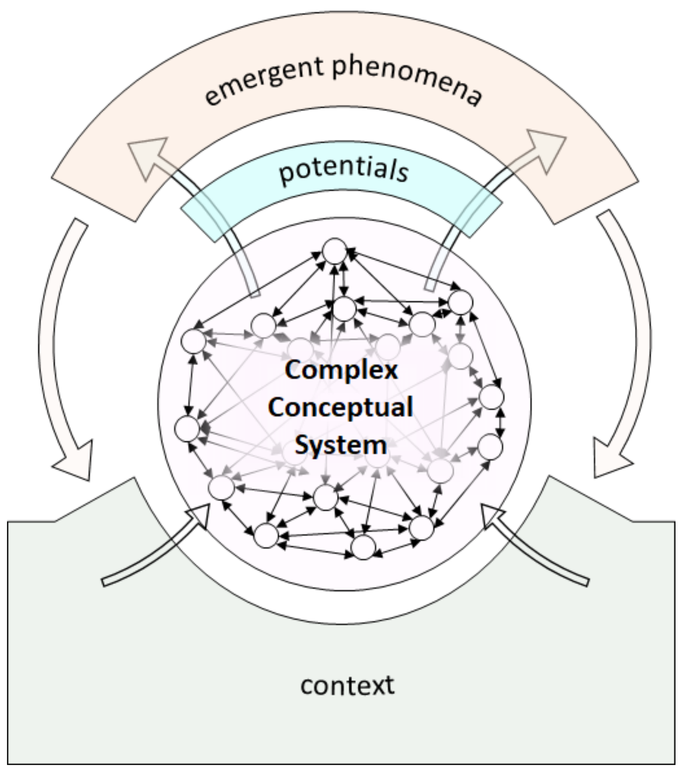
According to *The Guinness Book of World Records*, the largest recorded ant colony spans 6000 kilometers! How is it possible that these ants, no larger than grains of rice, are capable of producing such massive nests?! At the individual level, the actions of a humble ant appear to be quite banal and equally arbitrary; examining a singular ant, an observer could never predict the behavior and structure of an ant colony. The ant colony is a prototypical example of what is known as a complex system. It is only when the colony is viewed holistically, through observing the interactions between individuals and studying the emergent phenomena, that one could even begin to comprehend the system.

A complex system is a system with many elements in which knowledge about the individual elements and interactions cannot predict the complex nature of the system as a whole. The way that these elements (often referred to as actors, agents, or nodes) act and interact is often variable, but rule-based when observed at the individual level. Furthermore, these elements are strongly dependent on each other. The individuals within a complex system are interconnected and the interactions between them are often non-linear—meaning information can be transferred in more than one direction and from one individual to many (Bar-Yam, 2016). Furthermore, emergent phenomena of a complex system are a product of the interactions between elements, and cannot be explained through cause-and-effect deduction (Rowland, 2007). Consequently, within a complex system, the magnitude of an input cannot necessarily predict the output. Complex systems are collective behaviors that emerge as a result of the interplay of individual agents (Sherrington, 2010). Without emergent qualities, there would be no complex system, but simply the functioning of parts (Holland, 2014).



Another core tenet of complex systems is that such systems are organized without the presence of an external governing principle. The macro-level pattern could emerge from interactions at a lower level. Returning to the example of an ant colony, as the individual worker ants leave the nest and begin their odyssey in search of food, their trajectories are somewhat random. However, once these workers find a food source and take pieces back to the nest, they lay a pheromone trail for others to follow to the food source. Initially, there are many paths to follow—some are efficient, while others are long and convoluted. As workers arrive at the food source and return to the nest more quickly utilizing the more efficient paths, these pathways are more frequently selected for and their pheromone trails are strengthened in what is called a positive feedback loop (Jacobson, 2001). Eventually, all of the less frequented pheromone trails dissolve and optimal pathways are established. Therefore, the organization of the workers into their orderly march is not governed by an external principle, but rather, is emergent from the interactions between individual agents.

Complex systems stand in contrast to the idea of elementary physical phenomenology. Complex systems signature is in its *multiplicity* (Nicolis & Nicolis, 2012). For example, we know that due to gravity, any free falling object goes downwards. This is a well-defined fact with a single outcome caused by a single action of free-fall. However, we can not say the same for complex systems. Because, even though a single action may be followed by an initial cause, several different outcomes may occur in a complex system.

Complex systems are differentiated from two other types of systems: simple systems and complicated systems. Simple systems consist of few elements and complicated systems consist of many elements, but in both types of systems the relationships between these elements are linear and non-variable. In contrast, the associations between the elements within a complex system are interdependent and bidirectional (change in one element could diffuse throughout the system—a ripple effect); therefore, even seemingly minor influences can have significant effects. While the behavior of simple and complicated systems is predictable, the emergent phenomena of complex systems are non-linear and unpredictable. Simple and complicated systems can be studied through a bottom-up approach by reducing the subject matter down to its elementary building blocks and then rebuilding it from the ground up, inferring consequences along the way. The interdependence of elements within complex systems means that such systems cannot be reduced and studied by observing the system's component parts.

The interdependent nature of elements within complex systems begets states in which a system might be more stable through the influence of "attractors" or less stable through the influence of "repellors." Attractors describe systems in which the relationships between a system's elements provide positive feedback loops between one another, putting the system on a trajectory toward an attractor state. Repellors describe a system in which the relationships between a system's elements provide negative feedback loops and the interactions between elements produce tension within the system. This propels the system towards instability. According to Kunnen & van Geert (2012) complex dynamic systems typically self-organize away from repellors. In other words, many complex systems tend to behave toward equilibrium.

In order to better understand complex systems in the context of the real world, the researchers who study them often focus on examining the stability of the system. According to Bouchet, Thoms, and Parsons (2019), complex systems do not always operate in equilibrium conditions. Equilibrium of a system typically suggests that elements within a system are in harmony, and therefore, cannot be interrupted. However, sometimes even a minor change could lead to one of two scenarios: 1) the system goes through a phase transition after which the nature of the system is radically different than the initial state, or 2) significant entropy emerges, potentially causing the system to descend into disorder and rupture. Stability of a complex system is a measure of the resilience of the system in response to various inputs; therefore, evaluating the stability of a system provides insight into its ability to adapt and evolve as a function of the environment—the ability to regenerate and reorganize by itself (Brechet, 2012).

Complex Systems - Learning Activity Design Principles

- Help learners develop skills in differentiating "complicated" and "complex" systems, with an emphasis on identifying instances of emergence (which cannot be explained through linear cause-and-effect relationships).
- Engage learners in projects in which they analyze complex systems, particularly projects in which they can use their findings to develop ways of changing problematic complex systems.

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