Panarchy

Panarchy is the term coined to describe hierarchical systems where control is not only top down, as typically considered, but also bottom up [1]. Hierarchical organization is an important property of complex systems and is characterized by the vertical separation of low-frequency dynamics of large extent and high-frequency dynamics of small extent [2]. The partitioning of system dynamics manifests in the compartmentalization of structure and processes, which provides complex systems with common properties, including enhanced adaptive capacity and the ability to evolve faster than if the system were not compartmentalized [2]. Complex systems self-organize into hierarchies because this structure limits the possible spread of destructive phenomena (e.g., forest fires, epidemics) that could result in catastrophic system failure. Thus, hierarchical organization enhances the resilience of complex systems [2, 3].

A panarchy is composed of adaptive cycles, and an adaptive cycle describes the processes of development and decay in a system [1]. An adaptive cycle operates over a discrete range of scale in both time and space and is connected to adjacent adaptive cycles. Because adaptive cycles operate over specific ranges of scale, and a panarchy is composed of multiple adaptive cycles, a system's resilience is dependent upon the interactions between structure and dynamics at multiple scales [4]. The r-stage of an adaptive cycle is a period of exploitation of resources by system components. The r-stage is followed by the k-stage, which is characterized by the accumulation of system elements. Increasing connectivity during the k-stage leads to decreased resilience and collapse. This stage of collapse (Ω) unleashes the energy accumulated during the k-phase. Collapse during the Ω-phase is followed by reorganization during the α-phase, which is analogous to the pioneer stage in ecosystems. The top level of a panarchy is composed of a single adaptive cycle, and lower levels are comprised by a greater number of adaptive cycles, which are also compartmentalized from each other within a single scale. This within-scale compartmentalization adds resilience to panarchies by allowing experimentation and substitution [2]. In a hierarchy, lower-level structure and processes are dominated by higher levels in the hierarchy. Panarchy differs from this characterization of nesting as conditions can arise that trigger "bottom-up" change (i.e., cross-scale cascading) in the system [5]. For example, wetlands provide essential ecosystem services, such as flood control, aquifer recharge, and reserves of biodiversity. The cumulative effects of small-scale wetlands conversion has resulted in the degradation of ecosystem services at larger scales, as the impacts have manifested via cross-scale cascading [6]. This illustration of the "bottom-up" aspect of system dynamics demonstrates the importance of panarchy for characterizing social–ecological systems.

The self-organization of systems into hierarchies operates as a mechanism for systems to be resilient to perturbations [7]. Variables in a complex system interact with the system at distinct scales and create self-reinforcing patterns (through positive feedbacks) resistant to change [8]. Thus, the evolution of modularity or compartmentalization (e.g., hierarchy) should be expected in most systems that are at least partially closed [1]. Discontinuities are thresholds between levels of a panarchy, and may be expressed as gaps in rank-size distributions of variables in complex systems (e.g., city size in urban systems or species in ecological systems) and define aggregations of variables of similar size and frequency [9]. These size classes (i.e., aggregations) reflect the scales of opportunity (i.e., attractors) available in a given system [10]. The self-organization between variables (e.g., species) and a system (e.g., an ecosystem) drives the emergence of size classes of variables (e.g., species) of similar size and the emergence of scale-dependent structure [11]. In a world of increasing connectedness, understanding scale-dependent processes and structure is critical for navigating a turbulent future. Panarchy provides us with a powerful tool for unveiling the dynamics of scale-dependent structure and processes in complex systems.

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(*See also* **Cross-scale morphology**; **Adaptive management**; **Sustainability**; **Hierarchy theory, ecological**; **Cross-scale morphology**; **Community, ecological**; **Global ecology**; **Landscape ecology**; **Network ecology**; **Wildlife ecology**.)

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