Biological robustness and fragility

Xiao Xia (C2308025)

Introduction

Biological robustness is an essential property of biological systems. It refers to the ability of biological systems to maintain a certain function despite external and internal perturbations (Kitano, 2004). Mechanisms of biological robustness include system control, fail-safe mechanisms, modularity, and decoupling (Kitano, 2004). System control includes negative feedback and positive feedback. Negative feedback refers to robust adaptation to perturbations (Yi et al., 2000). Positive feedback refers to the amplification of the stimulus caused by the perturbations to achieve a bistable state that contributes to robustness (Ingolia, 2004). The fail-safe mechanism refers to that when a component of a biological system fails, it can be replaced by similar components or different components with overlapping functions to enhance robustness (Agrawal, 2001). Modularity refers to the mechanism that organisms can locally suppress perturbations to reduce the impact on the overall system (Simon, 1996). Decoupling refers to decoupling low-level changes with high-level functionality by buffering to reduce the impact of perturbation (Kitano, 2004).

In biological systems, robustness is achieved by continuously adding feedback controls to some general perturbations to attenuate their effects. This mechanism results in biological systems being extremely vulnerable to rare perturbations. This property of biological systems is called biological fragility. Biological robustness and fragility are considered conserved (Carlson & Doyle, 2002).

Examples of biological robustness and fragility

Bacterial chemotaxis is a typical manifestation of biological robustness. It means that bacteria can adjust the methylation level of their receptors and the activity of enzymes to adapt to the changes in the concentration of chemical inducers, so that they can adjust their behaviour according to the changes in the concentration of external inducers at the threshold of their sensory system, without being affected by the absolute value of the concentration of inducers (Barkai & Leibler, 1997).

Diabetes is a disease caused by biological fragility. Human blood glucose levels are robust and can resist the perturbation of a low food supply combined with high energy expenditure. But it also leaves the body fragile to perturbation in a state of high food supply combined with low energy expenditure, which can lead to diabetes (Kitano, 2004).

Biological robustness is an integral part of survival

Biological robustness is an important feature of biological systems. It exists in various basic biological processes, such as bacterial chemotaxis (Barkai & Leibler, 1997), cell cycle (Borisuk & Tyson, 1998), and developmental plasticity (Nijhout, 1998), which enables organisms to maintain specific functions in the face of external and internal perturbation.

Additionally, biological robustness is important for biological evolution. Evolvability requires the generation of a variety of non-lethal phenotypes and genetic buffering, while robustness can resist environmental and genetic perturbations, obtain mutation-specific robustness, developmental stability, and other characteristics, and promote evolution (Rutherford, 2003).

Consequences of fragility and countermeasures against it

Biological robustness and fragility are considered trade-offs. When biological robustness is gradually enhanced along with biological evolution, biological fragility will also be enhanced. Organisms will become more fragile in the face of some unusual perturbations, resulting in more deadly consequences and diseases, such as diabetes (Kitano et al., 2004). Moreover, the robustness mechanism in the organism means that even if a component of the system fails, it will still be protected because of its robustness, making treatment more difficult (Cassel & Pfeuffer, 1978). The primary countermeasure to biological fragility is to insulate organisms from the lethal environmental disturbances that target their fragility. Moreover, due to fail-safe mechanisms in robustness, we can reduce the impact of fragility by removing certain components that the system tolerates.

Conclusion and discussion

Biological robustness refers to the ability of biological systems to maintain certain functions in the face of external and internal perturbations, which is very important for the survival and evolution of organisms. Fragility is a property of organisms that are fragile to certain perturbations caused by the mechanism of robustness. Based on the mechanism of robustness and fragility, countermeasures can be designed to avoid the consequences of fragility. In future research, a mathematically reliable and unified theory of biological robustness can be established based on the research on robustness in engineering, physics, and chemistry. This could have major implications for understanding biological processes and creating treatments for diseases.

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