Chapter 12
Evolution and Bio-Inspired Design: Natural Limitations

Frank E. Fish and John T. Beneski

Abstract Biomimetics is the incorporation of novel structures and mechanisms from nature into the design and function of engineered systems. Promotion of biomimicry has been justified on the basis that evolution has modified structures and functions in organisms to achieve optimal solutions and maximize performance. Such justifications reflect an incomplete understanding of evolution and constraints imposed on biology. Evolution is not a conscious or predictive process and does not drive toward perfection. Organisms are not optimal with regard to any one specific function. Where a biological feature will out-perform available technologies, these features can be targeted for assimilation into bio-inspired designs. For engineers and entrepreneurial investors interested in a biomimetic approach, an understanding of evolution and the limitations and constraints that have shaped biological organisms are necessary to avoid unsupportable and overzealous claims.

Keywords Evolution · Darwin · Natural selection · Ffitness · Adaptation · Phenotype · Genetic variation · Design · Reproduction and replication · MantaBot · Autonomous underwater vehicle (AUV) · Muscle

12.1 Introduction

The field of biomimetics and bio-inspired design has become an important source of innovative ideas. Biomimetics attempts to produce engineered systems that possess characteristics, resemble, or function like living systems (Vogel 1998). The biomimetic approach seeks technological advancement through a transfer of

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innovation from natural to engineered systems. By emulating these biological characteristics in those instances where the performance of living organisms is superior to manufactured devices, the performance of engineered systems may be improved through biomimetics.

It has been a long-standing idea that new technologies can be developed from nature (Fish 1998; Vogel 1998; Lu 2004; Bar-Cohen 2006). Animals and plants have served as the inspiration for various technological developments. Copying biological organisms by the biomimetic approach attempts to seek common solutions from engineering and biology for increased efficiency and specialization (Vincent 1990; Ralston and Swain 2009). Bio-inspiration extends biomimicry by expanding and improving the original biological concept (Ralston and Swain 2009). Engineers that target the diverse specializations exhibited by organisms for technology transfer can effectively reduce the time for the development of innovative technological solutions.

Biologists have turned to physics and engineering for the answers when seeking explanations for the function of various adaptations involved with physiology and structural anatomy. The biology of adaptation is thus inferred through reverse-engineering. However, with biomimetics, the engineers must look to the biologists to provide working examples and mechanisms of physical phenomena. Novel approaches by living organisms, therefore, form the basis of the development of new technologies.

Biological organisms are in their own right machines. They are fully autonomous, self-powered, and self-repairing. The component structures that comprise these entities are adapted for particular functions that allow the organism to occupy a specialized environment space, or niche. The spectacular diversity of life-forms has produced a variety of mechanical and physiological solutions for interacting with both the biotic and abiotic environment. Inspired by such solutions, engineers are attempting to build machines that mimic the functions of organisms, but these machines and structures are limited and are nowhere near as sophisticated or versatile as real biological forms (Denny and McFadzean 2011).

Because biological designs result from the evolutionary process of “natural selection” (Darwin 1859), biological organisms are considered to have already performed the “cost-benefit-analysis,” optimizing particular designs for specific functions. In this sense, biology has provided a design prototype (Allen 2010). Over the course of millions of years, different lineages of organisms have, in effect, experimented with various combinations of morphologies, physiologies, and behaviors to enhance performance. The planet is thus considered to be an enormous natural laboratory, where an infinite number of experiments have been attempted over the eons (Lu 2004; Bar-Cohen 2012). The results of these experiments are the diverse assemblages of animals, plants, fungi, protozoans, and bacteria that inhabit the Earth today. They are considered the evolutionary winners. The losers are the organisms that have gone extinct or never came into existence. They were assigned to an evolutionary trash heap of maladaptation. It is “survival of the fittest.” However, such an appreciation of evolution is patently false. This erroneous rationale is too often employed as a natural justification for the perfection of nature and the power of the biomimetic approach. Many human-contrived inventions are thought to be the result of biomimicry (i.e., net spider web, submarine dolphin, wheel rolling round fruit; Lu 2004), although they may only be analogies with no cause and effect.

The purpose of this chapter is to provide a fundamental understanding of how evolution works and its importance with respect to biomimetics and bio-inspired design. The chapter has been written primarily for engineers as the mechanism of evolutionary change is generally known to biologists. However, biologists can also benefit from this chapter in understanding the inherent differences in the disciplines and seeing how a productive biomimetic design may be developed through a synergy of biology and engineering. By examining the relationship between evolution and biomimicry, limitations and constraints can be elucidated for nature-based technologies. It will then be possible to better target biological designs for technology transfer and more quickly bring biomimetic products to market.

12.2 Evolutionary Mechanics

Although the general principles of organic evolution are widely known, its implications are often misinterpreted or misdirected. This is unfortunate because evolution is arguably one of the most profound tenets of modern biology in that it provides a solid, unifying concept for all of biology's disciplines and subdisciplines as well as a common thread for continued investigation. At its core, evolution is a conceptual framework for the process by which living systems change over time. Because the time frame for evolutionary change is geological, it is difficult if not impossible to observe these changes directly. Instead, evolutionary biologists must rely on the results (or products) of evolution, which include all living systems past and present.

The genesis of modern evolutionary theory has a rich and colorful history involving numerous personalities. However, its formalization, development, and ultimate acceptance within the scientific community are generally attributed to Charles Darwin as documented in his seminal work "The Origin of Species" (Darwin 1859). In developing his theory, Darwin sought to explain the bewildering diversity of life by answering two basic questions: (1) How do organisms change over time? and (2) how do new types of organisms originate? Darwin's concept of evolution can be summarized as a series of observations and deductions (Fig. 12.1).

In contrast to his contemporaries, Darwin's extensive observations of nature led him to conclude that evolution operated at the level of the population rather than the individual. Darwin further concluded that populations evolved (changed over time) by differential reproductive success; that is to say, individuals with favorable traits leave more offspring than individuals with less favorable traits, thereby increasing the frequency of the favorable traits in the next generation. The measure of an individual's ability to pass its traits into the next generation is termed fitness.

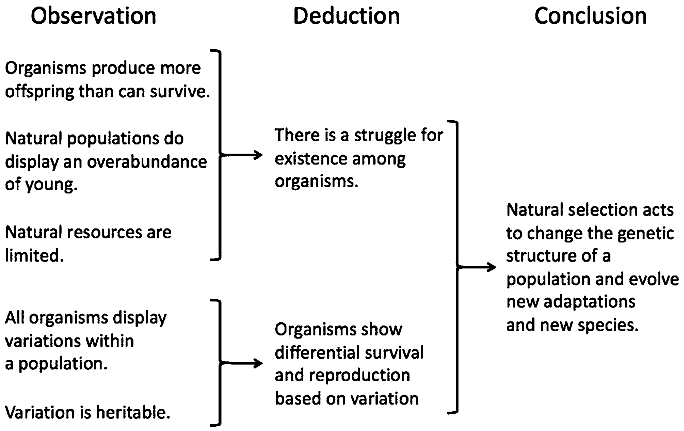

Fig. 12.1 The observations and deductions of Darwin (1859) that lead to the idea of evolution by natural selection

Individuals with a high fitness pass more of their traits into the next generation than individuals with a lower fitness. The process by which favorable traits are preferentially passed from generation to generation is termed natural selection.

Although Darwin's theory provided an elegant framework for the process by which populations change over time (natural selection), it lacked an adequate mechanism. Darwin's theory of natural selection relied on the passing of favorable traits from parent to offspring. However, the work of Gregor Mendel and therefore the genetic basis of inheritance were unknown to Darwin, and he therefore was unable to adequately explain how the traits of parents could be transferred to their offspring. R. A. Fisher, J. B. Haldane, Sewell Wright, and T. H. Huxley finally wed Darwinian evolution with the principles of genetic inheritance. The resulting elaboration of Darwinian evolution is variously referred to as neo-Darwinism, the Synthetic Theory of Evolution, or the New Synthesis. One of the first outcomes of this union was the field of population genetics.

According to the New Synthesis, evolution can be defined as the heritable changes that occur in a gene pool over time due to differential reproduction (i.e., ability to produce more offspring due to a heritable trait). This simple definition encompasses three key concepts: change, time, and populations. In studying evolution, it is important to distinguish between statements that apply to populations and statements that apply to individuals. Evolution occurs at the level of the population (populations evolve, individuals do not evolve). By contrast, natural selection occurs at the level of the individual by favoring the reproductive success of the fittest phenotypes. Phenotypic traits are characteristics of individuals that are coded for by specific genes (e.g., hair color, body size, wings). Therefore, if the frequency of a gene within a population changes, the frequency of the corresponding phenotypic trait in that population will also change. As such, evolutionary change does not occur within individuals, but occurs in a population over time as a consequence of which genes are passed from generation to the next generation. Evolutionary fitness is a measure of an individual's ability to pass genes on to the next generation. The more genes an individual passes on to the next generation, the higher the fitness of that individual.

It is important to note that by definition fitness is relative (there is no absolute fitness scale) and to recognize that fitness is not differential survival. To measure fitness, we compare the reproductive success of all phenotypes and then assign the phenotype with the highest reproductive success a fitness value of (1.0). For all other phenotypes, we assign a fitness value that reflects their reproductive success relative to the phenotype with the highest reproductive success. For example, if a second phenotype produced 80 % as many offspring as the fittest phenotype, it would be assigned a fitness value of (0.8); if a third phenotype produced 50 % as many offspring as the fittest phenotype, it would be assigned a fitness value of (0.5).

It is also important to note that selection operates on phenotypes, not the underlying genetics in that different combinations of genes or alleles can yield the same phenotype. Phenotypic traits include any morphological, physiological, behavioral, or other definable characteristic of an individual. Natural selection determines which phenotypic traits are favored and which are not. To be favored, a trait must increase the fitness (reproductive success) of an individual with that trait over an individual without it. Favored traits are often described as adaptive traits, so that adaptation is the process of acquiring favorable traits.

As a result of evolution, populations change through time (as traits change in response to changing gene frequencies) with the direction of change determined by natural selection. Evolution only works by selecting between alternative phenotypes already present in the population. This makes variation the raw material for evolutionary change. Yet, the process of evolution itself works by eliminating variation through natural selection. Continued evolution is therefore dependent on additional mechanisms, which add variation to a population.

Genetic variation is added to populations by several mechanisms. New genes can arise through mutations, genetic recombinations, or can be introduced (or reintroduced) by gene flow from neighboring populations (gene pools). In addition, the distribution and availability of genes within a population can be altered by various mechanisms or by chance (mating systems, genetic drift, genetic bottlenecks, and founder effects). For example, mating systems driven by female choice can lead to males and females being phenotypically different. Such species are referred to as being sexually dimorphic and the process leading to sexual dimorphism is termed sexual selection. Darwin recognized sexual selection is a special case of natural selection in which males and females are under different selective pressures. Because each of the different mechanisms for altering genetic composition can differ from population to population, each population of a species can be on a different evolutionary pathway. If these pathways diverge sufficiently, the original species can split into two new species.

As indicated by the fossil record, the rate and direction of evolutionary change are highly varied by both over time and taxonomic group. This variability is driven by multiple factors including changes in the range and scope of genetic variation, shifts in the adaptive landscape, and shifts in selective pressures. Various combinations of these factors over geological time have produced a wide range of evolutionary change that span from minor phenotypic adjustments to the apparent sudden appearance of new phenotypes (or disappearance of existing phenotypes). Because these factors are in constant flux, evolution is a continuous process and populations never stop changing.

One of the complications to studying evolution is that evolutionary change is not always evident. Although we define evolution as heritable changes in a gene pool, not all genetic change is translated into phenotypic change. In addition, the phenotypic consequences of genetic change are rarely predictable. Whereas some genetic mutations will have little if any effect on the phenotype, others can have profound effects depending, in part, on whether or not a gene codes for a functional or non-functional protein, whether the protein is a structural or regulatory protein, and the timing of protein expression.

Evolutionary change is limited or constrained by historical, developmental, and logistical factors. From a historical perspective, evolution implies a continuity of genetic information through time in the form of ancestor–descendant relationships. This ancestor–descendant relationship constrains evolution (descendants are limited by their ancestors). However, this relationship also provides a test for evolution in that character evolution should map to natural classifications, known as phylogenies, which in turn should reveal evolutionary trends. A phylogeny is the evolutionary history of an organism that shows its relationship to its ancestors and related species. Examination of evolutionary trends indicates that character evolution can be progressive or retrogressive and that generalized characters can provide a template for the radiation of more specialized characters across different groups of organisms.

Morphological evolution has strong ties to developmental programs. The specific area of biology that investigates this relationship is referred to as evo–devo (Arthur 2002; Gilbert 2003). According to evo–devo, developmental programs consist of a mosaic of interacting modules (Kuratani 2009; Breuker et al. 2006). Collectively, these modules add up to a specific body plan with a specific set of interdependent characteristics. The development of each module is influenced by the development of each other module both spatially and temporally. Modularity preserves the integrity and cohesiveness of each morphological unit while allowing for adjustments throughout the course of development in response to the interactions between the modules. When they are required for proper development, the interactions between modules can conserve existing morphological expression, thereby constraining the direction and magnitude of morphological change. However, temporal alterations in the expression of modules (heterochrony) can produce large, coordinated changes in morphology in a relatively short period of time. Therefore, developmental modularity can either canalize morphological change through spatial interactions or accelerate morphological change through temporal changes in expression or duplication of modules.

From a logistical perspective, not all evolutionary change is feasible. Each organism is a mosaic of interacting, interdependent characteristics. As such, individual characteristics do not evolve in isolation, but evolve in concert with all other characteristics. Whereas evolutionary modification to any particular character may have positive fitness effects on some characteristics, it may also have negative fitness effects on other characteristics. In these situations, evolution must settle for compromise rather than an optimized solution for each affected characteristic. Compromise selection can be driven by additional factors including seasonal variation, habitat variation, and ontogeny (development and life history). Each of these factors may provide competing selective pressures that vary across time, location, and age and thus further constrain the reach of evolution.

Despite the continuous march of evolutionary change and the numerous factors that influence, drive, and alter its direction and timing, the process of evolution is not restricted to greater and greater phenotypic divergence. It is not unusual for multiple evolutionary pathways to independently arrive at a common solution. These common solutions may be shared by unrelated groups (convergent evolution) or related groups (parallel evolution). Convergence not only demonstrates that there is more than one pathway to the same end point, but also demonstrates the power of natural selection to find a favorable solution from a variety of starting points.

12.3 Culture Clash

Evolution is the cornerstone of modern biological thought. It has propelled biology from a mere description of nature to a predictive science. The products of evolution are the adaptations. Adaptations are incorporated into the design of organisms to solve problems and to provide functions involved with survival and reproduction. In this case, nature has developed a technology through evolution. Biomimetics unites the natural technology of biology with physical technology of engineering. By incorporating both biology and engineering, the biomimetic approach requires that evolution be fully considered.

Effective transfer of technologies from biology to engineering requires the union of researchers working in these different fields. As simple as this may seem, there are differences between the two fields and their approaches to problem solving. The different approaches manifest themselves as cultural differences between the disciplines. Biologists and engineers often work apart. Whereas college biology curricula include courses in physics, engineering students are not necessarily required to take biology courses. Engineers may have little knowledge of biology beyond everyday experiences and evolution is often outside these experiences. Similarly, biologists have little appreciation for engineering issues as biological examples were not emphasized in physics classes and much of modern biology is chemistry-oriented (e.g., genetics, molecular biology) rather than physics-oriented (e.g., biomechanics).

A major difference between biologists and engineers is the concept of “design.” For the biologist, “design” refers to a description of the physical structure of component or a whole organism in relation to the environment that it must interact.

In this sense, "design" implies only a functionally proficient arrangement of the parts composing an organism, which are the result of natural selection (Vogel 1988). For example, the gazelle has a design for running swiftly through open terrain, and the dolphin has a design for efficient movement in the ocean. The engineer's concept of "design" not only encompasses the structure of a system, but also includes the process by which the system is conceptualized for a particular function. In this sense, design is a human endeavor that implies anticipation and purpose (Vogel 1988). The design process involves discovery, planning, development, construction, evaluation, and invention (Vogel 1998). The difference in how biologists and engineers view "design" leads to misunderstandings in the interpretations of the origin of biological structure and function.

Without a combined understanding of biology and engineering, oversimplified assumptions can retard the development of viable biomimetic applications. For example, the development of the airplane, although inspired by birds, required abandonment of a bird model. Airplanes do not flap their wings like birds to simultaneously produce lift and thrust. Such a mechanism is impractical in modern aircraft due to limitations from scaling and the high speeds necessary to remain aloft by commercial and military jets. Lift generation at a size and speed scale that is sufficiently large to carry a human requires steady-state aerodynamics rather than the unsteady flapping of a bird wing (Jakalb 1990; Harris 1989). As a result, the design of aircraft has advanced beyond the size and capabilities of birds for level flight.

Harris (1989) argued that slavish adherence to the bird as a model system for early airplanes held back design improvements through the early 1900s. Birds did serve as the inspiration for flight and the early development of wing design (Lilienthal 1911; Jakalb 1990). However, large aircraft do not emulate the design of the wings and their control for birds and other powered flyers, such as bats and insects. Today, interest has focused on the agility of birds to perform complex aerial maneuvers. Flying with the agility of birds is not presently possible as there is an absence of detailed information on sensory input and control of the complex mechanical linkages, which are associated with the motion of the wings. Indeed, even the sensing and regulation of airflow over the wing and control surfaces is not understood. In regard to maneuverability and agility, birds continue to demonstrate superior performance to manufactured aircraft.

If biomimetic products are to be produced, the difference in cultures between biologists and engineers needs to be recognized. Each group works with systems that are parameterized in fundamentally different ways (Vogel 1998; Fish 2006).

The development of machines which have been the focus of engineered systems is relatively large in size compared to their biological counterparts. Skyscrapers, jumbo jets, and ships are of a scale that dwarfs termite mounds, birds, and whales, respectively. Conversely, microscopic cells and viruses are smaller than machines. These biological entities are not only capable of performing particular functions but also have the capacity to change their programming for new or modified functionality. The new approach of nanotechnology seeks to work at a level smaller than the cell to produce biomolecular machines, and nanomaterials for structural components and surface textures (Ummat et al. 2006; Zhang et al. 2006). Differences in size between current engineered and biological structures affect the forces experienced by these systems. While large vehicles traveling through a fluid medium experience an environment that is dominated by inertial and gravitational fluid forces, small organisms may be more affected by viscous forces. Water striders (Gerridae) can cruise across a water surface supported by molecular cohesion and surface tension (Hu et al. 2003), whereas ships operate at the water surface by buoyancy from the mass of water displaced by the hull. Grappling with such disparate criteria requires a designer to possess a working knowledge of both the relevant biomechanics and the engineering issues associated with adapting the biology to a machine for some targeted application.

The forces related to the scale of the systems dictate the construction materials used. Engineered systems are composed of rigid materials. These materials include metals, ceramics, and hard plastics. Even where compliance is required, hard materials are used (e.g., spring steel). The choice of these rigid materials is a matter of practicality for simple durability considerations as non-living systems do not possess the capacity for self-repair. Biological systems are generally constructed from materials based on organic molecules. Metals are of limited availability as construction materials in biological systems. Iron, copper, and magnesium are broadly used, but only in respiratory processes and only as one atomic component of a significantly larger molecule. Iron and copper are part of the molecules hemoglobin and hemocyanin. These molecules are essential to capture oxygen for transport through the bodies of animals. Magnesium is part of the basic structure of chlorophyll and functions to absorb radiant energy for plants. Magnetite (Fe_3O_4) is found capping the small teeth of the grinding radula in mollusks (Gordon and Joester 2011). A class of organic compounds, called siderophores, is used by marine bacteria to complex with iron and collect the metal from an environment, where this material is limited (Martinez et al. 2003).

Proteins, carbohydrates, and lipids form structures and components of simple cells to complex plants and animals (Wainwright et al. 1976; Vincent 1990). These materials are created and often function in an environment that is wet. Although biological skeletons can be formed from ceramics (e.g., vertebrate bones, mollusk shell, sponge spicules), these structures are composites with varying amounts of organic molecules (Vogel 1988). Generally, organisms are primarily composed of biological materials that are compliant (Wainwright et al. 1976; Vogel 1988). These compliant structures are part of a design that permits the body to bend (Wainwright 1988). Where motion is restricted due to a rigid skeletal framework, the compliant materials permit flexibility at joints. Furthermore, compliant materials allow for the storage of elastic energy when stressed. Release of the elastic tension can be used for energy recycling in repetitive motion. The springing ligament in the horse's leg aids in reaccelerating the hoof when running. The Achilles tendon in the kangaroo is stretched when hopping and recycles enough energy in each step to maintain a nearly constant metabolic effort as speed increases (Alexander 1988).

Engineered systems generally use rotational motors. The energy to power these devices is derived from radiant energy, chemical transformation, or thermal and nuclear sources. The energy for movement and manufacturing in biology is restricted to chemical catabolism, although ultimately radiant energy from the sun is used to produce the chemical compounds. High-energy chemical bonds are broken to release energy. This energy is then transferred to intermediate compounds (e.g., ATP, creatine phosphate), which can be transported around the cell. With the exception of bacteria, rotational motors have not evolved in biological systems (Fig. 12.2). Movement in plants is powered by growth and fluid pressure. Animals utilize translational movements that are activated by a chemical motor, that is, muscle. Muscles contract while exerting a force to do work. As muscles cannot lengthen on their own, muscles are typically arranged as antagonistic pairs. As one muscle contracts, the other is lengthened either passively or while exerting a force. This results in oscillatory motions of the body of an animal or its appendages, but not rotary motion. Some energy is lost by cyclical accelerations.

Complex neural networks with multiple sensory inputs control animal systems, whereas engineered machines are controlled by simple computational systems with limited sensory feedback. A human brain of approximately 1.5 kg is composed of 100 billion cells with one quadrillion synaptic connections (Denny and McFadzean 2011). The large number of nerve cells (neurons) and neural connections is associated with a large range of behavioral responses. Whereas autonomous machines must be pre-programmed to produce an appropriate response to a particular known stimulus, animals can be plastic in their response.

Biological organisms are functionally multifaceted (i.e., they move, feed, remove wastes, and reproduce) and must compromise optimal solutions for specialized functions to perform adequately rather than maximally (Katz and Jordan 1997; Webb 1997). A machine is constructed with a particular and defined purpose or a mission that it was designed to fulfill (Denny and McFadzean 2011). Having an engineered system with a single purpose increases the maximal efficiency of the targeted operation. As biological organisms are multitasking, they must balance any one function with a number of other functions that compete for energetic resources within the body, but are necessary to maintain life (Fish 2006). Ultimately, all biological organisms are driven by three primary motivations of obtaining sustenance (i.e., food and water), security (i.e., avoid being killed, self-preservation), and sex (i.e., reproduction) (Denny and McFadzean 2011). These are criteria that are seldom included in engineering schematics.

Perhaps the greatest difference between biological and engineered systems is that biological systems are capable of reproduction. Mechanical systems can be manufactured in large lots with strict control for exact duplication. However, for organisms, the ability to reproduce is not confined to merely making copies of individual units. Indeed, new mutations and recombinations of genetic material increase variation, which is the raw material of evolution. Reproduction allows for changes that can lead to new evolutionary solutions or improvements in functional efficiency. Machines cannot autonomously replicate themselves. Improvements in

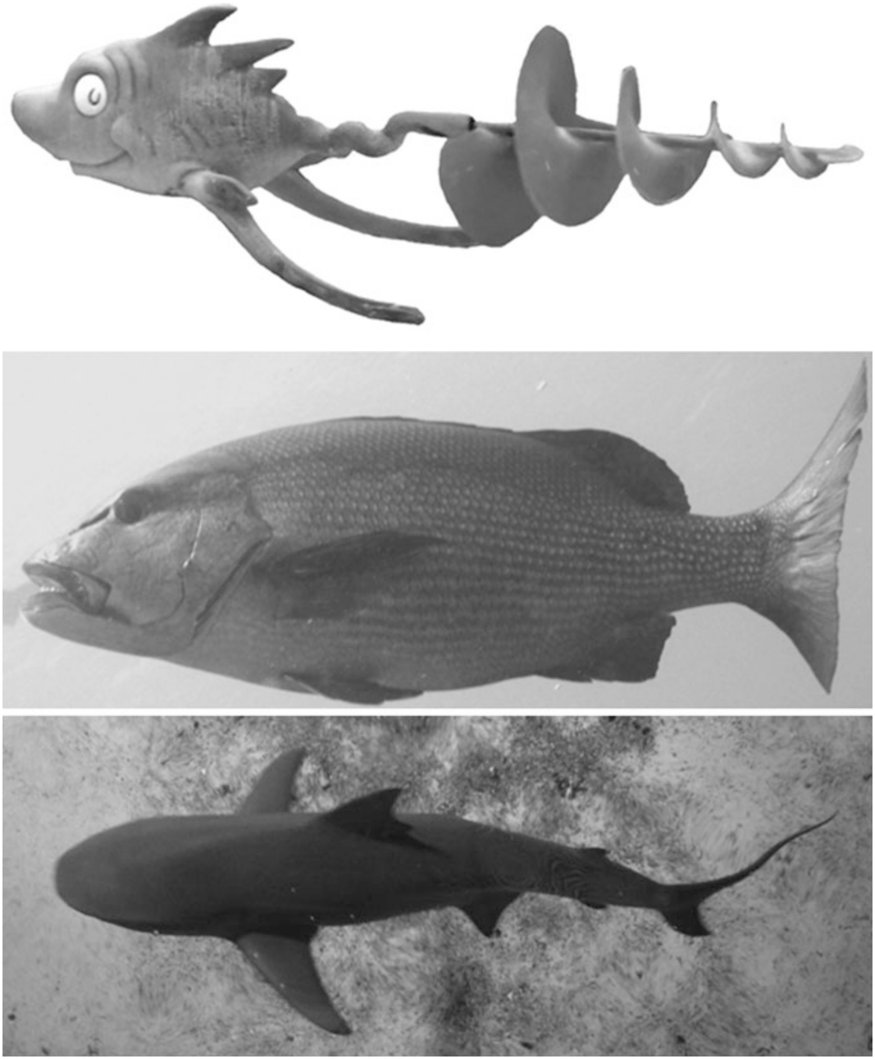

Fig. 12.2 Improbable and real fish propulsion systems. A mechanical fish model with a rotational screw propeller (*top*), based on the art of Dr. Seuss on display at Universal Orlando. Lateral view of a fish exhibiting fins for propulsion and stability (*middle*). Dorsal view of a shark swimming by undulations of the body and caudal fin (*bottom*)

machine design and function only come about from tinkering with established designs or scrapping the old design for a completely new approach.

Internal reproduction of the cells of the body affords organisms the ability to grow and self-repair. Growth permits change in a body. This change in size may afford the reproducing adult the capability of maximizing the production of young by increasing the space available for storage of gametes or housing and protecting the young prior to parturition. Over the course of growth and maturation of the young, their small initial size will allow them to feed on different foods and occupy different microenvironments, which fully mature individuals would not be able to exploit. The assemblage of different species at varying stages of development and size would enhance the stability of a given ecosystem.

The ability of organisms to self-repair is not merely associated with wound healing. It is also associated with immunity in fighting disease, invasion by foreign bodies, and with coagulation in limiting damage to the body. Organisms can prevent damage to delicate tissue by generating new cells to replace those cells, which have been damaged or abraded away. Another mechanism is to coat an irritant, rendering it harmless. For example, mollusks such as bivalves (e.g., clams, oysters) can secrete a smooth nacre material around a grain of sand to produce a pearl. The pearl prevents abrasion to the soft tissue (mantle) responsible for secreting the animal's shell. Literally, sand in the gears of a machine would generate enough friction to stop operation. Filters and lubrication must be designed into machines to reduce contaminants from wear or external sources.

Engineered systems are built with an assessment of potential for failure and with a plan for maintenance that is based on failure of prototypes. In the development of an engineered design, such considerations are known as failure criteria and dictate the physical limits for the form, function and materials used (Petroski 1996). Autonomic healing is only recently being attempted with battery technology (Blaiszik et al. 2012).

Besides the inherent differences between biological and engineered systems, a cultural disparity in the way engineers and biologists view the data in their respective disciplines. Engineers strive to limit the number of variables of any mechanical system, especially in the design of structures or devices with targeted functionality. Biologists consider a large number of variables. Furthermore, engineers analyze all the errors associated with a system in an attempt to control and reduce variation. Biologists study variation for each of the parameters that control a system. Indeed, variation in biological systems is the foundation of the evolutionary process, which is at the core of modern biological thinking.

12.4 MantaBot: Example of Biomimetics

The biomimetic approach demands careful observation of the whole biological system to identify the principles and attributes of the system that are appropriate to the function that is to be emulated. Thus, major limitations and constraints of any biological design must be defined before translation to an engineered system. As biological systems are the product of evolutionary mechanisms with their limitations, it is possible to improve on the design where the biology is constrained.

In the area of autonomous underwater vehicles (AUV), there is a need for AUVs that can be deployed quickly and can be adapted for a variety of missions (e.g., surveillance, search and rescue, sentry duty, logistics support, and chemical or biological agent detection) (Bandyopadhyay 2005; Colgate and Lynch 2004; Fish et al. 2003, 2012; Low 2011; Moored et al. 2011a). Parameters that are important for the next generation of AUV include efficiency, maneuverability, stability in high-energy environments, operation in the littoral zone and open ocean, station holding, and ability to follow bottom terrain. Design considerations include a rigid hull and minimum of control and propulsive surfaces. The animal kingdom has a number of organisms that meet these qualifications and provide a viable solution. Because of these performance and design characteristics, particular attention has focused on the development of a biomimetic autonomous undersea vehicle (BAUV) fin propulsor that mimics the biological principles and kinematics of the myliobatoid rays with particular interest in the manta (*Manta birostris*, Order Myliobatiformes, Family Mobulidae). The biological role of the manta and other myliobatoid rays conforms to the design space of a BAUV.

Batoid fishes (skates and stingrays) represent a group of over 500 elasmobranch species that have evolved dorsoventrally flattened bodies with reduced or whip-like tails and expanded pectoral fins that are fused to the head to form a broad flat disk (Rosenberger 2001; Douady et al. 2003). This deviation from the typical torpedo-shaped bodies of bony fish and sharks is an adaptation to living on the ocean bottom. The batoids swim solely by movements of their two greatly expanded pectoral fins (Breder 1926; Klausewitz 1964; Heine 1992; Rosenberger 2001). The pectoral fins have triangular, wing-like planforms with an aspect ratio (the ratio of span to chord) of 3.5 (Fish et al. 2012). The cross-sectional geometry of myliobatoid has a streamlined appearance. The lateral pectoral fins display symmetrical cross-sectional profiles reminiscent of engineered foils (Abbott and von Doenhoff 1959).

The manta ray (*Manta birostris*) is phylogenetically one of the most highly derived species of batoid fishes. Manta rays inhabit tropical seas of the world. They are adapted to a pelagic life in the open ocean, but may live inshore, and are found along reef fringes near deep water (Deacon et al. 1997). Mantas are filter feeders, preying on crustaceans and small fish. Other rays feed on benthic prey. The manta and other highly derived pelagic rays (e.g., *Myliobatis*, *Rhinoptera*, *Aetobatus, Manta*) swim by oscillatory locomotion (mobuliform mode). This mode of swimming consists of a small undulatory component (the wavelength of the undulation is greater than the chord length of the pectoral fin), and the pectoral fins are flapped dorsoventrally, analogous to the flight of birds (Breder 1926, 1964; Klausewitz Heine 1992; Rosenberger 2001).

The geometry of the fins and their kinematics for thrust production indicate a high-efficiency propulsive system. The streamlined shape of the body and fins of myliobatoids indicates a low drag profile (Fig. 12.3; Webb 1975; Vogel 1994; Fish and Lauder 2006). Both spanwise and chordwise flexibility are apparent as the pectoral fins are oscillated (Fig. 12.3; Klausewitz 1964; Heine 1992; Rosenberger 2001; Schaefer and Summers 2005; Fish et al. 2012). Spanwise and chordwise flexibility are associated with enhancing propulsive efficiency and thrust production. Spanwise flexibility prevents the total loss of thrust at the reversal of an oscillatory stroke (Liu and Bose 1997). Chordwise flexibility at the trailing edge of

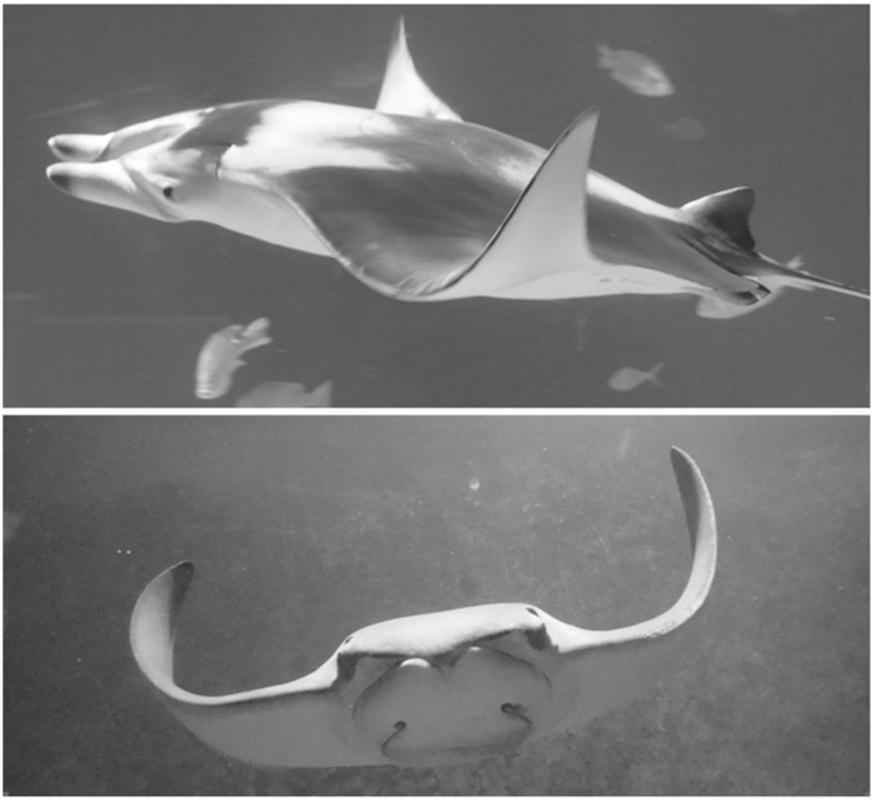

Fig. 12.3 Flexibility of the propulsive fins of batoids (*top*, manta; *bottom*, cownose ray)

the fin could increase the efficiency by up to 20 % with only a moderate decrease in the overall thrust (Katz and Weihs 1978, 1979; Bose and Lien 1989; Bose 1995; Prempraneerach et al. 2003). Actively swimming rays with flexible fins may have higher propulsive efficiencies compared to values predicted for models of rigid lifting surfaces. Hydrodynamic computations performed by Heine (1992) showed efficiencies of 0.7–0.9 for swimming rays. Efficiencies in this range are considered high, because few engineered propellers achieve efficiencies higher than 0.7 (Larrabee 1980; Liu and Bose 1993). In addition, oscillating biological hydrofoils with flexibility maintain high efficiency over an extended operational range (Fish and Lauder 2006). Standard fixed-pitch marine propellers have a maximum propulsive efficiency in only a very narrow range of operational speeds. Thus, oscillating hydrofoil propulsion as demonstrated by batoids is in keeping with the requirements for a BAUV.

The size of myliobatoid rays is appropriate as a model system for a BAUV. The manta is reported to be over 6 m wide and weigh over 1,580 kg, although other related species, such as the cownose ray (*Rhinoptera bonasus*), are smaller (Deacon et al. 1997; Compagno 1999). Scaling issues are inconsequential as the size and speed of these rays correspond to design and operation of AUVs. Thus, the hydrodynamics of the biological and engineered systems are equivalent as defined by important variables, the Reynolds number, *Re*, and the Strouhal number, *St*.

The Reynolds number represents the ratio of inertial forces to frictional forces and defines the flow conditions (laminar or turbulent) around a submerged body. A manta ray swimming at one body length/s would have a value of *Re* over three million, and data for the cownose ray from Heine (1992) indicate a *Re* of approximately 90,000. These high values indicate that inertial forces dominate.

Propulsion is provided by production of a caudally directed momentum jet of fluid. The momentum jet is generated by oscillatory motions of the enlarged pectoral fins (Fig. 12.4), leaving a wake of staggered alternately rotating vortices. The rate at which these vortices are shed and the efficiency of the propulsive movements are related to *St*. *St* is the ratio of inertial forces from local acceleration to inertial forces from convective acceleration and represents the degree of unsteadiness in the flow. *St* is the product of the propulsive frequency and vertical excursion of the fin divided by the velocity of the animal (Rohr and Fish 2004). The cownose ray has $St = 0.19$ (Heine 1992). This value is close to the Strouhal number range of 0.2–0.4, which is stated to be where the propulsive efficiency is maximal (Triantafyllou et al. 1993, 2000; Triantafyllou and Triantafyllou 1995; Rohr and Fish 2004).

There have been a number of attempts to develop a bio-inspired batoid AUV (Moored et al. 2011a, b). Robots have been constructed to mimic the oscillatory swimming of rays by motors (Gao et al. 2007; Yang et al. 2009; Zhou and Low 2010),

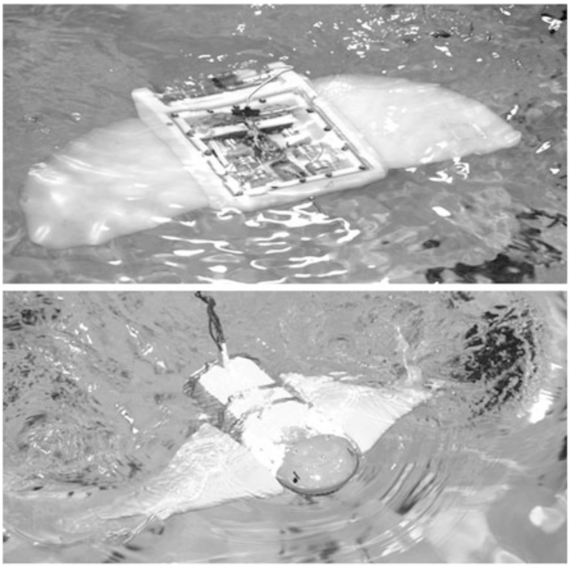

Fig. 12.4 Bioinspired robots (MantaBots) based on the design and swimming kinematics of rays. The mechanical rays were built by Princeton University (*top*) and the University of Virginia (*bottom*)

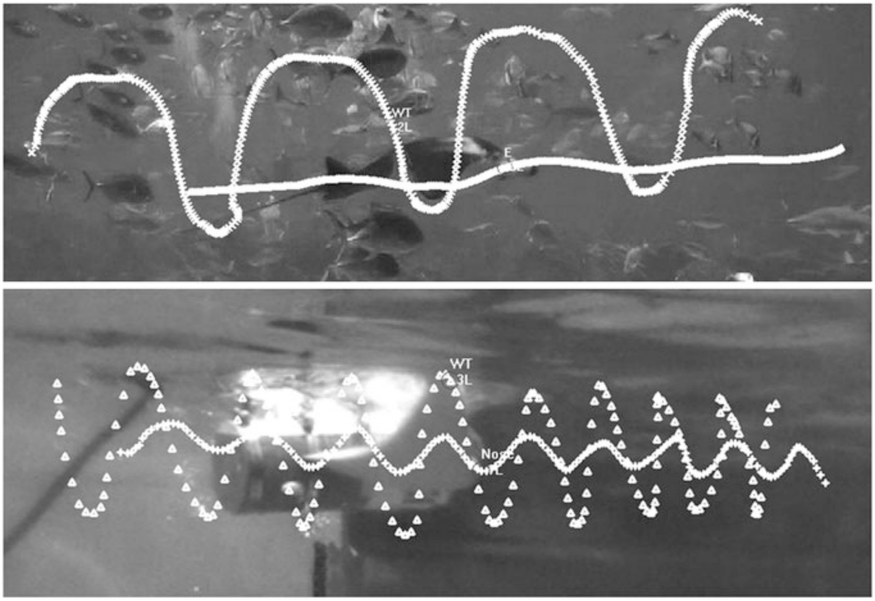

Fig. 12.5 Kinematic traces of the body and propulsive pectoral fins of a swimming manta (*top*) and MantaBot (*bottom*). The large oscillations are from the pectoral fins, and the small oscillations are indicated for the anterior end of the manta and the MantaBot. The manta shows asymmetrical movements of the fin strokes at lower frequency than for the MantaBot. Vertical motions of the anterior end were relatively greater for the MantaBot than the manta

pneumatic pectoral fins (Brower 2006; Suzumori et al. 2007; Cai et al. 2010), fluidic muscles (Festo 2008), and ionic polymer–metal composites (Takagi et al. 2006).

Recently, two prototypes (MantaBots) were developed and tested (Fig. 12.5; Pennisi 2011). The MantaBots were based on biologically derived data, which detailed the design geometry and kinematics of living batoids. Each MantaBot used different mechanisms to actuate the pectoral fins. In one version produced at Princeton University, four metal rods were actuated with a servomotor. The rods heaved a flexible plastic fin, producing varying degrees of spanwise and chordwise curvature (Moored et al. 2011b; Pennisi 2011). A second MantaBot was constructed at the University of Virginia and used a mobile tensegrity structure to move a propulsive elastomer fin (Pennisi 2011). The tensegrity structures consisted of truss-like structures, which acted like a skeleton tendon internal framework (Moored et al. 2011a, b; Fish et al. 2012). The rigid elements of the tensegrity structure were articulated. Two cable elements could generate tension to give integrity to the structure to support large loads and actuate movement.

While both MantaBots were capable of swimming and could perform elaborate maneuvers (Pennisi 2011), the propulsive movements of the pectoral fins were similar but not an exact duplication of a batoid (Fig. 12.4). The kinematics of the MantaBot pectoral fins was more symmetrical on the up- and down-strokes with respect to the longitudinal axis of the body than for live batoids. Living rays can swim faster and are more agile and maneuverable than the MantaBots (Parson et al. 2011). The MantaBots swam at just over 0.5 body lengths/s, and manta rays can swim at 0.8 body lengths/s. The amplitude of heave at the rostrum was 27 % of the fin tip amplitude of the MantaBot, whereas the heave amplitude was 12 % for manta (Fig. 12.4). *St* were 0.6 and 1.6 for the Princeton University and University of Virginia MantaBots, respectively. Such values were outside the range for maximum efficiency and above the value of *St* for the cownose ray (Heine 1992; Triantafyllou et al. 1993, 2000; Triantafyllou and Triantafyllou 1995).

For the MantaBots, engineering has derived separate solutions that provide similar motions, but are still limited compared to the actual rays. The skeletal, neural, sensory, and muscular systems of living organisms are still more complex than robotic systems. This complexity permits organisms to work within a large set of behavioral and performance responses. As further refinement to robotic systems is built into the design, emulation of biological systems will converge with the engineering. However, there are limitations to biological systems from evolutionary constraints that may reduce performance. Emulation of biological systems should only be taken to a point in which performance is maximized, but then can be enhanced through engineering of a bio-inspired design.

12.5 Evolutionary Constraints

Caution must be exercised when using evolution as a justification for the development of biomimetic products. Nature has served as inspiration for various devices for centuries, but the theory of evolution, as currently understood, has only been around since the mid-1800s. With the arrival of biomimetics and bio-inspired design as fields that could produce products and increase funding and investment, there has been an attempt to validate these fields with a natural justification. Evolution is seen as an iterative process that arrives at the best design. Therefore, the evolutionary process becomes imperative to highlight the advantages of natural designs. However, evolution does not hold all the answers or solutions to problems that affect our daily lives.

Evolution is a process that over the history of the Earth has produced a multitude of differing species that have developed solutions (adaptations) to local environments. In some cases, evolution has lead to different but analogous solutions to similar environments in different phylogenetic groupings. Consider swimming by a fish and a squid. The fish wags (undulates) its caudal fin from side to side to accelerate a mass of water into its wake, and thereby gain forward momentum (Fig. 12.2). The squid, however, uses jet propulsion to push the animal backward. Both animals can move rapidly through the water, but the mechanics of the propulsive systems differs. Flexibility of the vertebral column of the fish permits an undulatory wave to move posteriorly down the body to laterally flex the caudal fin. Because the body of the squid is held rigid by a non-flexing internal skeleton (i.e., pen), such movements are not possible in the squid, necessitating jetting. These differing solutions to the problem of rapid movement through water have further consequences. The fish can push a large volume of water at slow speed, thereby moving with a high efficiency, whereas the squid pulses a jet of fluid at a much higher speed to gain an equivalent momentum, resulting in a lower propulsive efficiency (O'Dor and Webber 1986).

For a non-biologist using evolution to justify biomimicry, the greatest mistake is inferring that evolution has an optimal design goal. Evolution is neither conscious nor predictive. Evolution is not visionary. Construction and organization of an organism's features have not evolved toward a specific goal, and evolution does not drive toward perfection. Evolutionary change by natural selection does not provide a "perfecting" principle, only a "better than" principle (Luria et al. 1981). Organisms evolve features not to be optimal or perfect, but merely to perform adequately (Katz and Jordan 1997; Webb 1997).

Genetic algorithms are used to mimic the process of evolution by natural selection. Genetic algorithms start with a population of randomly generated individuals [i.e., primordial ooze of hundreds or thousands of computer programs; Koza (1994)]. The individuals are evaluated iteratively by a fitness function, which represents a predetermined solution set. The solution set is encoded as a finite-length string that is composed of elements with a finite number of possibilities (Whitley 1994; Barrett 2002). By iteration and selection, a singular, predetermined optimal solution can be produced. However, biology is not driven by a predetermined optimal solution. The evolution of living organisms is shaped by the interactions of an organism with its environment, its phylogenetic history, and the genetic mechanisms that promote genetic diversity (e.g., mutation, recombination). Furthermore, evolution can work in the opposite direction from genetic algorithms to produce a diversity of solutions from a singular ancestral type. Each solution or species divides up the environment into various ecological niches.

Biological organisms are multitasking entities. An organism is a mosaic of integrated structures and functions to achieve evolutionary success (i.e., survive and reproduce). Some of these components may be at odds with other features of an organism. As a result, organisms must compromise optimal solutions for the necessity of having an integrated system that can perform a number of simultaneous functions. The integrated parts of an organism must share the limited metabolic energy available for maintenance and function. Increased allocation of limited resources to one component of a body may improve function, but be to the detriment of another component. Natural selection acts on an entire organism and not its individual parts (Luria et al. 1981). Despite the contrary argument (Bar-Cohen 2006; Allen 2010), evolution rarely leads to solutions with a maximal performance and with an economy of resources.

An example of how optimal design is lacking in biological organisms can be found in the structure and performance of the propulsive mechanics of fishes. Fish carry with them a large amount of muscle. Most of the muscle mass is not used during routine swimming, such as when a fish is cruising or migrating. Routine swimming is accomplished using muscle composed of slow oxidative (red) fibers

(Alexander and Goldspink 1977). These fibers use aerobic means of generating energy for muscle contraction and are highly efficient. As long as oxygen is available, red fibers can repeatedly contract over an extended period of time, but at a relatively slow rate. However, the bulk of the propulsive muscle mass is composed of fast glycolytic (white) fibers. These fibers contract faster and more powerfully than red fibers, but cannot sustain repeated contractions over a long time and have a very low efficiency. For fish that migrate long distances at low-to-moderate speeds, it makes more sense for these fish to have a muscle mass composed of a higher proportion of red fibers than white fibers. Indeed, carrying a large mass of white muscle seems detrimental. The inactive white fibers continue to metabolize nutrients, and the extra mass encumbers additional energy costs to move the body. Why then is so much of the musculature composed of white fibers? While not utilized all the time, the white fibers are advantageous during those brief instances when life and death are on the line. When a fish has to chase prey for food or to escape being preyed itself, it is advantageous to have a large mass of white fibers to generate the forces required to accelerate quickly. At these times, efficiency is not as important as rapid acceleration to close the distance on prey or increase the distance away from a predator. In addition, the fish must carry other organs that add to its mass, thereby impeding performance. Carrying large gonads and reproductive products can reduce swimming speed and survival, although reproductive organs are necessary for evolutionary fitness.

Not all possible structures and processes are available to organisms. As mentioned previously, biological organisms do not use metal as a framework for a physical support. The structures of organisms can only work within the constraints of materials based on organic molecules. The formation of these molecules is directed through recipes encoded on the DNA molecule and manufactured by living cells. Metabolic processes are only possible within a narrow range of temperatures for the formation of complex molecules. Above critical temperatures, proteins denature and cellular systems fail. Alternatively, synthetic manufacturing systems can use high temperatures and pressures to produce new molecular configurations or meld materials together in construction.

The wheel may be considered one of the greatest inventions by humans. It allows for a reduction in the energy cost for movement by reducing friction and eliminating oscillatory motions. The wheel is free to rotate continuously around an unattached central axis. Although the wheel is ubiquitous in engineered mechanical systems, it is rare in natural systems. With the exception of bacteria, multicellular organisms have not evolved wheels. Rotation movements translated over 360° are found in whole body rolling maneuvers by organisms, such as tumbleweeds, caterpillars, stomatopods, and desert spiders (Full et al. 1993; Armour and Vincent 2006). The energy for rolling is derived from air and water currents or from gravity. Self-actuating movements by animals are powered by muscles, which only allow a limited degree of rotation. A physical connection is made by muscles and stabilizing ligaments across a rotational joint. It is this construction of rotational joints that makes the evolution of wheels in animals impossible. As continuous rotation is not possible in the musculoskeletal system of animals, locomotion requires oscillatory movements. These oscillations are characterized by reversals in the direction of body and appendage movements. The energetics is impacted by operating in such a fashion. Periodic accelerations occur over a propulsive cycle. Thus, kinetic energy varies greatly and the efficiency is decreased (Alexander 1983).

Another constraint imposed by evolution is that the environment is in a non-equilibrium state, which places design criteria in a state of constant flux. Organisms must be plastic enough to deal with the constant changes in the environment. For any geographic location, the physical parameters of temperature, pressure, humidity will vary with time, season of the year, and across geological eons. Additional factors include the availability of food and shelter, distribution of predators, and prevalence of diseases. Changes in these factors can be unpredictable. This state of constant flux means that no design ever lasts indefinitely (Van Valen 1973). What is good today may not be good tomorrow. Furthermore, what is observed today may be on the way out. All species eventually go extinct.

The dinosaurs represent a successful group of medium to large reptiles that were the dominant land vertebrates on the planet for approximately 150 million years. However, in a geologically short period of time, the entire lineage went extinct. The only remnant of the dinosaurs is the offshoot that gave rise to the birds. Although dinosaurs might have evolved adaptations that solved a number of problems, their total extinction was due to a sudden catastrophic environmental change that overwhelmed the genetic capabilities of these animals to evolve to meet the ecological insult. The environmental changes that occurred afterward may have made it impossible for dinosaurs to reestablish themselves. Furthermore, the mammals usurped the ecological niches formerly occupied by the dinosaurs or formed new niches.

Organisms themselves can change the very environment in which they live, and not always for the better. Expectations of harmonious living between individuals and species (Benyus 1997) may be merely wishful thinking. Whereas harmonious symbiotic relationships have occurred such as in the origin of eukaryotic cells (Margulis and Sagan 1997) and organisms like lichens and corals, competition is fierce between individuals and species. Natural selection works at the level of the individual. Because there is an inherently selfish interest, life does not work for the best interests of the community. Adages such as “kill or be killed” and “Nature, red in tooth and claw” have an element of truism to them. Individual organisms can degrade the physical environment to their own benefit and the detriment of others. Certain plants will release secondary compounds that negatively affect the growth of neighboring plants. This strategy is referred to as allelopathy. The black walnut (*Juglans nigra*) releases a phenolic compound from its leaves, stems, branches, and roots. The toxic effect extends up to 27 m from the trunk of the tree (Lambers et al. 1998). Even the beaver (*Castor canadensis*) will modify its environment, so that various species are negatively impacted. By damming small streams, the creation of a pond will flood areas to the detriment of various terrestrial plants and animals and organisms that inhabit faster flowing water.

Lastly, in regard to the constraints imposed on evolutionary systems, design is constrained by evolutionary history. Species are merely terminal points on branches of an evolutionary bush. Organisms evolved along lines of common descent with shared genetically regulated developmental patterns, confining the design space. For example, the insulation of birds is fixed to a morphology that uses feathers, whereas mammals utilize fur. Both hair and feathers function similarly entrap an insulative air layer against the skin and maintain an elevated body temperature. These structures are derived from the keratinized scales of reptilian ancestors, although from different parts of the scales and with different molecular conformations (Vincent 1990). Once taking separate evolutionary pathways, species are limited with respect to developmental options. Although originally used for insulation, the feathers became co-opted for flight in the structure of the wings. Mammals cannot grow feathers. Therefore, the evolution of flight in mammals required a wing constructed of a flexible skin membrane, rather than a feathered wing. Whereas feathers have sufficient strength to maintain the wing surface and deal with aerodynamic forces generated by the flapping wing, the skin membrane in bats must be reinforced by elongation of the bony digits.

Phylogenetic history can impede performance by a species. Most fish breath solely using gills, which allows them to remain submerged and away from the surface of the water. This means that the drag on a swimming fish can be minimized. Moving in the proximity of the water surface incurs additional drag due to the formation of waves (Fish et al. 1991). Dolphins and whales (i.e., cetaceans) secondarily returned to the sea. These marine mammals evolved a body design analogous to fish for reduced drag (Fish and Hui 1991). However, dolphins and whales are restricted to the mammalian body plan, which uses lungs for gaseous respiratory exchange. Although it would be more efficient to possess gills and remain submerged, cetaceans must come to the surface to breathe. As the additional drag at the surface can be as high as five times the submerged drag (Fish and Hui 1991), the phylogenetic history of cetaceans can impose severe energetic penalties. Cetaceans have had to develop behavioral and physiological adaptations, such as porpoising and prolonged apnea, to avoid surface effects.

12.6 Final Comments

It is tantalizing to consider the development of new and superior technological designs for enhanced performance based on biological systems. However, such innovations have been elusive (Fish 1998, 2006). The commercial production of biomimetic products has been rare (Vogel 1998). There has been greater success from bio-inspiration. Strict adherence to biological designs in biomimicry rarely produces any practical results and in some cases can impede the development of engineered systems (Vogel 1994, 1998; Fish 1998). Yet, the fields of biomimetics and bio-inspired design are generating excitement. Biology can provide fresh solutions to more conventional approaches and even suggest new avenues of research. For engineering, the designs, structures, and materials of biology represent potentially untapped resources. Entrepreneurs, venture capitalists, and corporations speculate on the future of new designs (Petroski 1992; Vogel 1998). Each is hedging on getting a lead in the marketplace. The number of biomimetic-based patents has increased faster than the total of all US patents between 1985 and 2005 (Bonser 2006). "Biomimicry," "biomimetics," and "bio-inspired design" have become terms that draw attention to an emerging field of study and a source of investment capital. However, if these terms are not to be merely buzzwords that focus attention without comprehension, then clearer definitions and a conceptual biological framework are required.

As this chapter has emphasized, it is necessary to understand evolution with its inherent limitations to all possible designs. The technology that nature has evolved is not always ahead of the technology of human ingenuity (Vogel 1998). Only by understanding evolution and how organisms have adapted to their present and past environments can one avoid the pitfalls of overstatement regarding biomimicry. Besides an understanding of evolutionary mechanisms, practitioners of biomimicry must be aware of the limitations of biology for transition to engineered systems, and differences in the culture of biologists and engineers.

How can the process of bio-inspired design be accomplished to live up to the expectations for the development of new products? To address this question, one must first ask the question, "What needs to be improved?" Engineering is a goal-directed, applied science. The technological problem must be outlined to determine the direction of design for improvement in functionality. Next, biological structures or processes need to be identified that perform better than the current technology or solve the problem from a direction different from the current design path. The input of a biologist, who has knowledge of the workings of the system, is requisite. Simplified explanations of biological phenomenon from the popular literature and general media are inadequate to base development of new designs. This step is followed by research on the mechanism of action by the biological structure or process. In this analysis, considerations of the limitations of the biology are necessary. Any limitations due to energy efficiency, construction of materials and morphology must be evaluated with respect to a cost-benefit analysis. For example, engineered systems can be economically constructed as the performance of the materials used and the forces to be encountered are highly predictable. Alternatively, biological systems require increased safety factors due to the unpredictability of the environment and variation in the structural design of the organism (Alexander 1998), where the "safety factor" is the ratio of a component's strength or performance to the maximum expected load during operation (Diamond 1998). The cost to introduce the biological advancement or replicate it may be uneconomical. Finally, the biomimetic approach requires a coordinated effort of biologists, engineers, industrial designers, and business people to produce future bio-inspired products.

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