Biological Robustness and Fragility

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Biological robustness and fragility are two fundamental properties of biological systems. Both properties are widely observed at all scales, from proteins, cells and biochemical networks to immune systems, organisms, and natural populations. In domains such as evolvable systems, biological organisms and complex diseases and therapy design, these two properties can provide us with a basic theoretical basis and guiding principles.

Biological robustness is a property that allows a system to maintain its functions despite external and internal perturbations[1]. An organism is always in a changing environment, but it can maintain a relatively stable internal environment that allows it to survive in a variety of environments, thus biological robustness is best reflected in an organism's adaptation to its environment. In terms of mechanisms, the main ones that find biological robustness are feedback, redundancy, modularity, and structural stability of biological systems. For instance, P53 is an oncogene in organisms that controls apoptosis and helps cells to repair defects in their genes, thus preventing cancer. Research has found that the P53 cell cycle and apoptosis control network is inherently robust to random knockdown of its proteins, implying resistance to mutational perturbations provided by the structure of the network itself[2].

In the biological world, robustness is integral part of survival for organisms. At different scales, possible perturbations include genetic mutations, localized stochastic fluctuations in molecular concentrations, loss of structural integrity, infectious diseases, endogenous threats such as cancer, temperature fluctuations, altered species interactions in the physical environment[3]. Robustness plays an significant role to the adaptive diversification of populations, allowing cryptic genetic variation to accumulate in populations that can later be adopted or adapted for rapid evolution in new environments[4].

Biological fragility is often used to characterise the sensitivity of a biological system to a disturbance and the difficulty of recovery. It has been reported that biological systems are typically more fragile against unexpected mutations. For instance, MyD88 is a key junction molecule in the Toll-likereceptor signalling pathway and has an important role in the transmission of upstream information and disease development. The immune system normally provides individual organisms with robustness against pathogenic threats, but it will be fragile under unexpected perturbations such as dysfunction of MyD88[5].

The consequences of biological fragility can be dramatic, not only for the individual organisms, but also for the larger system, which may be irreversibly affected. Within the marine ecosystem, coral reefs cover only 0.1% of the ocean's surface area yet are home to around 40% of marine species. The data suggest that some unexpected disturbances, such as El Niño and marine pollution, may cause widespread coral mortality, further jeopardising the species richness of the entire marine ecosystem.

To avoid biological fragility, both the systemic level and the micro level are areas that are being addressed by researchers. Studies have shown that biological robustness and fragility are correlated with each other. Of which Kitano suggested that the robustness and fragility trade-offs are fundamental to complex dynamic systems, especially the systems that are evolved to be robust against certain perturbations are extremely fragile to unexpected perturbations[1]. In recent years, a growing number of studies in this field that incorporate data-intensive computing are providing insights into biological systems.

At the macro level, the core approach is systematic ecological conservation. The scientific planning of ecological reserves and species conservation can significantly avoid the fragility of local ecosystems. Species diversity and species abundance have been significantly increased after several years of ecological conservation at the Guapiaçu Ecological Reserve (Brazil), while regular collection of data on climate, infectious diseases, etc. allows researchers to detect the current situation of the ecological environment and biological chain[6]. Meanwhile, a research at the Norwegian University of Science and Technology uses machine learning algorithms to predict the extinction risk of data deficient species with features including climate change, invasive species, and pollution[7]. Data science technologies can help to analyse fragile areas in biological systems in a more targeted way, to promote better conservation programmes.

At the micro level, studies have focused more on enhancing the adaptability of individual organisms to their environment through the study of biological traits, genes, protein receptors, etc., to further avoid the fragility of biological systems. Modern genetic engineering, such as transgenics, allows plants to be significantly more tolerant to abiotic stress conditions such as drought, high temperatures and high salinity, thus avoiding fragility to some extent[8]. In addition, with the development of AI techniques, computational biology has introduced AI algorithms to enable workflows ranging from protein structure analysis to drug development. In the near future it may also help to achieve the avoidance of vulnerabilities in biological systems.

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