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Seven governing principles in biology

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In physical science such as physics and chemistry, there are governing principles that are universal and applicable to all relevant systems, including energy conservation, entropy increase, uncertainty principle in quantum mechanics, and chemical equilibrium. However, what are governing principles in biology that are unique to all living systems? After collecting opinions and thoughts from diverse scientists and engineers all over the world, I summarize seven governing principles or laws in biology: central dogma, evolution, biological robustness, regeneration, reproduction, development, and causality. Some of these are not necessarily unique in biological systems from a reductionist's point of view (e.g., causality), and others are applicable predominantly to eukaryotes (e.g., reproduction and development). Notably, many engineering systems have mimicked biological systems to enhance their performance. In this perspective article, I discuss these principles to better understand the rules of life and help construct improved engineering systems that we can use and control in an ethical, safe, and rational way.

KEYWORDS

central dogma, evolution, biological robustness, regeneration, reproduction, development, causality, engineering system

1 Introduction

We constantly ask questions regarding our meaning of existence. To partly answer these questions, we have studied our physical world, discovering governing principles in physics and chemistry, including thermodynamic laws in chemistry, chemical equilibrium principles, uncertainty principle in quantum mechanics, Einstein's relativity theory, and Newton's laws. These principles are elegant, simple, and universal. However, are there such laws in biology? If so, what are such governing principles that are unique to biology? I have asked these questions almost every day since 1991, and I have recently collected researchers' opinions and insights, while traveling for more than 300 days and interacting with diverse people since November 2021. In this article, I summarize biological principles that are unique to living systems. In addition, I discuss engineering systems that mimic these biological principles to enhance their performance. Such discussions will deepen our understanding of the rules of life and help create better and safer engineering systems such as artificial intelligence and ChatGPT (Silver et al., 2016; Michaud et al., 2022; Gao et al., 2023).

2 Central dogma

There is no doubt that central dogma should be one of the governing principles in biology. Genetic information is transferred from DNA to protein by transcription and translation, and this information transfer is the core of modern molecular biology. Interestingly, the information age or the use of the word "bit" for "binary digit" began with Claude Shannon's seminal paper in 1948 (Shannon, 1948), 5 years prior to the discovery of the DNA double helix. DNA replication is related to the fourth and fifth principles, regeneration and reproduction, respectively, which will be discussed later. I found that researchers generally think about genetic information transfer, rather than DNA replication, when they mention central dogma. Thus, I focus on the information transfer in this section.

Scientists first saw the biological alphabet ATGC 70 years ago, well summarized by and culminated with the discovery of the DNA helix structure (Moon, 2023). The Sanger and next-gen DNA sequencing technologies have then allowed researchers to read the alphabet, words, sentences, and paragraphs. With DNA synthesis technology, researchers have written letters, words, sentences, and poems, facilitating the discovery of the rules of life. Combined with state-of-the-art technologies such as CRISPR genome or base editing (Jinek et al., 2012; Jiang et al., 2013; Komor et al., 2017), DNA can now store information, including a huge number of books, music, and data (Church et al., 2012). Interestingly, the early synthetic biology studies focused on mimicking digital electronic circuits (Elowitz and Leibler, 2000; Gardner et al., 2000; Moon et al., 2012), and now digital information is being stored using DNA (Sheth et al., 2017; Lin et al., 2020). Notably, biological systems are more analog than digital, and the genetic information flow, governed by central dogma, should be understood in an analogous manner (Daniel et al., 2013), rather than ON and OFF of gene expression although different levels of abstraction and digitalization can facilitate our understanding of the complex biological systems (Shen-Orr et al., 2002; Endy, 2005).

3 Evolution

Evolution makes living organisms unique, compared to other physical and engineered systems. Evolution means changes in genetic information typically over a long time. Although other physical systems also change or degrade over time, the unique aspect of evolution is the selection of adapted organisms in response to environmental changes. With directed evolution technologies that use a variety of selection pressures in a short period (Arnold et al., 2001), the field of synthetic biology has advanced significantly. However, with metabolic burdens and intrinsic selection pressure that lead to the accumulation of loss-of-function mutants, evolution is the most challenging problem that bioengineers have faced and will face (Rottinghaus et al., 2022). Notably, the concept of evolution has been adopted by other fields of study such as genetic algorithms in computer science (Renner and Ekárt, 2003), but evolution is a sword with two edges for biological researchers who are optimizing genetic circuits by directed evolution and trying to ensure their mutational stability, as well as computer scientists who are developing self-evolving artificial intelligence that can both benefit and potentially harm humans.

4 Biological robustness, homeostasis, or biological control

Biological robustness is the ability of biological systems to maintain their functions against perturbations and uncertainty (Kitano, 2004; 2007). This is truly unique to living cells, and many engineered systems mimic living organisms to achieve this ability, including thermostats, airplane controllers, car cruise controllers, and pH controllers for fermentations. Biological robustness is also a comprehensive concept, including homeostasis and biological control (Aoki et al., 2019). In essence, biological robustness is characterized by the entropy decrease within the living system while the bigger increase of entropy occurs in the surrounding environment. Unfortunately, biological robustness is achieved by spending a lot of energy, and reckless human activities have caused many global issues, including climate crisis, pollution, food shortage, pandemic, and quickly diminishing resources (Moon, 2022).

We should discover new ways to live without sacrificing our planet. For example, I view the entire planet as a huge living system where diverse individual organisms (acting as a cell of the "multicellular" planet) used to maintain biological equilibrium (e.g., prey-predator population oscillation) or robustness through material recycling (e.g., plant or bacterium growth on dead creatures as discussed below). However, our planet may be approaching the tipping point of a catastrophic collapse by only boosting cancerous growth of humans and destroying diverse other "cells" of the multicellular planet. As I have previously proposed (Moon, 2022), nitrogen-fixing bacteria can replace chemical nitrogen fertilizers (Temme et al., 2012), food supplements such as lycopene can be bio-manufactured from plastic waste (Diao et al., 2023) instead of extracting them from foods, and bacteria might help humans keep warm without using too much petroleum-based energy (Dhatt et al., 2023). In this way, biological robustness of the planet and humans can be maintained hand in hand.

5 Regeneration

Regeneration is another unique biological process, as T.S. Eliot describes April as "the cruelest month, breeding lilacs out of the dead land" in the Waste Land. With the decomposition and degradation of dead bodies (i.e., entropy increase), new creatures are born and grow (i.e., entropy decrease inside the living cells with its increase outside these cells). This process occurs universally, including the growth of plants, fungi, and bacteria using depolymerized biomass and waste and that of the plant scavenger such as herbivores. The regeneration process has even inspired many art pieces and movies, including the movie Matrix where humans' metabolic energy is exploited by the machines. Unfortunately, humans have recently generated more waste than the entire living systems can use for their regeneration in a timely manner. However, synthetic biology can harness its engineering power to address this issue by developing waste valorization technologies, processes for capturing carbon dioxide, and plastic-eating microbes (Yoshida et al., 2016; Liew et al., 2022; Moon, 2022).

6 Reproduction

In addition to regeneration that recycles materials and energy of typically dead bodies and waste to produce new components of living cells, reproduction is unique to biology in that reproduction typically requires male and female. However, reproduction is not necessarily universal because it is mostly limited to eukaryotic cells. From mating yeasts to love-making people, this reproduction process also allows for DNA recombination, contributing to genotypic and phenotypic diversity and evolution. For humans and some animals, this biological characteristic is linked to one of the basic instincts, triggering complex emotions and sometimes challenging issues.

7 Development

Although not necessarily universal, another unique rule is that living systems, especially eukaryotes, have a developmental process. Although even a microbial community from a single ancestor often consists of differentially "developed" cells (e.g., antibiotic-susceptible actively growing cells and antibiotic-resistant dormant cells (Dewachter et al., 2019)) and a photosynthetic bacterium can be developed into a filamentous structure consisting of photosynthetic and nitrogen-fixing cells (Berla et al., 2013), the development process is predominantly found in eukaryotic organisms. It can be hypothesized that multicellular systems have evolved from a community of cooperating single cells that originate from a single prokaryotic ancestor (Lyons and Kolter, 2015; Mizuno et al., 2022). Interestingly, in mammals, the development process is precisely controlled over the long period, making them unique (e.g., a new-born baby period, childhood, adolescent period, and adulthood). Notably, humans require not only biological development but also intellectual and social development through education, making us develop in a slow but unique way, compared to other organisms, although other animals also learn social behaviors such as dominance hierarchy (i.e., a ranking system within the habitat) and playing (e.g., dogs enjoying the company of other dogs).

8 Causality

Causality can be too general to be applicable to biological systems only. As the "butterfly effect" says that a butterfly's small movement can lead to a disastrous storm in an opposite part of the globe, causality is a term describing a cause and effect in physical, chemical, and biological worlds. Nevertheless, I include causality as one of the seven governing principles in biology because it gives living systems the meaning of existence or uniqueness: decision or choice and its resultant consequence. Perhaps, humans live to discover our meaning of existence although not all find it while living in this world. Living systems, from microbes to humans, also make decisions constantly by an intelligent process, gut feeling, automatically induced response, or stochastic gene expression. Each decision or choice also leads to a deterministic or stochastic cascade of cause-and-effect or choice-and-fate, influencing many biological processes discussed above, including those relevant to the other six governing principles. Notably, causality can sometimes be easy to predict (e.g., adrenaline increase in response to threats and bacterial chemotaxis), but it can often be very difficult to predict due to the complex gene regulatory or metabolic network as well as a complicated web of intercellular or interspecies interactions (Becskei and Serrano, 2000; Paulsson, 2004; Pedraza and van Oudenaarden, 2005; Austin et al., 2006; Ley et al., 2006). Despite the complexity in understanding or predicting causality, all current living systems may be the products of causality processed by evolution.

9 Conclusion

In this article, I discuss and summarize the seven governing principles in biology that have been collected from many researchers and thought leaders all over the world for almost 2 years while traveling and meeting them in person. Although some of the seven principles may be considered not unique in biology by some people (e.g., causality), others are unique and universal in biology (e.g., central dogma and evolution). Many engineering systems have mimicked biological systems to make them function better, and we have witnessed their amazing improvement. For example, ChatGPT and artificial intelligence have evolved through machine learning (Duan et al., 2019), and many engineering systems have been built and optimized such that they maintain their robustness under fluctuating conditions (Kitano, 2004; Kitano, 2007). With a plethora of new technologies, it is time to think about biological systems, including ourselves, to better understand humans and better control engineering systems. I urge readers to start discussing the ethical, societal, economic, and safety implications of these seven principles when developing and assessing engineering systems mimicking biological systems.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, and further inquiries can be directed to the corresponding author.

Author contributions

TM: Conceptualization, Funding acquisition, Investigation, Writing–original draft, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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