How Life Learned to Live

Adaptation in Nature

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Preface

This is more than an illustrated book on biophysics for the layman. It is also the story of an adventure that started in the laboratories of the University of California at Berkeley, where I began to ask myself whether today's naturalists, buried under instruments and flooded with scientific literature, have not strayed too far from nature.

My work at Berkeley dealt with the transformation of sunlight into chemical energy by photosynthesis in plants. My studies were conducted not in a sunlit garden, but behind a mountain of electronic and optical instruments. For the most part, my mind had to dwell in a world of abstract models and formulas. Of course that was necessary at such a high level of research, but every time I walked through the woods of the Sierra Nevada and watched my scientific project "breathe" I felt how essential and productive the contact with nature was for me. Progress in research is not based on thinking alone; intuition, inspiration, and chance are equally important. How to put oneself into the way of the most interesting inspiration may be a matter of opinion. I developed my own ideas on the subject.

When I decided to write a book about the application of the laws of physics in nature so as to learn more about the subject, I was convinced from the start that I would have to combine this work with actual experience in nature. I had no desire to merely contribute a mass of information to libraries; rather, I meant to see for myself, and perhaps take pictures of, those processes that interested me.

When my contract with the university expired in 1971, I packed my photographic gear and headed south along the Pan American Highway, the dream road of the Americas. It was to be more than two years before the South American continent would let me go again. During this time I crossed all of its fascinating wilderness areas: the Galapagos Islands off the coast of Ecuador, the Andes all the way to Patagonia and Tierra del Fuego, the coast of Peru and Chile with its bird islands, and the wilderness region of the Chaco in Paraguay and Bolivia. I visited the Matto Grosso territory in Brazil and made my way through the jungle along the freshly cut route of the Trans-Amazon Highway. Finally, I embarked upon a journey of many legs along the entire length of the Amazon River, from its delta to the Andes. At all times, I was looking for interesting biophysical phenomena.

My financial resources were rather limited. I managed to stay within my means by leading the simple life and using the native modes of transportation. For a time I worked as scientific advisor to the mining industry in the Atacama Desert of Chile. I covered thousands of miles by truck or on the deck of some small freighter. Where there were no roads, I traveled for weeks on foot or on horseback. It was sometimes difficult to reach a remote and uninhabited area without shelling out a lot of money to hire a four-wheel-drive, a boat, or a plane. Often I had to wait a long time for an opportunity to share a ride, and quite often I had to take a chance and ask to be dropped somewhere in the wilds in a spot that seemed interesting. Some of the pictures in this book were taken under rather hazardous conditions; but my adventures were well worth the trouble, and they made dealing with scientific problems fascinating and productive.

This venture, these experiences with man and nature, changed my entire attitude toward the natural sciences. I now see them as much more than a testing ground for a handful of competing scientists. First and foremost, they ought to be a source of enjoyment and inspiration for the many who are interested in nature.

Also, biophysics could become a pioneer of modern science, and not only in the transformation of visible light. With the transpiration system of the trees nature has succeeded in converting the heat of the sun into mechanical energy. Mangrove plants use their suction and transpiration apparatus to desalinate sea water. Why should we not try to duplicate these mechanisms with our technology?

Mankind invests enormous financial resources and the most sophisticated technologies to guard against the perils of atomic energy, while all around us enormous quantities of clean solar energy are going to waste. Is this venture worth the price? The expansion of atomic-energy supplies has become a matter of controversy. Energy from the atom is more expensive than had been expected, represents a potential source of danger, and creates radioactive waste that will be a burden to future generations. Moreover, atomic energy infringes upon the secret rule of nature's energy household. Energy should be inexhaustible, clean, and convertible in the smallest units.

Only solar energy complies with these conditions. In tropical zones and deserts an average of some 250 watts in luminous energy reaches each square meter of soil. In central Europe the figure is still above 100 watts. The radiation energy of each square kilometer could, if harnessed, supply a respectable power plant. Green plants tap no more than 2 percent of irradiating solar energy, yet they are adequately provided. Why does man not turn to solar energy? Why does he not try to emulate the plants and build chemical energy from the sun? There is an abundance of infertile land and unused expanses of water available which could serve as windows for power plants. No scientific reason can be proffered against the possibility of photochemical energy conversion, but we do find explanations why so far only modest progress has been made in the area of solar energy conversion. The problems are too difficult to be tackled by individual scientists and small groups, and immediate success is too improbable. And who likes to sacrifice his own career to others? For a breakthrough, strong financial and psychological motivation is needed that would sweep along many capable scientists and large institutions. Atomic energy got such a push because of war and military confrontation. Perhaps the present energy shortage will smooth the way for economical use of solar energy. Let us hope that we won't be too late in remembering that nature has been operating a similar process for millions of years.

People in general think of nature and physical technology as opposite and conflicting worlds. Many live only in the technical, others only in the natural world. Both groups advocate their own interests and convictions. Why should it not be possible to work toward technological progress that is in harmony with nature? The schizophrenia from which we suffer is rooted in our schooling. Our biology studies disregard the fascinating technology of nature. Our studies in physics or technology pay just as little heed to the ingenious technical inventions in the animal and plant kingdoms. Would not an engineer familiar with the technological ideas of nature have more respect for nature? Would not a naturalist who realized that life requires technology have more understanding for technological progress? Knowledge that reconciles nature and physical technology could pave the way for the progress of technology not as a threat to man, but to his benefit.

Contents

1

Technology Against a Life-Threatening Environment

Life came into this world more than 3 billion years ago. It began somewhere as a helpless combination of organic molecules in a very harsh physical environment. Everything seemed to conspire against survival: the strong solar radiation, which could split the delicate chains of the molecules; the cold, which could freeze life's first cautious movements; the heat, which could turn carefully ordered structures back into chaos; and the pressures, which could easily squeeze fragile cells to death.

Inorganic nature had stretched a deadly net of unalterable physical laws around life's delicate beginnings. Life's only chance to prevail lay in learning to master these forces. The problems it had to face were overwhelming. For one thing, in order to develop it had to tap the only inexhaustible source of energy: solar radiation. But how could particles of light be caught, and how could their energy be stored for use as needed? Primitive life never asked these questions. It possessed neither creative intelligence nor the will to solve problems. Propagation was the sole driving power behind the evolution of life.

Life drew its creativity from a stock of chance mutations in the genetic code of successive generations. Those descendants that were better able to withstand the environment survived and passed on the technical knowhow by which they had slipped through the loopholes of physical laws. They developed methods and mechanisms by which they were able to cope with the hard struggle for survival. Competing for food and space, the living creatures began to spread and to colonize the most hostile regions of the Earth: the dry, heat-baked deserts, the oxygen-poor highlands, the atmosphere, the frozen arctic and antarctic terrains, and the darkness of the oceans.

How has life fared in its confrontation with physics, which started so unequally? To what degree has life succeeded in exploring the laws of inanimate nature and using them to its advantage?

A turkey buzzard above the Peruvian desert. Life sends its front-line patrols into the most inhospitable regions of the Earth.

Lichen communities of algae and fungi have come to within 400 kilometers of the South Pole. There they exist at an average temperature of −15°C. In the Himalayas, they are found at an altitude of 7,000 meters (not high enough, though, for an altitude record; migrating geese fly over Mount Everest at 8,800 meters). Numerous large and small living creatures of the subpolar regions of North America and Asia survive temperature lows of −50°C. On the other end of the scale, algae live in hot springs at 85°C and fish at 50°C. Life has also conquered the world of high pressures. Whales dive to depths of 1,000 meters, where each square centimeter carries the weight of 100 kilograms. They have conquered decompression sickness and are able to remain underwater for 1–2 hours without renewing their air supply. The swiftest land creatures, the cheetah and the ostrich, reach speeds of 100 kilometers per hour, and some hawks fly at 200 kilometers per hour. Specialized sea predators such as the tuna swim at speeds of over 40 knots, or about 75 kilometers per hour, and can easily overtake atomic submarines. Small golden plovers (sandpipers) from Alaska and Canada fly nonstop 3,500 kilometers across the Pacific to Hawaii or across the Atlantic to South America for a winter vacation each year. The arctic tern, steering by mysterious navigational signals, covers up to 29,000 kilometers on its annual round trip between the

Arctic and Antarctica. Some insects move their wings up to a thousand times per second. In the darkness of the night, bats hunt for insects with almost infallible precision thanks to their ultrasonic equipment. Some snakes locate their prey by means of infrared-sensitive organs. There are fishes that use electrical fields to scan murky river waters.

As these examples show, life has met the physical challenge with flying colors. But how were increasingly complicated biophysical systems able to develop at all in the course of evolution? A fundamental law of thermodynamics is that irreversible processes—such as life—occur only when the entropy (the degree of disorder) increases thereby. Heat distributed evenly through space no longer flows back to its source, and an escaped gas never condenses by itself. Life does not break any physical laws, but it makes very clever use of ways to circumvent them. The natural law of increasing entropy applies only to closed systems (systems that do not exchange energy with their environment). Living organisms can develop toward increasing order and complexity because they absorb energy from outside. They organize themselves at the expense of increasing entropy in their surroundings. As soon as a living creature ceases to absorb energy, it must submit to the law of entropy and disintegrate: It dies.

It is entirely realistic to assume that human technological and scientific progress is polarized. Why, for example, do we build atomic rather than solar power stations? From the scientific viewpoint, there is nothing to be said against using solar energy to produce fuels. Nature provides a model in the photosynthetic mechanism of the plants on which all higher forms of life depend. If nonetheless an enormous investment is being made in fission, the reasons are to be found in history and psychology rather than in science. Perhaps nothing more than an encouraging chance discovery or some propitious political situation would have steered technology in the other direction. The "state of the art" merely indicates the actual development on the basis of some chance conditions, and says nothing about potential alternate achievements that could have been arrived at with the same effort. To try to imagine what other roads technology could have taken may be a difficult and speculative endeavour, but nature could serve as a guide. The statistical patterns according to which nature's techniques develop allow for a much more objective unfolding of all potentials. They are limited—by natural selection—only insofar as they are guided by the advantages they bring to life. Such a selection should be equally favorable to man.

This book will show, by means of noteworthy examples, how life has learned to master the physical problems posed by nature, and how it has chosen ways that sometimes differ widely from those of man.

2

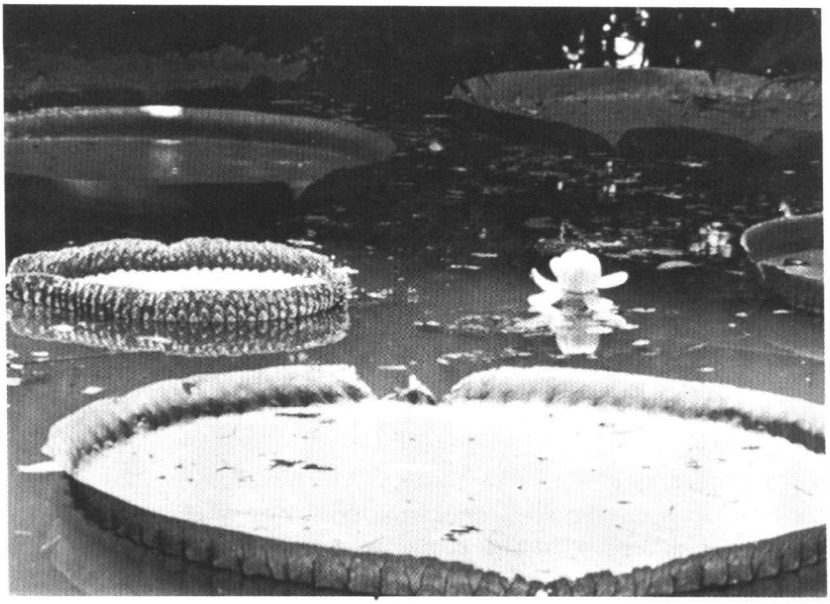
Mechanics and Building Techniques

Architecture and materials

Three guidelines of modern architecture are equally valid for biological forms: A building should be the realization of clear, elegant structural ideas; it should be solid and economic; and it should be esthetically harmonious with its environment. It is difficult to give intellectual reasons why we regard many forms of nature as esthetically pleasing. The fact is that biological structures have been subject to ruthless selection through millions of years and have been custom-designed with great precision for their specific purpose. One would need only to make the proper choice among the various forms of nature in order to solve some architectural problems without painstaking technical research.

A famous example is the water lily *Victoria amazonica*. The supports and reinforcements on the undersurface of its wide floating leaves served as a model when Sir Joseph Paxton designed the Crystal Palace of London in the middle of the nineteenth century. It is hardly probable that biology also inspired Fuller's self-supporting dome, but it is interesting to note that the dome's assembly of triangular or hexagonal elements is found among the siliceous structures of tiny diatoms. Honeycomblike shapes and fluted structures, too, are frequently encountered in nature. A vast array of models is available in nature for sensible ways of packaging, for mechanical strutting, and for geometrically optimal layout.

Still, some of the architectonic tasks nature has to face differ considerably from the aims of human architects. Moreover, we are talking about structures whose functions are not altogether understood by biologists. (This is the case with the wondrous diatoms, which—although they are mostly suspended in water and filled with liquid, and thus

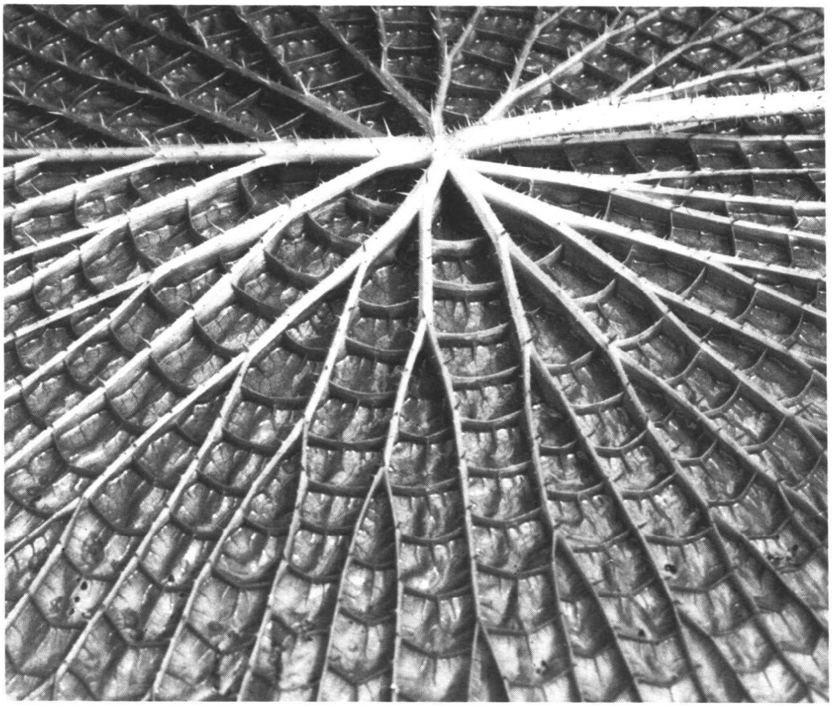


The giant *Victoria amazonica* unfolds its true splendor only in its natural environment: the quiet, jungle-shadowed backwaters of the Amazon River.

are subject to very little compression—seem to be perfect models for self-supporting domes.) Besides, most of the fascinating biological structures owe their shape to physiological necessities rather than to those of statics or architecture. For example, some are designed in such a way as to be well able to carry matter, absorb light, reflect heat, and breathe simultaneously.

Except for cases in which it is possible to define unequivocally the physical functions of biological structures, nature is a source of constructive and artistic inspiration rather than true architectural solutions. What architecture ought to learn from nature, above all, is the art of coping with a host of technical problems that require simultaneous optimal solutions. Architecture cannot afford to focus on the construction of sophisticated housing projects and factories without at the same time coming to grips with problems of transportation, pollution, leisure, and social contact.

Though it is not easy to imagine how nature would go about building a metropolis, it is certain that there would be little resemblance to one of our population centers, which are far from being harmoniously functioning organisms. Though human life depends on the plant world as the supplier of oxygen and food, vegetation has to a large extent

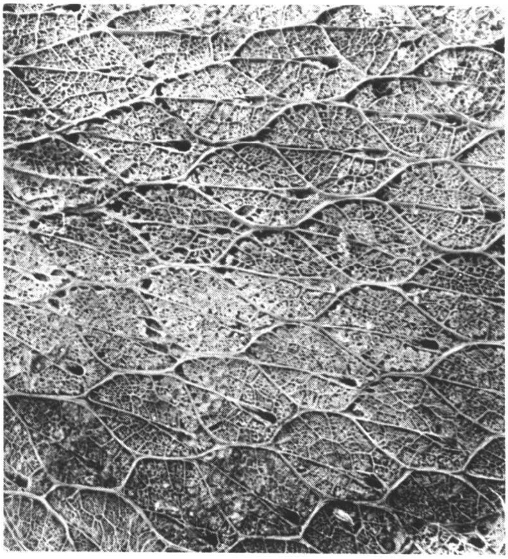


The undersurface of a *Victoria amazonica* leaf.

been exiled from the cities. Precious energy from the sun is wasted on roofs, parking lots, and streets, and dust and exhaust gases impair breathing. Nature certainly would make a radical attempt at providing optimal conditions for life.

Since life needs light, air, and a protective shield, it is in theory subject to conditions similar to those that prevail for a photochemical surface reaction. Such a reaction is the process of photosynthesis in green leaves, by which light is transformed into chemical energy. Perhaps, then, nature would build cities similar to the submicroscopic thylakoid structures—the power stations of plants, which consist of self-contained flat membrane sacs, often stacked like rolls of coins and linked to each other by many cross-connections. The units are arranged so as to make maximal use of light and to form as large a contact surface as possible with the environment—architectonic criteria our cities still fail to meet adequately.

A bird's-eye view of a natural metropolis would show nothing but green. No roofs, parking lots, or highways would be visible. All flat

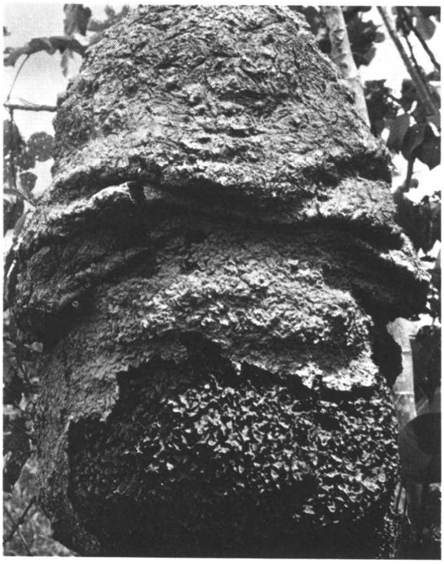


Structures on the stalk of a rotting Indian fig (Galapagos Islands).

surfaces would be covered with woods, parks, and gardens. The vertical structures would be the facades of offices, residential buildings, cafés, and boutiques, all with access to nature. Inside the "thylakoid structures" would be sufficient space for transportation, parking lots, shopping malls, and factories, which could manage with artificial light.

A building material must have strictly defined physical properties once it is put into a structure. Sometimes toughness and brittleness are required, sometimes strength and elasticity, sometimes good heat insulation. Paper, cardboard, and wood fiberboard, which have very good insulating properties, are made of small particles of wood and straw glued together with some bonding agent. Such building materials are used by several large families of animals. Wasps build their featherweight structures with wood, which they gnaw off and then mix with saliva. The reason their nests are usually gray is that they use weathered wood, which is relatively easy to loosen. Numerous species of ants (*Lasius*) build big cardboard nests which are subdivided into complex warrens of corridors and chambers.

The potter wasp (*Eumenes*) uses moist loam to build mud containers for its brood. If the mud is too dry, it is moistened before being scraped off; then it is transported in small pellets and drawn into thin strips



The partially exposed "cardboard" structure of a termite colony (Amazon region, Colombia).

before being used to build the wall of the container. The oven bird also uses moist mud for its nest, but adds plant fibers as reinforcement.

Mortar too has been used by animals. In the region of the Amazon one sometimes sees clay vessels swinging from branches in the middle of the wilderness. These are the nests of a species of wasps (*Polybia*) that mix clay and sand to build their castles. The leaf-cutting bee (*Chalicodoma*) uses dry stone dust or sand and mixes it with saliva, forming small mortar pellets to build its brood cell.

The most efficient builders are the termites. Their structures are as hard as concrete and often several meters high. In tropical areas of Central and South America, termite structures are especially eye-catching wherever settlers have cleared land by burning; among the charred trunks stand the black lumps of termite fortresses. Termites often use bits of earth, sand, or wood as building material, which they glue together with their droppings and their saliva. Some termites (*Apicotermes*) build their castles entirely out of their excrement, which dries quickly and does not decay.

Walls fitted together of natural stone are also to be found in the animal world. The South Asian jawfish (*Gnathypops rosenbergi*), which digs vertical holes, uses stones and shells to keep the walls from caving in. The caddis worm, which lives on brook and pond bottoms, often