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Dear Patrons,

Interested in how the iPad may be used in academia?

We are asking for your participation in our study, “iPad Use in Academia.” This study will help us learn how faculty and students are incorporating the iPad into the classroom and how the iPad is different from other technological tools in how academia teaches/learns. Survey participants will be asked if they would like to participate in a focus group on the subject. Those who are willing will join us for one of several focus groups where they will be given the opportunity to play with and discuss advantages and disadvantages of the iPad in the classroom. The open discussion will help us learn how faculty and students use this new technology and how it compares with other technology used in academia.

We are seeking any faculty or students with an interest in the use of the iPad in academia regardless of whether or not you have used one before! The survey will take approximately 15 minutes to complete.

You can find the survey at http://www.surveymonkey.com/s/iPad_Use_Survey. The study is being conducted by Donell Callender from the Texas Tech University Libraries. If you have questions, you can call her at 806-742-2238 #267 or by email at donell.callender@ttu.edu.

This study has been approved by the Institutional Review Board at Texas Tech University.

Thank you,

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1

THE ENVIRONMENTAL CRISIS

The environment has just been rediscovered by the people who live in it. In the United States the event was celebrated in April 1970, during Earth Week. It was a sudden, noisy awakening. School children cleaned up rubbish; college students organized huge demonstrations; determined citizens recaptured the streets from the automobile, at least for a day. Everyone seemed to be aroused to the environmental danger and eager to do something about it.

They were offered lots of advice. Almost every writer, almost every speaker, on the college campuses, in the streets and on television and radio broadcasts, was ready to fix the blame and pronounce a cure for the environmental crisis.

Some regarded the environmental issue as politically innocuous:

> Ecology has become the political substitute for the word "motherhood."—Jesse Unruh, Democratic Leader of the State of California Assembly*

But the FBI took it more seriously:

> On April 22, 1970, representatives of the FBI observed about two hundred persons on the Playing Fields shortly after 1:30 p.m. They were joined a few minutes later by a contingent of George Washington University students who arrived chanting "Save Our Earth." . . . A sign was noted which read "God Is Not Dead; He Is Polluted on Earth." . . . Shortly after 8:00 p.m. Senator Edmund Muskie (D), Maine, arrived and gave a short anti-pollution speech. Senator Muskie was followed by journalist I. F. Stone, who spoke for twenty minutes on the themes of anti-pollution, anti-military, and anti-administration.—FBI report entered into Congressional Record by Senator Muskie on April 14, 1971

Some blamed pollution on the rising population:

> The pollution problem is a consequence of population. It did not much matter how a lonely American frontiersman disposed of his waste. . . . But as population became denser, the natural chemical and biological recycling processes became overloaded. . . . Freedom to breed will bring ruin to all.—Garrett Hardin, biologist

> The causal chain of the deterioration [of the environment] is easily followed to its source. Too many cars, too many factories, too much detergent, too much pesticide, multiplying contrails, inadequate sewage treatment plants, too little water, too much carbon dioxide—all can be traced easily to *too many people.*—Paul R. Ehrlich, biologist

Some blamed affluence:

> The affluent society has become an effluent society. The 6 percent of the world's population in the United States produces 70 percent or more of the world's solid wastes.—Walter S. Howard, biologist

And praised poverty:

> Blessed be the starving blacks of Mississippi with their outdoor privies, for they are ecologically sound, and they shall inherit a nation.—Wayne H. Davis, biologist

But not without rebuttal from the poor:

> You must not embark on programs to curb economic growth without placing a priority on maintaining income, so that the poorest people won't simply be further depressed in their condition but will have a share, and be able to live decently.—George Wiley, chemist and chairman, National Welfare Rights Organization

And encouragement from industry:

> It is not industry *per se*, but the demands of the public. And the public's demands are increasing at a geometric rate, because of the increasing standard of living and the increasing growth of population. . . . If we can convince the national and local leaders in the environmental crusade of this basic logic, that population causes pollution, then we can help them focus their attention on the major aspect of the problem.—Sherman R. Knapp, chairman of the board, Northeast Utilities

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*Quotations and factual information are referenced, and often amplified, in the Notes section beginning on p. 301.

Some blamed man's innate aggressiveness:

> The first problem, then, is people. . . . The second problem, a most fundamental one, lies within us—our basic aggressions. . . . As Anthony Storr has said: "The sombre fact is that we are the cruelest and most ruthless species that has ever walked the earth."—William Roth, director, Pacific Life Assurance Company

While others blamed what man had learned:

> People are afraid of their humanity because systematically they have been taught to become inhuman. . . . They have no understanding of what it is to love nature. And so our airs are being polluted, our rivers are being poisoned, and our land is being cut up. —Arturo Sandoval, student, Environmental Action

A minister blamed profits:

> Environmental rape is a fact of our national life only because it is more profitable than responsible stewardship of earth's limited resources.—Channing E. Phillips, Congregationalist minister

While a historian blamed religion:

> Christianity bears a huge burden of guilt. . . . We shall continue to have a worsening ecologic crisis until we reject the Christian axiom that nature has no reason for existence save to serve man.—Lynn White, historian

A politician blamed technology:

> A runaway technology, whose only law is profit, has for years poisoned our air, ravaged our soil, stripped our forests bare, and corrupted our water resources. —Vance Hartke, senator from Indiana

While an environmentalist blamed politicians:

> There is a peculiar paralysis in our political branches of government, which are primarily responsible for legislating and executing the policies environmentalists are urging. . . . Industries who profit by the rape of our environment see to it that legislators friendly to their attitudes are elected, and that bureaucrats of similar attitude are appointed.—Roderick A. Cameron, of the Environmental Defense Fund

Some blamed capitalism:

> Yes, it's official—the conspiracy against pollution. And we have a simple program—arrest Agnew and smash capitalism. We make only one exception to our pollution stand—everyone should light up a joint and get stoned. . . . We say to Agnew country that Earth Day is for the sons and daughters of the American Revolution who are going to tear this capitalism down and set us free. —Rennie Davis, a member of the "Chicago Seven"

While capitalists counterattacked:

> The point I am trying to make is that we are solving most of our problems . . . that conditions are getting better not worse . . . that American industry is spending over three billion dollars a year to clean up the environment and additional billions to develop products that will *keep* it clean . . . and that the real danger is *not* from the free-enterprise Establishment that has made ours the most prosperous, most powerful and most charitable nation on earth. No, the danger today resides in the Disaster Lobby—those crepe-hangers who, for personal gain or out of sheer ignorance, are undermining the American system and threatening the lives and fortunes of the American people. Some people have let

> the gloom-mongers scare them beyond rational response with talk about atomic annihilation. . . . Since World War II over one *billion* human beings who worried about A-bombs and H-bombs died of other causes. They worried for nothing.—Thomas R. Shepard, Jr., publisher, *Look* Magazine

And one keen observer blamed everyone:

> We have met the enemy and he is us.—Pogo

Earth Week and the accompanying outburst of publicity, preaching, and prognostication surprised most people, including those of us who had worked for years to generate public recognition of the environmental crisis. What surprised me most were the numerous, confident explanations of the cause and cure of the crisis. For having spent some years in the effort simply to detect and describe the growing list of environmental problems—radioactive fallout, air and water pollution, the deterioration of the soil—and in tracing some of their links to social and political processes, the identification of a single cause and cure seemed a rather bold step. During Earth Week, I discovered that such reticence was far behind the times.

After the excitement of Earth Week, I tried to find some meaning in the welter of contradictory advice that it produced. It seemed to me that the confusion of Earth Week was a sign that the situation was so complex and ambiguous that people could read into it whatever conclusion their own beliefs—about human nature, economics, and politics—suggested. Like a Rorschach ink blot, Earth Week mirrored personal convictions more than objective knowledge.

Earth Week convinced me of the urgency of a deeper public understanding of the origins of the environmental crisis and its possible cures. That is what this book is about. It is an effort to find out what the environmental crisis *means*.

Such an understanding must begin at the source of life itself: the earth's thin skin of air, water, and soil, and the radiant solar fire that bathes it. Here, several billion years ago, life appeared and was nourished by the earth's substance. As it grew, life evolved, its old forms transforming the earth's skin and new ones adapting to these changes. Living things multiplied in number, variety, and habitat until they formed a global network, becoming deftly enmeshed in the surroundings they had themselves created. This is the *ecosphere*, the home that life has built for itself on the planet's outer surface.

Any living thing that hopes ~~to~~ live on the earth must fit into the ecosphere or perish. The environmental crisis is a sign that the finely sculptured fit between life and its surroundings has begun to corrode. As the links between one living thing and another, and between all of them and their surroundings, begin to break down, the dynamic interactions that sustain the whole have begun to falter and, in some places, stop.

Why, after millions of years of harmonious co-existence, have the relationships between living things and their earthly surroundings begun to collapse? Where did the fabric of the ecosphere begin to unravel? How far will the process go? How can we stop it and restore the broken links?

Understanding the ecosphere comes hard because, to the modern mind, it is a curiously foreign place. We have become accustomed to think of separate, singular events, each dependent upon a unique, singular cause. But in the ecosphere every effect is also a cause: an animal's waste

Good [illegible]

becomes food for soil bacteria; what bacteria excrete nourishes plants; animals eat the plants. Such ecological cycles are hard to fit into human experience in the age of technology, where machine A always yields product B, and product B, once used, is cast away, having no further meaning for the machine, the product, or the user.

Here is the first great fault in the life of man in the ecosphere. We have broken out of the circle of life, converting its endless cycles into man-made, linear events: oil is taken from the ground, distilled into fuel, burned in an engine, converted thereby into noxious fumes, which are emitted into the air. At the end of the line is smog. Other man-made breaks in the ecosphere's cycles spew out toxic chemicals, sewage, heaps of rubbish—testimony to our power to tear the ecological fabric that has, for millions of years, sustained the planet's life.

Suddenly we have discovered what we should have known long before: that the ecosphere sustains people and everything that they do; that anything that fails to fit into the ecosphere is a threat to its finely balanced cycles; that wastes are not only unpleasant, not only toxic, but, more meaningfully, evidence that the ecosphere is being driven towards collapse.

If we are to survive, we must understand *why* this collapse now threatens. Here, the issues become far more complex than even the ecosphere. Our assaults on the ecosystem are so powerful, so numerous, so finely interconnected, that although the damage they do is clear, it is very difficult to discover how it was done. By which weapon? In whose hand? Are we driving the ecosphere to destruction simply by our growing numbers? By our greedy accumulation of wealth? Or are the machines which we have built to gain this wealth—the magnificent technology that now feeds us out of neat packages, that clothes us in man-made fibers, that surrounds us with new chemical creations—at fault?

This book is concerned with these questions. It begins with the ecosphere, the setting in which civilization has done its great—and terrible—deeds. Then it moves to a description of some of the damage we have done to the ecosphere—to the air, the water, the soil. However, by now such horror stories of environmental destruction are familiar, even tiresome. Much less clear is what we need to learn from them, and so I have chosen less to shed tears for our past mistakes than to try to understand them. Most of this book is an effort to discover which human acts have broken the circle of life, and why. I trace the environmental crisis from its overt manifestations in the ecosphere to the ecological stresses which they reflect, to the faults in productive technology—and in its scientific background—that generate these stresses, and finally to the economic, social, and political forces which have driven us down this self-destructive course. All this in the hope—and expectation—that once we understand the origins of the environmental crisis, we can begin to manage the huge undertaking of surviving it.

2

THE ECOSPHERE

To survive on the earth, human beings require the stable, continuing existence of a suitable environment. Yet the evidence is overwhelming that the way in which we now live on the earth is driving its thin, life-supporting skin, and ourselves with it, to destruction. To understand this calamity, we need to begin with a close look at the nature of the environment itself. Most of us find this a difficult thing to do, for there is a kind of ambiguity in our relation to the environment. Biologically, human beings *participate* in the environmental system as subsidiary parts of the whole. Yet, human society is designed to *exploit* the environment as a whole, to produce wealth. The paradoxical role we play in the natural environment—at once participant and exploiter—distorts our perception of it.

Among primitive people, a person is seen as a dependent part of nature, a frail reed in a harsh world governed by natural laws that must be obeyed if he is to survive. Pressed by this need, primitive peoples can achieve a remarkable knowledge of their environment. The African Bushman lives in one of the most stringent habitats on earth; food and water are scarce, and the weather is extreme. The Bushman survives because he has an incredibly intimate understanding of this environment. A Bushman can, for example, return after many months and miles of travel to find a single underground tuber, noted in his previous wanderings, when he needs it for his water supply in the dry season.

We who call ourselves advanced seem to have escaped from this kind of dependence on the environment. The Bushman must squeeze water from a searched-out tuber; we get ours by the turn of a tap. Instead of trackless terrain, we have the grid of city streets. Instead of seeking the sun's heat when we need it, or shunning it when it is too strong, we warm and cool ourselves with man-made machines. All this leads us to believe that we have made our own environment and no longer depend on the one provided by nature. In the eager search for the benefits of modern science and technology we have become enticed into a nearly fatal illusion: that through our machines we have at last escaped from dependence on the natural environment.

A good place to experience this illusion is a jet airplane. Safely seated on a plastic cushion, carried in a winged aluminum tube, streaking miles above the earth, through air nearly thin enough to boil the blood, at a speed that seems to make the sun stand still, it is easy to believe that we have conquered nature and have escaped from the ancient bondage to air, water, and soil.

But the illusion is easily shattered, for like the people it carries, the airplane is itself a creature of the earth's environment. Its engines burn fuel and oxygen produced by the earth's green plants. Traced a few steps back, every part of the craft is equally dependent on the environment. The steel came from smelters fed with coal, water, and oxygen—all nature's products. The aluminum was refined from ore using electricity, again produced by combustion of fuel and oxygen or generated by falling water. For every pound of plastic in the plane's interior, we must reckon that some amount of coal was needed to produce the power used to manufacture it. For every manufactured part, gallons of pure water were used. Without the earth's natural environmental constituents—oxygen, water, fuel—the airplane, like man, could not exist.

The environment makes up a huge, enormously complex living machine that forms a thin dynamic layer on the earth's surface, and every human activity depends on the integrity and the proper functioning of this machine. Without the photosynthetic activity of green plants, there would be no oxygen for our engines, smelters, and furnaces, let alone support for human and animal life. Without the action of the plants, animals, and microorganisms that live in them, we could have no pure water in our lakes and rivers. Without the biological processes that have gone on in the soil for thousands of years, we would have neither food crops, oil, nor coal. This machine is our biological capital, the basic apparatus on which our total productivity depends. If we destroy it, our most advanced technology will become useless and any economic and political system that depends on it will founder. The environmental crisis is a signal of this approaching catastrophe.

The global ecosystem is the product of several billion years of evolutionary change in the composition of the planet's skin. The earth is between 4.5 and 5.0 billion years old. How it was formed from the cloud of cosmic dust that produced the solar system is not yet clear. But we do know that the earth was at first a lifeless, rocky mass, bathed in an atmosphere consisting largely of water vapor, hydrogen gas, ammonia, and methane.

The basic events that, from this simple beginning, generated the complex skin of the earth, including its living inhabitants, are now fairly well known. A fundamental question concerns the origin of life. Living things are made up nearly exclusively of the same four elements—hydrogen, oxygen, carbon, and nitrogen—that comprised the earth's early atmosphere. But in living things these elements take on enormously complex molecular forms, constituting the class of *organic* compounds. The basic feature of an organic compound is a connected array of carbon atoms, arranged in a straight or branched chain, or in rings. Built into this basic structure are the other major atoms—hydrogen, oxygen, and nitrogen (and, less frequently, additional ones such as sulfur, phosphorus, and various metals) in proportions and spatial arrangements that are characteristic of each specific organic compound. The resulting variety and complexity is staggering.

What process could convert the few simple molecules in the earth's early atmosphere into the monumentally complex, yet highly selected, assemblage of organic compounds that we now find in living things? For a long time it was believed that this accomplishment was the unique capability of living things. This would mean that life, in its full chemical competence, somehow appeared in a single, spontaneous event on the earth or came to the earth through space from some other source. According to this view, the origin of life must have preceded the appearance of organic chemicals on the earth.

We now know that the reverse is true and that organic compounds were derived from the simple ingredients of the earth's early atmosphere by nonliving, geochemical processes—and themselves later gave rise to life. The geochemical origin of organic compounds has been imitated in the laboratory; a mixture of water, ammonia, and methane, exposed to ultraviolet light, an electric spark, or just heat, produces detectable amounts of such organic compounds as amino acids—which linked together become proteins. Ultraviolet light was readily available from solar radiation on the primitive earth's surface. There is now good reason to believe that under this influence the simple compounds of the earth's early atmosphere were gradually converted into a mixture of organic compounds. Thus, to use an image favored by the originator of this theory, Professor A. I. Oparin, there appeared on the earth a kind of "organic soup."

It was within this soup that the first living things developed, two to three billion years ago. How that happened is a fascinating but poorly understood problem; fortunately we do know enough about the characteristics of the first forms of life to establish their dependence—and their effects—on the environment.

It now seems quite clear that the first forms of life were nourished by the ancient earth's organic soup. All living things require organic substances as food, which is the source of both the energy that drives them and their own substance. Oxygen was lacking in the early earth's atmosphere, so that the first living things must have derived energy from organic foods without combusting them with oxygen. This type of metabolism—fermentation—is the most primitive energy-yielding process in living things; it always produces carbon dioxide.

Themselves the products of several billion years of slow geochemical processes, the first living things became, in turn, powerful agents of geochemical change. To begin with, they rapidly depleted the earth's previously accumulated store of the organic products of geochemical evolution, for this was their food. Later the first photosynthetic organisms reconverted carbon dioxide into organic substances. Then, the rapid proliferation of green plants in the tropical temperature of the early earth deposited a huge mass of organic carbon, which became in time coal, oil, and natural gas. And with the photosynthetic cleavage of the oxygen-containing water molecule, the earth acquired free oxygen in its atmosphere. Some of the oxygen was converted to ozone, an avid absorber of ultraviolet radiation. Now, for the first time, the earth's surface was shielded from solar ultraviolet radiation, a serious hazard to life. This event enabled life to emerge from the protection of its original underwater habitat. With free oxygen now available, more efficient forms of living metabolism became possible and the great evolutionary outburst of plants and animals began to populate the planet. Meanwhile terrestrial plants and microorganisms helped to convert the earth's early rocks into soil and developed within it a remarkably complex system of interdependent living things. A similar system developed in surface waters. These systems control the composition of the soil, of surface waters, and the air, and consequently regulate the weather.

There is an important lesson here. In the form in which it first appeared, the earth's life system had an inherently fatal fault: the energy it required was derived from the consumption of a *nonrenewable* resource, the geochemical store of organic matter. Had this fault not been remedied, the rapid self-propagated growth of life would have consumed the earth's original "organic soup." Life would have destroyed the condition for its own survival. Survival—a property now so deeply associated with life—became possible because of a timely evolutionary development: the emergence of the first photosynthetic organisms. These new organisms used sunlight to convert carbon dioxide and inorganic materials to fresh organic matter. This crucial event reconverted the first life-form's waste, carbon dioxide, into its food, organic compounds. It closed the loop and transformed what was a fatally linear process into a circular, self-perpetuating one. Since then the perpetuation of life on the earth has been linked to an essentially perpetual source of energy—the sun.

Here in its primitive form we see the grand scheme which has since been the basis of the remarkable continuity of life: the reciprocal interdependence of one life process on another; the mutual, interconnected development of the earth's life system and the nonliving constituents of the environment; the repeated transformation of the materials of life in great cycles, driven by the energy of the sun.

The result of this evolutionary history can be summarized in a series of propositions about the nature of life and its relation to the environment:

Living things, as a whole, emerged from the nonliving skin of the earth. Life is a very powerful form of chemistry, which, once on the earth, rapidly changed its surface. Every living thing is intimately dependent on its physical and chemical surroundings, so that as these changed, new forms of life suited to new surroundings could emerge. Life begets life, so that once new forms appeared in a favorable environment, they could proliferate and spread until they occupied every suitable environmental niche within physical reach. Every living thing is dependent on many others, either indirectly through the physical and chemical features of the environment or directly for food or a sheltering place. Within every living thing on the earth, indeed within each of its individual cells, is contained another network—on its own scale, as complex as the environmental system—made up of numerous, intricate molecules, elaborately interconnected by chemical reactions, on which the life-properties of the whole organism depend.

Few of us in the scientific community are well prepared to deal with this degree of complexity. We have been trained by modern science to think about events that are vastly more simple—how one particle bounces off another, or how molecule A reacts with molecule B. Confronted by a situation as complex as the environment and its vast array of living inhabitants, we are likely—some more than others—to attempt to reduce it in our minds to a set of separate, simple events, in the hope that their sum will somehow picture the whole. The existence of the environmental crisis warns us that this is an illusory hope. For some time now, biologists have studied isolated animals and plants, and biochemists have studied molecules isolated in test tubes, accumulating the vast, detailed literature of modern biological science. Yet these separate data have yielded no sums that explain the ecology of a lake, for instance, and its vulnerability.

I make this confession as a preliminary to my own effort, in what follows, to describe the environmental system in a way that may help us understand the present crisis. The confession is intended as a reminder that any such description rests on clumsy intellectual crutches. We have so long neglected the task of understanding natural, complex processes, such as those in the environment, that our methods are still crude and uncertain.

Consider the numerous ways of thinking about the environment. First there is its spatial complexity: how can we encompass in a unifying idea the existence, as a stable, continuing entity, of the richly populated, kaleidoscopic ambiance of a tropical jungle and the seemingly dead, unchanging desert? Then there is the multiplicity of living things in the environment: what common features can explain the environmental behavior of a mouse, a hawk, a trout, an earthworm, an ant, the bacteria of the human intestine, or the algae that color Lake Erie green? Then there is the variety of biochemical processes that are not only internal to every living thing, but that also mediate its interactions with other living things and the environment: how can we hold within a single set of ideas photosynthesis, the fermentative decay of organic matter, oxygen-requiring combustion, or the intricate chemical dependence of one organism on another which leads to parasitism?

Each of these separate views of the environmental system is only a narrow slice through the complex whole. While each can illuminate some features of the whole system, the picture it yields is necessarily false to a degree. For in looking at one set of relationships we inevitably ignore a good deal of the rest; yet in the real world everything in the environment is connected to everything else.

One interesting slice through the environment can be taken by tracing the movement of the chemical elements that make up the environmental system. A good choice is the element nitrogen—a crucial constituent of both life and the nonliving environment. The four chemical elements that make up the bulk of living matter—carbon, hydrogen, oxygen, and nitrogen—move in great, interwoven cycles through the ecosphere: now a component of the air, now a constituent of a living organism, now part of some waste product in water, after a time perhaps built into mineral deposits or fossil remains.

Among these four elements of life, nitrogen is particularly important because it is so sensitive an indicator of the quality of life. A first sign of human poverty is a reduced intake of nitrogenous food. A certain outcome is poor health, for so much of the body's vital machinery is made of nitrogen-bearing molecules: proteins, nucleic acids, enzymes, vitamins, and hormones. Nitrogen is, therefore, closely coupled to human needs, and, as we shall see, the global processes that govern the movement of nitrogen are in a particularly delicate balance.

In the ecosphere, nitrogen is found in relatively few basic chemical forms. A striking feature of nitrogen chemistry is that molecules that contain nitrogen linked to oxygen are rather rare. About 80 per cent of the earth's nitrogen is in the air as chemically inert nitrogen gas. Of the remaining 20 per cent, a good deal is a part of the soil's humus, a very complex organic substance. Another significant fraction is contained in living things—almost entirely as organic compounds.

With these facts as a guide, let us look at some features of the nitrogen cycle in the natural environment. The soil is a useful place to begin, for it is, of course, the initial source of nearly all food and many industrial raw materials. The soil is a vastly complex ecosystem, the result of an intricate balance among a wide variety of microorganisms, animals, and plants, acting on a long-established physical substrate.

Nitrogen can enter the soil through nitrogen fixation, a process carried out by various bacteria and algae, some of them living free in the soil and others associated with the roots of legumes such as clover or with the leaves of some tropical plants. Nitrogen also enters the soil from the decay of plant matter and of animal wastes. Much of it eventually becomes incorporated into the soil's humus. Humus slowly releases nitrogen through the action of soil microorganisms, which finally convert it into nitrate. In turn, the nitrate is taken up by the roots of plants and is made into protein and other vital parts of the crop. In nature the plants become food for animals, animal wastes are returned to the soil, and the cycle is complete.

By far the slowest step in this cycle is the release of nitrate from humus. As a result, the natural concentration of nitrate in the soil water is very low and the roots need to work to pull it into the plant. For this work the plant must expend energy, which is released by biological oxidation processes in the roots. The required oxygen must reach the roots from the air, a process that is efficient only if the soil is sufficiently porous. Soil porosity is very dependent on its humus content, for humus has a very spongy structure. Thus, soil porosity, therefore its oxygen content, and hence the efficiency of nutrient absorption by plant roots are closely related to the humus content of the soil. The efficient growth of the plant reconverts inorganic nutrients into organic matter (the plant substance), which when decayed in the soil contributes to its humus content, thus enhancing the soil's porosity and thereby supporting efficient plant growth.

It is useful to pause at this point and consider the implications of the two sets of relationships that have just been described: one the over-all movement of nitrogen atoms through the soil cycle, the other the interdependence of the plant's efficient growth and the structure of the soil. Note that the two cycles are not of the same sort. One describes the literal movement of a physical entity, the nitrogen atom; the other is more abstract, involving a set of dependencies of one process on another. The two cycles are strongly connected at a crucial point—humus. In one cycle, humus is the major store of soil nitrogen for plant growth; in the other, it is responsible for the physical condition of the soil that enables the efficient use of nutrients, including nitrogen released from the humus.

This duality in the role of humus in the soil amplifies the effects of changes in soil condition. Thus, if the soil's humus content declines, the availability of nitrate for plant growth is reduced. Since at the same time the efficiency of nitrate absorption by the roots also falls, the effect of humus on plant growth is self-accelerating. Or, viewed in the opposite sense, adequate soil humus ensures not only a good supply of nutrient nitrogen, but also its thrifty use by the plant. Any environmental agent, such as humus, that links two or more cycles is likely to play a powerful role in the system as a whole. Such a link enhances the complexity of the system, the fineness of its network, and thereby contributes to its stability. For this very reason, when such a link is weakened, the ecological fabric is likely to unravel.

Obviously, to appreciate the crucial significance of a link such as humus, we must see it, simultaneously, in *both* its roles. Unfortunately this type of vision is not fostered by the kind of specialization that isolates biologists into separate camps: experts on soil structure *or* on plant nutrition. As we shall see a little later on, the natural tendency to think of only one thing at a time is a chief reason why we have failed to understand the environment and have blundered into destroying it.

In natural waters a similar nitrogen cycle prevails, except that the large reserve of organic nitrogen, represented in the soil by humus, is lacking. In aquatic ecosystems, nitrogen moves cyclically through the following closed sequence: fish produce organic wastes; decaying microorganisms release nitrogen from organic forms and combine it with oxygen to form nitrate; this is reconverted to organic forms by algae; algal organic matter nourishes small aquatic animals; these in turn are eaten by the fish. The balance between the rate of decay of organic materials and the rate of algal growth determines the concentrations of nitrate in the water. In nature, little nitrate reaches the water from the soil because of its thrifty use in the soil

cycle. As a result, the nitrate content of natural surface water is very low, of the order of one part per million, and the algal population is correspondingly low; the water is clear and largely free of noxious organic debris.

Compared with the other ecological arenas—soil and water—the air is the largest, most uniform around the globe and affected least directly by biological action. In nature, air is remarkably uniform in composition: about 80 per cent nitrogen gas, nearly 20 per cent oxygen gas, with a very low concentration of carbon dioxide (about .03 per cent), very much lower concentrations of a few rare gases such as helium, neon, and argon, and variable amounts of water vapor. Like everything else on earth, the behavior of the global sea of air is governed by cycles, but these involve largely physical phenomena rather than chemical or biological ones.

On a short time-scale, the air cycle is simply what we call "weather." The weather cycle is driven by the sun's energy, which bathes the earth incessantly. Any substance on the earth's surface that absorbs solar energy—for example, soil—is warmed by it unless the energy causes a change in state. Energy absorbed by ice, a solid, instead of warming it, can convert it to the liquid state—water. Energy absorbed by water either warms it or converts it to the gaseous state—water vapor. If the energy-absorbing material is readily changed in state—for example, the water in the ocean—a good part of the absorbed solar energy does not raise the temperature. So after a sunny day, the sand is hot and the water relatively cool. Before sundown, air above the hot sand, being warm and light, rises; the cooler air over the water flows in to take its place—there is a cool on-shore breeze.

Absorbed by the oceans, which cover two-thirds of the earth's surface, a good deal of the solar energy is taken up by the conversion of liquid water to water vapor—the process of evaporation. Every gram of water vapor carried in the air embodies a fixed amount of solar energy (about 536 calories per gram). When the reverse process—condensation of water vapor into liquid—occurs, this same quantity of energy is released. So, energy absorbed from the sun, say, during hot summer days in the Caribbean Sea fills the air with water vapor. As the water vapor rises from the earth's surface, it strikes the very cold air of the stratosphere and begins to condense, to form rain. For every gram of water vapor that condenses to rain, 536 calories of energy are released. This heats the air, causing it to rise; cool air rushes in near the surface to replace the rising hot air—winds are created. This is the origin of Caribbean hurricanes.

These are only small examples of weather—the daily changes in the air that bathes each place on the earth. For our purpose, the main thing to keep in mind is that the weather is a means of moving the air mass that covers a particular locale, such as a city, and a way of washing airborne materials—such as pollutants—out of it. The weather keeps the air clean. Anything that becomes airborne, caught by the weather, is eventually brought to earth where it enters the environmental cycles that operate in the water and the soil.

If there is little air movement, whatever is introduced into the air by local activities—for example, smog—tends to accumulate in the air. Still-air conditions have a way of perpetuating themselves. When air is still, it tends to develop into an upper zone of warm air and a lower zone

of cold air. This reverses the usual situation, in which the lower layers of air are warmer than the upper ones; it is therefore called an *inversion*. Since cold air is denser than warm air, vertical circulation is prevented under inversion conditions. An inversion may hold the air mass over a city in place for some days. When that happens, as it did in New York City in November 1965, pollutants may accumulate to the point of an emergency.

These weather changes are chiefly in the lower reaches of the atmosphere—the layer between the earth's surface and about 40,000 to 50,000 feet above it. Above that point is the stratosphere, where there is nearly no moisture, no clouds, no rain or snow. Some things that enter the air are so light as to escape into the stratosphere, where they may remain for a long time. Some of the radioactive debris produced by nuclear explosions is associated with such small particles, and they may remain in the stratosphere for months.

On a much longer time-scale, changes in the composition of the air can have strong effects on the amount and kind of solar radiation that reach the earth's surface. These effects are influenced by the amounts of airborne dust particles, water vapor, clouds, carbon dioxide, and ozone. Generally, water vapor and clouds have a shielding effect; radiation directed toward the earth from the sun is scattered by water droplets and much of it may then fail to reach the earth. Therefore cloudy conditions tend to reduce the earth's temperature.

Carbon dioxide has a special effect because it is transparent to most of the sun's radiation except that in the infrared region of the spectrum. In this respect, carbon dioxide is like glass, which readily transmits visible light, but reflects infrared. This is what makes glass so useful in a greenhouse in the winter. Visible energy enters through the glass, is absorbed by the soil in the greenhouse, and then is converted to heat, which is reradiated from the soil as infrared energy. But this infrared energy, reaching the greenhouse glass, is bounced back and held within the greenhouse as heat. This explains the warmth of an otherwise unheated greenhouse on a sunny winter day. Like glass, the carbon dioxide in the air that blankets the earth acts like a giant energy valve. Visible solar energy easily passes through it; reaching the earth, much of this energy is converted to heat, but the resultant infrared radiation is kept within the earth's air blanket by the heat reflection due to carbon dioxide.

Thus, the higher the carbon dioxide concentration in the air, the larger the proportion of solar radiation that is retained by the earth as heat. This explains why on the early earth, when the carbon dioxide concentration was high, the average temperature of the earth approached the tropical. Then, as great masses of plants converted much of the carbon dioxide to vegetation—which became fossilized to coal, oil, and gas—the earth became cooler. Now that we have been burning these fossil fuels and reconverting them to carbon dioxide, the carbon dioxide concentration of the atmosphere has been rising; what effect this may be having on the earth's temperature is now under intense scientific discussion.

Another constituent of the air, ozone, plays a special role in governing the radiation that is received at the earth's surface. Ozone is a chemically reactive molecule composed of three atoms of oxygen joined in a triangle. It is a good absorber of ultraviolet radiation. Ozone is

formed from oxygen, but since it reacts vigorously with substances near the earth's surface, it is present, as such, only in the upper reaches of the stratosphere. So, when the earth's atmosphere acquired its oxygen from the photosynthetic activity of green plants, the planet also acquired a high-altitude blanket of ozone. Until then the earth's surface was bathed in intense ultraviolet radiation, which was, in fact, the energy source that converted the early earth's blanket of methane, water, and ammonia into the soup of organic compounds in which the first living things originated. However, ultraviolet radiation is very damaging to the delicate balance of chemical reactions in living cells, and it is likely that the first living things survived only by growing under a layer of water sufficiently thick to protect them from the ultraviolet radiation that reached the earth's surface.

Only when oxygen was formed, and with it the protective layer of ozone, was the intensity of ultraviolet radiation on the earth's surface reduced sufficiently to allow living things to emerge from the protection of water and begin to inhabit the earth's surface. The continued existence of terrestrial life is dependent on the layer of ozone in the stratosphere—a protective device that itself is the product of life. Should the ozone in the stratosphere be reduced, terrestrial life would be seriously threatened by solar ultraviolet radiation. It is unfortunate that some human activities raise this threat. An example is the supersonic transport (the SST).

In broad outline, these are the environmental cycles which govern the behavior of the three great global systems: the air, the water, and the soil. Within each of them live many thousands of different species of living things. Each species is suited to its particular environmental niche, and each, through its life processes, affects the physical and chemical properties of its immediate environment.

Each living species is also linked to many others. These links are bewildering in their variety and marvelous in their intricate detail. An animal, such as a deer, may depend on plants for food; the plants depend on the action of soil bacteria for their nutrients; the bacteria in turn live on the organic wastes dropped by the animals on the soil. At the same time, the deer is food for the mountain lion. Insects may live on the juices of plants or gather pollen from their flowers. Other insects suck blood from animals. Bacteria may live on the internal tissues of animals and plants. Fungi degrade the bodies of dead plants and animals. All this, many times multiplied and organized species by species in intricate, precise relationships, makes up the vast network of life on the earth.

The science that studies these relationships and the processes linking each living thing to the physical and chemical environment is *ecology*. It is the science of planetary housekeeping. For the environment is, so to speak, the house created on the earth *by* living things *for* living things. It is a young science and much of what it teaches has been learned from only small segments of the whole network of life on the earth. Ecology has not yet explicitly developed the kind of cohesive, simplifying generalizations exemplified by, say, the laws of physics. Nevertheless there are a number of generalizations that are already evident in what we now know about the ecosphere and

HOWEVER BARRY COMMONER, DIRECTOR ...

HAS DEVELOPED FOUR LAWS OF ECOLOGY

that can be organized into a kind of informal set of "laws of ecology." ~~These are described in what follows.~~

The First Law of Ecology:
Everything Is Connected to Everything Else

Some of the evidence that leads to this generalization has already been discussed. It reflects the existence of the elaborate network of interconnections in the ecosphere: among different living organisms, and between populations, species, and individual organisms and their physicochemical surroundings.

38 The single fact that an ecosystem consists of multiple interconnected parts, which act on one another, has some surprising consequences. Our ability to picture the behavior of such systems has been helped considerably by the development, even more recent than ecology, of the science of cybernetics. We owe the basic concept, and the word itself, to the inventive mind of the late Norbert Wiener.

The word "cybernetics" derives from the Greek word for helmsman; it is concerned with cycles of events that steer, or govern, the behavior of a system. The helmsman is part of a system that also includes the compass, the rudder, and the ship. If the ship veers off the chosen compass course, the change shows up in the movement of the compass needle. Observed and interpreted by the helmsman this event determines a subsequent one: the helmsman turns the rudder, which swings the ship back to its original course. When this happens, the compass needle returns to its original, on-course position and the cycle is complete. If the helmsman turns the rudder too far in response to a small deflection of the compass needle, the excess swing of the ship shows up in the compass—which signals the helmsman to correct his overreaction by an opposite movement. Thus the operation of this cycle stabilizes the course of the ship.

In quite a similar way, stabilizing cybernetic relations are built into an ecological cycle. Consider, for example, the fresh-water ecological cycle: fish–organic waste–bacteria of decay–inorganic products–algae–fish. Suppose that due to unusually warm summer weather there is a rapid growth of algae. This depletes the supply of inorganic nutrients so that two sectors of the cycle, algae and nutrients, are out of balance, but in opposite directions. The operation of the ecological cycle, like that of the ship, soon brings the situation back into balance. For the excess in algae increases the ease with which fish can feed on them; this reduces the algal population, increases fish waste production, and eventually leads to an increased level of nutrients when the waste decays. Thus, the levels of algae and nutrients tend to return to their original balanced position.

In such cybernetic systems the course is not maintained by rigid control, but flexibly. Thus the ship does not move unwaveringly on its path, but actually follows it in a wavelike motion that swings equally to both sides of the true course. The frequency of these swings depends on the relative speeds of the various steps in the cycle, such as the rate at which the ship responds to the rudder.

Ecological systems exhibit similar cycles, although these are often obscured by the effects of daily or seasonal variations in weather and environmental agents. The most famous examples of such ecological oscillations

are the periodic fluctuations of the size of fur-bearing animal populations. For example, from trapping records in Canada it is known that the populations of rabbits and lynx follow ten-year fluctuations. When there are many rabbits the lynx prosper; the rising population of lynx increasingly ravages the rabbit population, reducing it; as the latter become scarce, there is insufficient food to support the now numerous lynx; as the lynx begin to die off, the rabbits are less fiercely hunted and increase in number. And so on. These oscillations are built into the operation of the simple cycle, in which the lynx population is positively related to the number of rabbits and the rabbit population is negatively related to the number of lynx.

In such an oscillating system there is always the danger that the whole system will collapse when an oscillation swings so wide of the balance point that the system can no longer compensate for it. Suppose, for example, in one particular swing of the rabbit–lynx cycle, the lynx manage to eat *all* the rabbits (or, for that matter, all but one). Now the rabbit population can no longer reproduce. As usual, the lynx begin to starve as the rabbits are consumed; but this time the drop in the lynx population is not followed by an increase in rabbits. The lynx then die off. The entire rabbit–lynx system collapses.

This is similar to the ecological collapse which accompanies what is called "eutrophication." If the nutrient level of the water becomes so high as to stimulate the rapid growth of algae, the dense algal population cannot be long sustained because of the intrinsic limitations of photosynthetic efficiency. As the thickness of the algal layer in the water increases, the light required for photosynthesis that can reach the lower parts of the algal layer becomes sharply diminished, so that any strong overgrowth of algae very quickly dies back, releasing organic debris. The organic matter level may then become so great that its decay totally depletes the oxygen content of the water. The bacteria of decay then die off, for they must have oxygen to survive. The entire aquatic cycle collapses.

The dynamic behavior of a cybernetic system—for example, the frequency of its natural oscillations, the speed with which it responds to external changes, and its over-all rate of operation—depends on the relative rates of its constituent steps. In the ship system, the compass needle swings in fractions of a second; the helmsman's reaction takes some seconds; the ship responds over a time of minutes. These different reaction times interact to produce, for example, the ship's characteristic oscillation frequency around its true course.

In the aquatic ecosystem, each biological step also has a characteristic reaction time, which depends on the metabolic and reproductive rates of the organisms involved. The time to produce a new generation of fish may be some months; of algae, a matter of days; decay bacteria can reproduce in a few hours. The metabolic rates of these organisms—that is, the rates at which they use nutrients, consume oxygen, or produce waste—is inversely related to their size. If the metabolic rate of a fish is 1, the algal rate is about 100, and the bacterial rate about 10,000.

If the entire cyclical system is to remain in balance, the over-all rate of turnover must be governed by the slowest step—in this case, the growth and metabolism of the fish. Any external effect that forces part of the cycle to operate faster than the over-all rate leads to trouble. So, for example, the rate of waste production by fish determines the rate of bacterial decay and the rate of oxygen consumption due to that decay. In a balanced situation, enough oxygen is produced by the algae and enters from the air to support the decay bacteria. Suppose that the rate at which organic waste enters the cycle is increased artificially, for example, by dumping sewage into the water. Now the decay bacteria are supplied with organic waste at a much higher level than usual; because of their rapid metabolism they are able to act quickly on the increased organic load. As a result, the rate of oxygen consumption by the decay bacteria can easily exceed the rate of oxygen production by the algae (and its rate of entry from the air) so that the oxygen level goes to zero and the system collapses. Thus, the rates of the separate processes in the cycle are in a natural state of balance which is maintained only so long as there are no external intrusions on the system. When such an effect originates outside the cycle, it is not controlled by the self-governing cyclical relations and is a threat to the stability of the whole system.

Ecosystems differ considerably in their rate characteristics and therefore vary a great deal in the speed with which they react to changed situations or approach the point of collapse. For example, aquatic ecosystems turn over much faster than soil ecosystems. Thus, an acre of richly populated marine shoreline or an acre of fish pond produces about seven times as much organic material as an acre of alfalfa annually. The slow turnover of the soil cycle is due to the rather low rate of one of its many steps—the release of nutrient from the soil's organic store, which is very much slower than the comparable step in aquatic systems.

The amount of stress which an ecosystem can absorb before it is driven to collapse is also a result of its various interconnections and their relative speeds of response. The more complex the ecosystem, the more successfully it can resist a stress. For example, in the rabbit–lynx system, if the lynx had an alternative source of food they might survive the sudden depletion of rabbits. In this way, branching—which establishes alternative pathways—increases the resistance of an ecosystem to stress. Most ecosystems are so complex that the cycles are not simple circular paths, but are crisscrossed with branches to form a network or a fabric of interconnections. Like a net, in which each knot is connected to others by several strands, such a fabric can resist collapse better than a simple, unbranched circle of threads—which if cut anywhere breaks down as a whole. Environmental pollution is often a sign that ecological links have been cut and that the ecosystem has been artificially simplified and made more vulnerable to stress and to final collapse.

The feedback characteristics of ecosystems result in amplification and intensification processes of considerable magnitude. For example, the fact that in food chains small organisms are eaten by bigger ones and the latter by still bigger ones inevitably results in the concentration of certain environmental constituents in the bodies of the largest organisms at the top of the food chain. Smaller organisms always exhibit much higher metabolic rates than larger ones, so that the amount of their food which is oxidized relative to the amount incorporated into the body of the organism is thereby greater. Consequently, an animal at the top of the food chain depends on the consumption of an enormously greater mass of the bodies of organisms lower down in the food chain. Therefore, any *non*metabolized material present in the lower organisms of this chain will become concentrated in the body of the top one. Thus, if the concentration of DDT (which is not readily metabolized) in the soil is 1 unit, earthworms living in the soil will achieve a concentration of from 10 to 40 units, and in woodcocks feeding on the earthworms the DDT level will rise to about 200 units.

All this results from a simple fact about ecosystems—everything is connected to everything else: the system is stabilized by its dynamic self-compensating properties; these same properties, if overstressed, can lead to a dramatic collapse; the complexity of the ecological network and its intrinsic rate of turnover determine how much it can be stressed, and for how long, without collapsing; the ecological network is an amplifier, so that a small perturbation in one place may have large, distant, long-delayed effects.

The Second Law of Ecology: Everything Must Go Somewhere

This is, ~~of course~~, simply a somewhat informal restatement of a basic law of physics—that matter is indestructible. Applied to ecology, the law emphasizes that in nature there is no such thing as "waste." In every natural system, what is excreted by one organism as waste is taken up by another as food. Animals release carbon dioxide as a respiratory waste; this is an essential nutrient for green plants. Plants excrete oxygen, which is used by animals.

Animal organic wastes nourish the bacteria of decay. Their wastes, inorganic materials such as nitrate, phosphate, and carbon dioxide, become algal nutrients.

A persistent effort to answer the question "Where does it go?" can yield a surprising amount of valuable information about an ecosystem. Consider, for example, the fate of a household item which contains mercury—a substance with serious environmental effects that have just recently surfaced. A dry-cell battery containing mercury is purchased, used to the point of exhaustion, and then "thrown out." But where does it really go? First it is placed in a container of rubbish; this is collected and taken to an incinerator. Here the mercury is heated; this produces mercury vapor which is emitted by the incinerator stack, and mercury *vapor* is toxic. Mercury vapor is carried by the wind, eventually brought to earth in rain or snow. Entering a mountain lake, let us say, the mercury condenses and sinks to the bottom. Here it is acted on by bacteria which convert it to methyl mercury. This is soluble and taken up by fish; since it is not metabolized, the mercury accumulates in the organs and flesh of the fish. The fish is caught and eaten by a man and the mercury becomes deposited in his organs, where it might be harmful. And so on.

This is an effective way to trace out an ecological path. It is also an excellent way to counteract the prevalent notion that something which is regarded as useless simply "goes away" when it is discarded. Nothing "goes away"; it is simply transferred from place to place, converted from one molecular form to another, acting on the life processes of any organism in which it becomes, for a time, lodged. One of the chief reasons for the present environmental crisis is that great amounts of materials have been extracted from the earth, converted into new forms, and discharged into the environment without taking into account that "everything has to go somewhere." The result, too often, is the accumulation of harmful amounts of material in places where, in nature, they do not belong.

The Third Law of Ecology: Nature Knows Best

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~~I have found it useful to explain~~ this principle by means of an analogy." Suppose you were to open the back of your watch, close your eyes, and poke a pencil into the exposed works. The almost certain result would be damage to the watch. Nevertheless, this result is not *absolutely* certain. There is some finite possibility that the watch was out of adjustment and that the random thrust of the pencil happened to make the precise change needed to improve it. However, this outcome is exceed-

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There is a close, and very meaningful, analogy in biological systems. It is possible to induce a certain range of random, inherited changes in a living thing by treating it with an agent, such as x-irradiation, that increases the frequency of mutations. Generally, exposure to x-rays increases the frequency of all mutations which have been observed, albeit very infrequently, in nature and can therefore be regarded as *possible* changes. What is significant, for our purpose, is the universal observation that when mutation frequency is enhanced by x-rays or other means, nearly all the mutations are harmful to the organisms and the great majority so damaging as to kill the organism before it is fully formed.

In other words, like the watch, a living organism that is forced to sustain a random change in its organization is almost certain to be damaged rather than improved. And in both cases, the explanation is the same—a great deal of "R & D." In effect there are some two to three billion years of "R & D" behind every living thing. In that time, a staggering number of new individual living things have been produced, affording in each case the opportunity to try out the suitability of some random genetic change. If the change damages the viability of the organism, it is likely to kill it before the change can be passed on to future generations. In this way, living things accumulate a complex organization of compatible parts; those possible arrangements that are not compatible with the whole are screened out over the long course of evolution. Thus, the structure of a present living thing or the organization of a current natural ecosystem is likely to be "best" in the sense that it has been so heavily screened for disadvantageous components that any new one is very likely to be worse than the present ones.

This principle is particularly relevant to the field of organic chemistry. Living things are composed of many thousands of different organic compounds, and it is sometimes imagined that at least some of these might be improved upon if they were replaced by some man-made variant of the natural substance. The third law of ecology suggests that the artificial introduction of an organic compound that does not occur in nature, but is man-made and is nevertheless active in a living system, is very likely to be harmful.

This is due to the fact that the varieties of chemical substances actually found in living things are vastly more restricted than the *possible* varieties. A striking illustration is that if one molecule each of all the possible types of proteins were made, they would together weigh more than the observable universe. Obviously there are a fantastically large number of protein types that are *not* made by living cells. And on the basis of the foregoing, one would reason that many of these possible protein types were once formed in some particular living things, found to be harmful, and rejected through the death of the experiment. In the same way, living cells synthesize fatty acids (a type of organic molecule that contains carbon chains of various lengths) with even-numbered carbon chain lengths (i.e., 4, 6, 8, etc., carbons), but no fatty acids with odd-numbered carbon chain lengths. This suggests that the latter have once been tried out and found wanting. Similarly, organic compounds that contain attached nitrogen and oxygen atoms are singularly rare in living things. This should warn us that the artificial introduction of substances of this type would be dangerous. This is indeed the case, for such substances are usually toxic and frequently carcinogenic. And, I would suppose from the fact that DDT is nowhere found in nature, that somewhere, at some time in the past, some unfortunate cell synthesized this molecule—and died.

One of the striking facts about the chemistry of living systems is that for every organic substance produced by a living organism, there exists, somewhere in nature, an enzyme capable of breaking that substance down. In effect, no organic substance is synthesized unless there is provision for its degradation; recycling is thus enforced. Thus, when a new man-made organic substance is synthesized with a molecular structure that departs significantly from the types which occur in nature, it is probable that no degradative enzyme exists, and the material tends to accumulate.

Given these considerations, it would be prudent, I believe, to regard every man-made organic chemical *not* found in nature which has a strong action on any one organism as potentially dangerous to other forms of life. Operationally, this view means that all man-made organic compounds that are at all active biologically ought to be treated as we do drugs, or rather as we *should* treat them —prudently, cautiously. Such caution or prudence is, of course, impossible when billions of pounds of the substance are produced and broadly disseminated into the ecosystem where it can reach and affect numerous organisms not under our observation. Yet this is precisely what we have done with detergents, insecticides, and herbicides. The often catastrophic results lend considerable force to the view that "Nature knows best."

The Fourth Law of Ecology: There Is No Such Thing as a Free Lunch

In my experience, this idea has proven so illuminating for environmental problems that I have borrowed it from its original source, economics. The "law" derives from a story that economists like to tell about an oil-rich potentate who decided that his new wealth needed the guidance of economic science. Accordingly he ordered his advisers, on pain of death, to produce a set of volumes containing all the wisdom of economics. When the tomes arrived, the potentate was impatient and again issued an order—to reduce all the knowledge of economics to a single volume. The story goes on in this vein, as such stories will, until the advisers are required, if they are to survive, to reduce the totality of economic science to a single sentence. This is the origin of the "free lunch" law.

In ecology, as in economics, the law is intended to warn that every gain is won at some cost. In a way, this ecological law embodies the previous three laws. Because the global ecosystem is a connected whole, in which nothing can be gained or lost and which is not subject to over-all improvement, anything extracted from it by human effort must be replaced. Payment of this price cannot be avoided; it can only be delayed. The present environmental crisis is a warning that we have delayed nearly too long.

The preceding pages provide a view of the web of life on the earth. An effort has been made to develop this view from available facts, through logical relations, into a set of comprehensive generalizations. In other words, the effort has been scientific.

Nevertheless, it is difficult to ignore the embarrassing fact that the final generalizations which emerge from all this—the four laws of ecology—are ideas that have been widely held by many people without any scientific analysis or professional authorization. The complex web in which all life is enmeshed, and man's place in it, are clearly—and beautifully—described in the poems of Walt Whitman. A great deal about the interplay of the physical features of the environment and the creatures that inhabit it can be learned from *Moby Dick*. Mark Twain is not only a marvelous source of wisdom about the nature of the environment of the United States from the Mississippi westward, but also a rather incisive critic of the irrelevance of science which loses connection to the realities of life. As the critic Leo Marx reminds us, "Anyone familiar with the work of the classic American writers (I am thinking of men like Cooper, Emerson, Thoreau, Melville, Whitman, and Mark Twain) is likely to have developed an interest in what we recently have learned to call ecology."

Unfortunately, this literary heritage has not been enough to save us from ecological disaster. After all, every American technician, industrialist, agriculturalist, or public official who has has condoned or participated in the assault on the environment has read at least some of Cooper, Emerson, Thoreau, Melville, Whitman, and Mark Twain. Many of them are campers, bird-watchers, or avid fishermen, and therefore to some degree personally aware of the natural processes that the science of ecology hopes to elucidate. Nevertheless, most of them were taken unawares by the environmental crisis, failing to understand, apparently, that Thoreau's woods, Mark Twain's rivers, and Melville's oceans are *today* under attack.

The rising miasma of pollution has helped us to achieve this understanding. For, in Leo Marx's words, "The current environmental crisis has in a sense put a literal, factual, often quantifiable base under this poetic idea [i.e., the need for human harmony with nature]." This is perhaps the major value of the effort to show that the simple generalizations which have already emerged from perceptive human contact with the natural world have a valid base in the facts and principles of a science, ecology. Thus linked to science, these ideas become tools for restoring the damage inflicted on nature by the environmental crisis.