Article

A review on biological adaptation: with applications in engineering science

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Abstract

Biological adaptation refers to that organisms change themselves at morphological, physiological, behavioral and molecular level to better survive in a changing environment. It includes phenotype adaptation and molecular adaptation. Biological adaptation is a driving force of evolution. Biological adaptation was described from Darwinian theory of evolution to the theory of molecular evolution in present paper. Adaptive control and adaptive filtering were briefly described also.

Keywords biological adaptation; evolution; environment; adaptive control; adaptive filtering.

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1 Introduction

We often find some very interesting biological phenomena. For example, when we meet some of the brightly colored mushroom, we will know that it is definitely toxic; chameleon can change the body color and plant leaves will fall on the ground in the fall, etc. All these are attributed to biological adaptation. As early as in the 19th century, biological adaptation had been mentioned in the Lamarckian theory. Biological adaptation was further improved in the theory of Darwinian evolution. Thus biological adaptation was generally based on the Darwinian theory. In the Darwinian era, biological adaptation was interpreted at the phenotypic level, e.g., the structural, physiological and behavioral aspects of biological phenotype. Since the beginning of the 20th century, as the advance of molecular biology and molecular genetics, people began to focus on biological adaptation at the molecular level, i.e., interpreting biological adaptation to the environment through gene regulation.

Biological adaptation has significant implications and has been widely used in industry, aerospace, transportation, machinery, electronics, control technology, signal processing, etc., to design various adaptive systems that are mainly controlled by computer and mathematical procedures. Adaptive control and adaptive filtering, are two of the most important applications which have been used in automatic control and chaos elimination.

So far there are fewer special literatures on biological adaptation. In present study, we will review the development of the theory of biological adaptation, adaptation at both phenotypic and molecular levels, and adaptation in engineering science.

2 Evolution and Biological Adaptation

2.1 Lamarckian theory

As early as in the 19th century, the famous French naturalist Lamarck proposed the terminology “evolution” in his book, *Philosophy of Zoology*. He was the first scientist who has first proposed biological evolution (Li, 2009). Lamarckian theory argues that all the world's major organisms have originated from evolution, rather than from the creation of God. It holds that organisms evolve from simple to complex. Changes in environmental conditions will result in the relative adaptations of organisms. The diversity of the environment facilitates biological diversity. Moreover, Lamarck proposed two famous rules in evolutionary biology, "Use and disuse" and "Inheritance of acquired characteristics". He thought the two rules are not only causes of biological variation but also the process of adaptation formation. "Use and disuse" means that frequently used organs evolve, and not often used organs will gradually degenerate. "Inheritance of acquired characteristics" means that the acquired biological traits can be inherited by subsequent generations. For example, giraffe with a longer neck will in general give birth to offspring with a longer neck (Kronfeldner, 2007).

Lamarck believed that adaptation is the main process of biological evolution. He is also the first to propose the viewpoint that organisms adapt to the environment. Later, in Darwin's theory of biological evolution, biological adaptation to the environment was more fully discussed.

2.2 Darwinism

2.2.1 Natural selection and survival of the fittest

During the mid-19th century, after collecting a lot of basic evidence, Darwin published the book, *The Origin of Species*, in which the theory of biological evolution, with natural selection as the core, was created. It gave a comprehensive interpretation on the occurrence and evolution of the entire biosphere. Darwin proposed the central rules of his theory, natural selection and survival of the fittest (Lewens, 2010). He believed that all organisms compete with each other, and the organisms fitted the environment will survive and others will be eliminated. Following these rules, organisms evolve from simple to complex based on natural selection (Bradon, 1990; Kutschera, 2009).

The evolution of a birch moth in Britain can best interpret the Darwinism. The birch moth was of gray type before 1850. However, its black mutant was found in Manchester in 1850. After the late 19th century, with the development of industrialization, H_2S in the exhaust gas killed gray lichen on the tree bark, and coal smoke blackened trunk. As a result, the gray moths, originally resting on gray lichen for protection, were easily predated by birds when they rested on black trunk, while the black type of months survive and evolve. A rapid increase in the frequency of black type, and declining in gray type was thus recorded. By the end of 19th century, the former increased from less than 1% to more than 90%, and the latter decreased from over 90% to less than 5% (Gu, 2007). This is a classic example of Darwinian biological adaptation. We can find that the environment is inseparable from biological adaptation.

2.2.2 Modern theory of biological evolution

Modern theory of biological evolution is also called modern Darwinism. It is a theory appeared in the 20th century. It is based on the Darwin’s theory of natural selection, except that it argues that biological evolution is resulted from changes in the genetic frequencies of population. It further clarifies the essence of heredity and variations, and the mechanism of natural selection (Zou and He, 2001). Because adaptation is the result of natural selection, so this theory interprets biological adaptation as directional changes of genetic frequencies in population.

2.3 Adaptationism and anti-adaptationism

2.3.1 Adaptationism

Adaptationism has emerged since Darwin's theory of evolution was published and the thought that organisms evolve from adaptation to the environment and natural selection is widely accepted. Sponsored by Wallace and Weismann, it started to be popular in the early 19th century to the 20th century (Dong, 1999). Adaptationism holds that adaptation is the sole result of natural selection, and the formation of almost all biological traits is the result of adaptation (Resnik, 1997; Yu and Li, 2012).

2.3.2 Anti-adaptationism

Anti-adaptationism argues that adaptation/natural selection is not the only reason for biological evolution (Yu and Li, 2012). It holds that the behaviors, structure and functionalities of organisms could not be described by adaptation only. Among these, neutralism is the major theory.

2.4 Theory of molecular biology

Before the 20th century, people always interpreted biological adaptation by natural selection. Since the beginning of the 20th century, as the development of molecular biology and molecular genetics, molecular biologists have described biological adaptation with the genetic variations of organisms (Radwan and Babik, 2012), of which the most famous is the neutral theory of molecular evolution (Jukes, 2000).

3 Biological Adaptation

3.1 Definition

Biological adaptation is a driving force of evolution. The occurrence of biological adaptation is to counter the changing environment. From Darwinian theory of evolution to the theory of molecular evolution, biological adaptation has been discussed at phenotypic level and molecular level (Chen and Deng, 2001), which indicates the mechanism of biological adaptation is very complex. Nevertheless, these theories have a common basis, i.e., organisms change themselves, at morphological, physiological, behavioral and molecular level, in order to better survive in a changing environment (Smith, 1979; Zhang and Liu, 2006; Fenichela et al., 2011). The process adapting to the environment is called biological adaptation. Biological adaptation acts at different levels, from molecular to phenotypic levels, and its objective is to coordinate with the environment.

3.2 Adaptation of organisms to the environment

3.2.1 Universality of adaptation

There are various unpredictable and uncontrollable environmental factors. Organisms must adapt to the environment for surviving, otherwise they will extinct (Zheng, 2008). All organisms have their own adaptation traits in behaviors, or morphological structures, or physiological functionalities, etc.

3.2.2 Relativity of adaptation

On the other hand, biological adaptation is not absolute. The adaptation of an organism to the previous environment may become non-adaptive to the changed environment. The stability of genetic molecules is a reason for the relativity of adaptation. Genetic traits are steadily inherited by the next generation, so these traits and genetic molecules are unable to simultaneously follow the rapid changes in the environment. For example, domesticated rabbits wer evolved from wild rabbits. Burrowing habit of domesticated rabbits, inherited from wild rabbits due to the stability of genetic molecules, is not conducive to escape predators, as functioned by wild rabbits.

3.3 Interaction between organisms and the environment

Organisms adapt to the environment in order to survive. On the other hand, the environment may be changed by organisms. For example, the earthworm excretes nitrogen, phosphorus, and potassium, which can increase the fertility of the soil and improve the soil's nutrients.

4 Phenotypic adaptation

4.1 Phenotypic adaptation of plants

Plants adapt to various environments, e.g., cold, salty, warm, and other harsh environments, through morphological and structural changes in roots, stems, leaves, flowers, fruits, etc. To adapt to the environment, they must store water and oxygen, and resist other harsh conditions. For example, in order to store more water in its storing cells, xeric plants, such as cacti, has particularly well developed palisade tissue (Shields, 1951). Formation of mangrove’s breathing roots is to better reserve atmosphere. Leaves of tropical plants have relatively larger area for better transpiration, and so on.

4.2 Phenotypic adaptation of animals

4.2.1 Morphology

Morphological adaptation of animals includes camouflage, mimicry, warning coloration, convergent adaptation, divergent adaptation: (1) camouflage. It means that animals share the same or similar body color as the environment. For example, chameleons can change their body color to that of the environment to protect themselves from the enemy. (2) Mimicry refers to the similar appearance of an animal as other biotic/abiotic phenomenon, so that they can confuse the enemies and protect themselves. Flies and bees, for example, can imitate the birds and escape predation. (3) Warning coloration refers to that animals yield the body color (very bright or terrified color) remarkably contrasting to the environment to attract other animals’ attention and thus warn them. For example, the ladybug’s bright appearance reminds the production of a disgusting smell. (4) Convergent adaptation refers to that different species of animals have the same or similar morphological structure to adapt to their living environment (Ma et al., 2006). For example, the xeric plants living in the same arid desert environment, share similar morphological appearance, internal structure, life history characteristics, and physical characteristics, under the same or similar selection pressures. (5) Divergent adaptation refers to the biological adaptation of animals that the same species living in different environments evolves to form distinct morphological appearance and internal structure and so on.

4.2.2 Physiology

Physiological functions of animals are very important to the survival. Water, light, air, soil, temperature and other environmental factors affect the physiological functions. Camels live in arid environments. Their kidneys have strong ability of re-absorption. A special protein in the blood can reserve water under the condition of little water supply. Some animals’ hibernation is an adaptation to extreme temperatures, which helps to reduce metabolism in order to survive in winter.

4.2.3 Behaviors

The formation of some behaviors of animals is attributed to biological adaptation. For example, the gecko always breaks its tail to escape. Behavioral adaptation usually involves the biological stress. Stress refers to the biological response to external stimulation, e.g., the paramecium adapts to different temperatures by distinct behaviors (Duncan, 2011).

5 Biological Adaptation at Molecular Level

5.1 Neutral theory of molecular evolution

Neutral theory of molecular evolution was founded by the Japanese geneticist Kimura in 1968. The neutral theory of molecular evolution applies only for evolution at the molecular level. The theory holds that most evolutionary changes and most of the variation within/between species is not caused by natural selection, but by random drift of neutral mutant alleles (Kimura, 1968). A neutral mutation does not affect an organism's ability to survive and reproduce. The theory allows for the possibility that most mutations are deleterious, but holds that because these are rapidly purged by natural selection, they are not significant to molecular variation within/between species. Non-deleterious mutations are assumed to be mostly neutral (Masatoshi et al., 2010). The theory also assumes that the fate of neutral mutations is determined by the sampling processes described by specific models of random genetic drift (Kimura, 1983).

5.2 Adaptation mechanisms at molecular level

5.2.1 Regulation of gene expression

Gene expression is regulated in the process of from DNA to protein, including transcription and translation. In this process proteins are synthesized to maintain the desired mechanism for life activities. Genes express according to different needs, which makes organisms adapt to changing environments. For example, when a living body has a sufficient glucose supply, bacteria can utilize glucose as an energy and carbon source; they do not need to synthesize enzymes that use other sugars. Nevertheless, without enough glucose supply, bacteria will activate more genes to use other hydrocarbons present in the environment, such as lactose, galactose, arabinose, etc., in order to meet the needs of the body, or else they will die.

5.2.2 Gene mutations and gene duplications

Both gene mutations and duplications are popular in molecular evolution. Gene mutation refers to the additions, deletions, or changes in the order of arrangement of base pairs in genomic DNA, which causes changes in genetic structure. Gene duplication refers to the duplication of a DNA fragment containing the gene, also known as duplicated gene. Changes in genetic structure from mutations, production of new genetic functions and increase in expression of genes, contribute to the adaptation of organisms (Kondrashov, 2012).

In terms of gene mutations, the researchers have found two new gene mutations (EGLN1 and PPARA) which can help the mountainous Tibetan to contain less hemoglobin in the blood, in order to use oxygen more efficiently than people living in low-altitude areas (Simonson et al., 2012). As for gene duplications, white arm langur monkeys mainly eat leaves. It is found that the pancreatic ribonuclease gene of the leaf monkey, which is responsible for normal digestion, has duplicated. One of two genes is responsible for the production of pancreatic ribonuclease, and another duplicated gene produces other ribonuclease to digest other foods (Li et al., 2010).

5.3 Fitness

Fitness refers to the degree that organisms fit environmental conditions. Fitness is mainly measured by comparing the biological genotypes. Genotypes with great fitness will more likely be passed on to offspring (Ma, 1995).

6 Adaptation in Engineering Science

Biological adaptation has been recognized since Darwin’s era. Currently people are using the principles of biological adaptation to develop various self-adjusting techniques. These adaptive techniques try to adjust the system’s structure and behaviors by themselves, in response to the changes of environmental conditions.

At the early 1990s, German Aerospace Research Institute started to study adaptive technology in aerospace science (Li et al., 2010). Since then, adaptive technology has attracted attentions from various areas. At first, adaptive technology is mainly used in transportation and mechanics. Up till now it has been used in solid state physics, materials science, mechatronics, medical technology, aerospace, optical communications, machinery and equipment manufacturing, robotics, transportation machinery, electronic equipment, control lines, signal processing, and other industries.

6.1 Adaptive control

6.1.1 Theory

Adaptive control means that in confront of the uncertainty of the system, how to design an appropriate control technique to achieve the best performance of the system. Uncertainty of the system refers to that the structural parameters may be influenced by the environment, and other random factors. Dynamic models, usually (stochastic) differential/difference equations that include various feedback mechanisms, are developed to achieve adaptive control. By using adaptive control, the system automatically adjusts its parameters or structure to maintain a good performance.

6.1.2 Research overview

Adaptive control was proposed in the early 1950s. In adaptive control, the system operates by comparing the deviation between expected and observed outputs, i.e., feedback control. By the 1970s, with the advance of computer technology and the development of adaptation theory, adaptive control has been greatly developed, not only in the machinery industry, but also in other areas, such as chemical industry, medical science, and physics, etc (Liu, 2007). The main types of adaptive control systems include self-tuning regulator, model reference adaptive control systems, self-stabilization system, self-optimizing systems, self-organizing systems and learning control systems (Zhang, 2013). Of which the model reference adaptive systems and self-tuning adaptive control systems, are the most classic adaptive control systems.

A model reference adaptive system is mainly composed of reference model and controller. The output of the reference model is set as the expected output. By comparing the deviation between reference model and observed outputs, the controller fixes the state or parameters of the system, so that the output of the controlled system can maximally approximate the expected. Model reference adaptive control system is initially based on local optimization of parameters. Now it is used in the autopilot of aircraft and ship, toptical tracking servo-system of telescope, speed control system of SCR, and robotic control systems, etc (Liu et al., 2004).

The self-tuning system is designed based on the minimum variance theory. It is mainly composed of regulator, reference model, subtractor, and self-tuning regulator. Subtractor is used to estimate the deviation between the expected (reference model) and observed outputs, and self-tuning regulator corrects regulator’s parameters according to the deviation calculated by the substractor (Alexandridis and Sarimveis, 2005). Currently this technology has been successfully used in the paper industry, chemical industry, metallurgy, and the autopilot system of aircraft, etc.

6.1.3 Problems

There are still some problems in the design of adaptive control: (1) stability is a major topic in the operation of adaptive control, which has not been well solved; (2) convergence of system algorithm is still to be improved; (3) adaptive control is used in a few systems only; (4) robustness of the system is easily impaired by the changes of external factors (Liu et al., 2004; Sanei and French, 2004; Alexandridis and Sarimveis, 2005; Liu, 2007).

6.2 Adaptive filtering

6.2.1 Theory

The adaptive filtering system adjusts the parameters and signals of filters by using the adaptive algorithm. The adaptive algorithm calculates the time-varying coefficients for processing signals. Currently the most widely used adaptive algorithms include Least Mean Square (LMS) and Recursive Least Square (RLS) adaptive algorithms (Khalili and Tinati, 2010).

LMS adaptive algorithm takes least mean square error as the best criterion. It is a gradient steepest descent method. It estimates gradient vector from output signal, and thus minimize the mean square error between the desired signal and the observed signal (Sheu et al., 2012). LMS is simple and easy to operate, but the convergence of the algorithm is low. RLS is complex but it has a better performance in convergence.

Currently they are mainly used in noise control, signal prediction, system identification, echo cancellation, and beam-forming of antenna array.

6.2.2 Research overview

Adaptive filtering was first proposed in the early 1940s. Wiener developed a linear adaptive filter, i.e., Wiener filter, to eliminate noise. By the early 1960s, people began to develop various nonlinear filters, and Kalman filtering theory was thus developed (Lippuner and Moschytz, 2004). Both filters depend upon the known signals and they have fixed adaptive coefficients. By the mid-1970s, the adaptive filtering theory was basically developed. The theory of optimal filtering design was proposed then.

7 Summary

Biological adaptation has always been focus of biological evolution, both are inextricably linked. Darwinian evolution focuses on the biological adaptation at visible level, including morphology, physiology and behaviors. The theory of molecular evolution stresses the role of gene regulation and gene mutations in biological adaptation. Both natural selection and molecular interpretation are indispensible to perfectly describe biological adaptation. Biological adaptation is a complex phenomenon. The mechanism of adaptation, for example, the correlation between the adaptation at phenotypic and molecular levels, will still be a topic for biologist for a long time. Biological adaptation inspired applications, such as adaptive control and adaptive filtering, have made great achievements in the past years and are attracting more attention from around the world.

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