Evolutionary Systems

All biological systems result from an evolutionary process. The sophistication, robustness, and adaptability of biological systems represent a powerful motivation for replicating the mechanisms of natural evolution in the attempt to generate software and hardware systems with characteristics comparable to those of biological systems. More than 40 years ago, computer scientists and engineers began developing algorithms inspired by natural evolution (Rechenberg 1965; Fogel et al. 1966; Holland 1975) to generate solutions to problems that were too difficult to tackle with other analytical methods. Evolutionary computation rapidly became a major field of machine learning and system optimization and, more recently, it spread into the area of hardware design by exploiting new technologies in reconfigurable electronic circuits, computer-assisted manufacturing, material production tech nologies, and robotics. Before delving into the features of natural and artificial evolution, we wish to emphasize that there is a major, and often neglected, difference between these two processes. Whereas natural evolution does not have a predefined goal and is essentially an open-ended adaptation process, artificial evolution is an optimization process that attempts to find solutions to predefined problems. Therefore, while in natural evolution the fitness of an individual is defined by its reproductive success (number of offspring), in artificial evolution the fitness of an individual is a function that measures how well that individual solves a predefined problem. The consequence of this difference is that artificial evolution, as it is formulated today, cannot possibly hope to match the diversity and creativity generated by natural evolution because, by definition, artificially evolved systems will all tend to satisfy the predefined problem.

1.1 Pillars of Evolutionary Theory

Biology is making continuous progress in the description of the components that make up living organisms and of the ways in which those components work together. However, the ultimate explanation is to be found in the theory of natural evolution. As Dobzhansky (1973) put it, "nothing in biology makes sense except in the light of evolution." A bewildering number of books and articles have been written on the theory of natural evolution, but its foundations are rather simple and elegant.

POPULATION

DIVERSITY

HEREDITY

The theory of natural evolution rests on four pillars: population, diversity, heredity, and selection. The premise for evolution is the existence of a *population*, which here we will loosely define as a pool of two or more individuals. In other words, we cannot speak of evolution of a single organism. *Diversity* means that the individuals of the population vary from one another to some extent. Individual diversity, both within and between species, has been observed and described for thousands of years. *Heredity* indicates that individual characters can be transmitted to offspring through reproduction. The notion that individual characters are hereditary was suggested in the

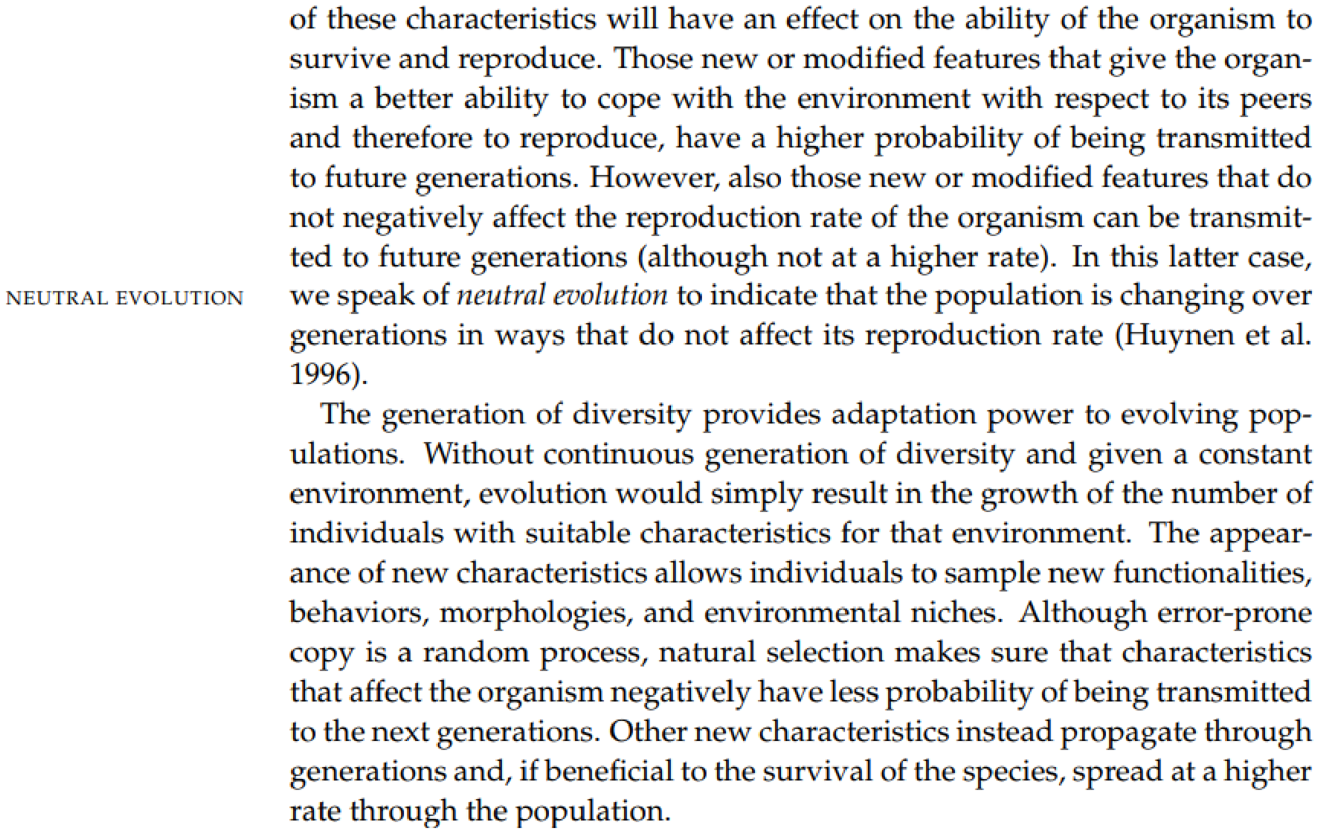
SELECTION

eighteenth century by Maupertuis (1753). *Selection* indicates that only part of the population is capable of reproducing and transmitting its characters to future generations. Natural selection, put forward by Darwin (1859) and Wallace (1870) in the nineteenth century, is based on the premise that individuals tend to make several offspring and that not all of them may reproduce. The selection of individuals that can reproduce is not completely random, but regulated by environmental constraints. For example, if an environment contains too many individuals for the available food , those individuals that are better or faster at gathering food will have a higher chance of survival and reproduction.

PROGRESS

Natural selection is the most debated, often misunderstood, and abused pillar of natural evolution. In the engineering community, it is commonly described as selection of the fittest; "fittest" is often associated with "best"; and selective reproduction of the best is often associated with progress. However, organisms are not always selected for how well they score individually. For example, some animal societies maintain a number of altruistic individuals that pay a cost in terms of reproduction for the good of their society. Furthermore, selective reproduction of the fittest does not necessarily imply progress in the two common meanings of the word. One meaning of progress is that new individuals are better than previous ones. However, natural selection has no comparative memory. The only way in which selection operates is here and now. Individuals are selected against the environment and/or their peers at a specific point in space and time. For example, prey at a given point in evolutionary time may be very good at escaping the current generation of coevolving predators they are confronted with, but may not be better than prey of previous generations when predators were different. In general, any change in the environment over time creates different selection conditions and therefore does not guarantee that recent generations are comparatively better than older generations selected in different environmental conditions. The other meaning of progress is that individuals tend to become better in the future. This notion of progress implies a final goal or optimal state of matter. However, natural evolution has no goal, no plan, and no end. In the best case, the combination of variety, heredity, and selection can increase *today* the rate of individuals whose parents had more suitable characteristics *yesterday*.

Where does population diversity come from? From an evolutionary perspective, generation of diversity takes place during reproduction. Offspring are copies of selected parents with small variations. This error-prone copy process can generate individuals with new or modified characteristics. Some



NEUTRAL EVOLUTION

of these characteristics will have an effect on the ability of the organism to survive and reproduce. Those new or modified features that give the organism a better ability to cope with the environment with respect to its peers and therefore to reproduce, have a higher probability of being transmitted to future generations. However, also those new or modified features that do not negatively affect the reproduction rate of the organism can be transmitted to future generations (although not at a higher rate). In this latter case, we speak of *neutral evolution* to indicate that the population is changing over generations in ways that do not affect its reproduction rate (Huynen et al. 1996).

The generation of diversity provides adaptation power to evolving populations. Without continuous generation of diversity and given a constant environment, evolution would simply result in the growth of the number of individuals with suitable characteristics for that environment. The appearance of new characteristics allows individuals to sample new functionalities, behaviors, morphologies, and environmental niches. Although error-prone copy is a random process, natural selection makes sure that characteristics that affect the organism negatively have less probability of being transmitted to the next generations. Other new characteristics instead propagate through generations and, if beneficial to the survival of the species, spread at a higher rate through the population.

Again, evolutionary adaptation does not necessarily imply progress in the two meanings of the word described earlier. Natural evolution may simply increase diversity by continuously generating new organisms that occupy new environmental niches. Or, it may increase complexity by incrementally adding new features to previous ones, provided that previous features do not represent a cost for the organism, do not interact negatively with new features, or simply have a higher probability to be preserved than to be replaced by the error-prone copy mechanism. Considering the enormous explanatory power and relative simplicity of the basic tenets of evolutionary theory, we might expect to find in the literature a compact and universal model that formally describes the evolution of populations, something akin to the laws of thermodynamics or to Newton's laws of physics. In practice, the complexity of the factors that affect the mechanisms and dynamics of evolution has not yet been sufficiently understood to allow the development of a universal formalism. Nonetheless, several formal models have been developed to address specific issues, mainly in the field of population genetics. It is worth pointing out that the great majority of these formal models describe evolutionary phenomena in terms of their effect on the variation rate of the population size or of a given character of the evolving individuals. In other words, formal measures of evolution, if we may liberally call them so, describe frequencies of the occurrence of given characters, or of given types of organism, over generations. For example, these models predict that in a relatively stable environment the percentage of individuals with fitter characteristics will gradually grow until they dominate the population (Fisher 1930). These models do not address the notion of performance and progress in evolving populations, but only the change in proportion of organisms of a certain type.