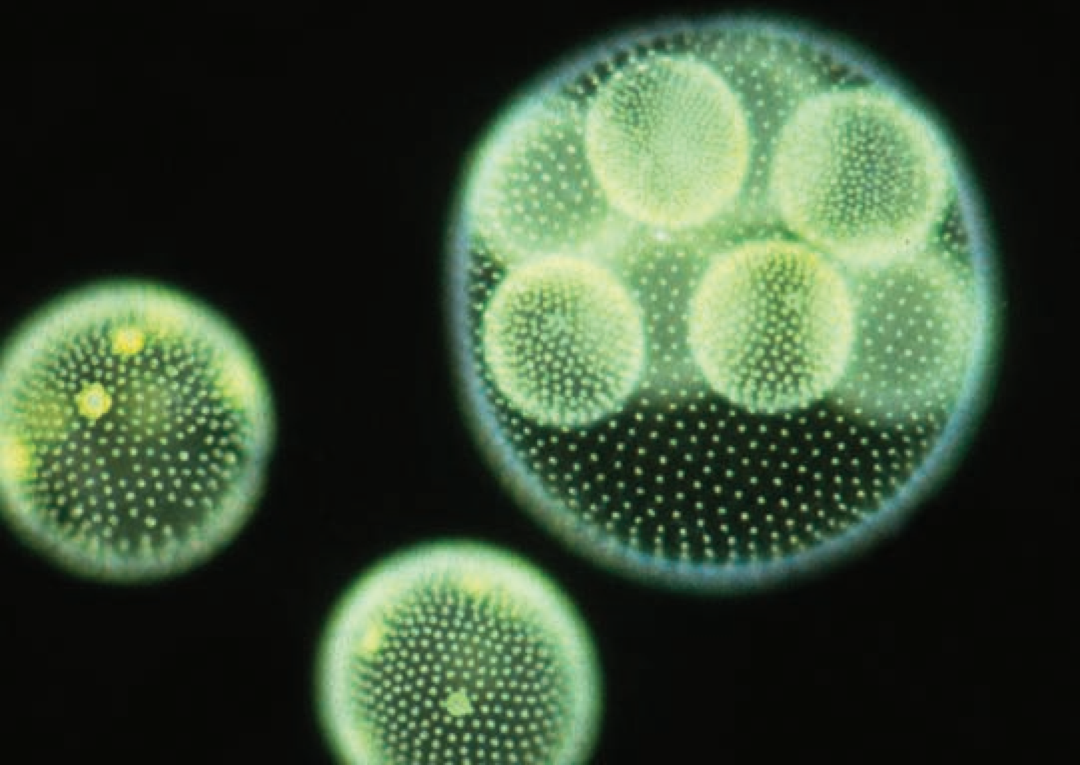
WILLIAM F. LOOMIS

# LIFE AS IT IS

## BIOLOGY FOR THE PUBLIC SPHERE



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# THE VALUE OF LIFE

FOR THE LAST HUNDRED YEARS, WE HAVE HAD FRONT ROW SEATS AT one of the greatest shows on earth—the birth and flowering of modern biological sciences. The insights and techniques for understanding the roles of specific macromolecules in the functions of cells and organisms have transformed biology from a descriptive to a predictive science. Over the years, universal rules have been proposed, considered, rejected, modified, and accepted. The baroque activities of cells during the development of embryos have been laid bare by molecular color coding of each cell type as it arises. Embryogenesis is no longer a mysterious process with long lists of names for the different structures we see in fish, birds, and mammals. It is a play of genes and proteins, and in it the potential that lies in every fertilized egg unfolds.

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FIGURE 1.0 Radiation of the eukaryotes. This tree is rooted on a set of archaebacteria. Single-celled protists diverged before the split between plants and animals. The positions of the nodes and the branch lengths are quantitatively determined by genomic comparisons.

When we can see each act of the play, we learn about ourselves, for each of us was once a fertilized egg. The principal actors are the ancient genes that evolved long ago in other roles, and which have taken on new parts by subtle changes in their makeup. The realization that all life is connected at the basic level changes how we think about life. We can learn about ourselves by studying simpler life-forms, testing treatments in model organisms, and treating cells for what they are, rather than what they might become. We can consider how the brain develops emotions, feelings, thoughts, and memories, and how it generates a sense of self and a feeling of responsibility. The science of mind can be used to tackle the problems that come from having such an overdeveloped organ as the brain.

We are the only beings on the planet who carry on a continuous internal conversation with ourselves, the only ones with a movie-in-the-brain that plays images of people and things from the past, the present, and the future. It makes us a curious species with high self-regard. And because we think we're special, we often lose sight of our basic nature. In writing this book, I have tried to use modern biological insights to think sensibly about a whole lot of things—birth, death, cloning, abortion, euthanasia, evolution, individuality, consciousness, and morality. Only when we see life on earth as a grand and precarious creation that we are a part of, not apart from, will we be able to pass on our resources and knowledge to future generations.

Modern biology has also raised thorny questions as never before. Like the rebel god Prometheus, molecular biology has brought us the power to light up the darkness or burn down the house. Knowing how genes work opens up avenues for a healthier life, or it can shake the foundations of our society. The ability to clone both genes and organisms has begun a new era in biology. There are no rebel gods in this story, although there are heroes and a few charlatans. Mostly this book is an attempt to offer a reasoned discussion of the difficult problems facing every society given the new knowledge. Forethought (which is the translation of the name Prometheus) can be used to see the road ahead and to attempt to avoid the worst of the potholes. However, we should never lose sight of the preciousness and excitement of life. It is the greatest adventure we will ever know.

## THE NATURE OF LIFE

Life is everywhere—in the air, on the soil, in the oceans. Birds fly, mammals run, fish swim, plants grow tall. But by almost any way of counting or weighing, most living matter on this planet is made up of organisms that grow and divide as single cells too small to see with the naked eye. They are the bacteria and algae that have flourished in the seas for billions of years. Over the first two billion years, they slowly changed the very chemistry of the earth's surface, so that the atmosphere became rich in oxygen. Once this happened, most of these early organisms had to retreat to deep, dark regions that were still anaerobic, but a few were able to survive the toxicity of oxygen and live near the surface. They evolved the ability to use oxygen's reactive properties to burn nutrients more efficiently and generate energy at a high rate. These aerobic organisms gave rise to multicellular organisms that could use their size to graze on smaller cells. Organisms that you could see with the naked eye appeared about a billion years ago and gave rise to the animals and plants that we have around us now. Only in the last 10 million years did the great apes come out of the primate line, and one of them evolved into us, *Homo sapiens.* The children of primates are born almost defenseless and need to be nurtured for a long period before they are able to fend for themselves. Nurtured life is one of the most precious things in the world. But, given all the bacteria and algae that divide to give rise to new cells every day, life itself is cheap.

It is only we humans who ask, "What is life?" We ask when life begins—Is it when an egg is fertilized by a sperm? When the egg divides? When it gives rise to an embryo that can live on its own? Or only when it is born? We ask, when is life over—Is it when the heart stops? When all brain activity has ceased? Or when the probability of recovery is negligible? Or is it when the body grows cold and rigor mortis sets in? These are important questions, but they are asked as if only mammals mattered. Perhaps it would be useful to first think of life from the broader point of view of all organisms and then return to the especially human aspects of life.

"What is the characteristic feature of life? When is a piece of matter said to be alive?" wrote Erwin Schroedinger in his book *What Is Life?* His answer was, "When it goes on 'doing something', moving, exchanging material with its environment, and so forth, and that for a much longer period than we would expect an inanimate piece of matter to 'keep going' under similar circumstances" (Schroedinger 1944). Living things might continue to move after the point when a pebble would have stopped. They might continue to grow after the point when a gel would have swollen to its full extent. They might continue to divide in a regular fashion after the point when a sand castle would have fallen down. Dead things stop after a while, but living things keep on going. In fact, they have been growing, dividing, and changing since life first arose on this planet.

All living forms consist of single cells or groups of cells that take up matter or energy from the environment, grow, and divide to increase their number. Most of them can move in one way or another to find a better source of food or energy, or to fit better into the structure of a tissue. Cells are usually too small to see with the unaided eye, but a few become enormous. An ostrich egg is a single cell, but after fertilization it quickly divides up into millions of cells, so that each cell in an ostrich chick is about ten micrometers in diameter and could fit on the point of a needle. Bacteria are even smaller, some as small as one micrometer in diameter, which is about the theoretical limit for a cell. You need a good microscope to see bacteria.

All cells are surrounded by a membrane with a central layer of fatty acids that limits the flow of water and small molecules back and forth between the cell and the environment. These membranes give each cell a degree of individuality and privacy while not precluding cooperation. Chemical reactions go on inside the cellular membrane and convert substances taken up from the environment into needed molecules. The reactions that together form the central metabolic pathways interconnecting most of the common subunits are found in all cells. These reactions are catalyzed by a set of proteins that fold in a manner that permits them to distinguish among the small molecules and bind only to some and not others. Proteins are long chains of twenty to two hundred amino acids in a row, where any of twenty different amino acids can be found at any position. However, each protein has a unique sequence that determines the shape it will take up. If all possible sequences of one hundred amino acids are considered, there could be $20^{100}$ different sequences. But only a tiny fraction of the total number of possible sequences is found in any living being. Proteins able to catalyze the same chemical reaction in cells of different types often have very similar amino acid sequences.

For instance, a bacterial protein that catalyzes the interconversion of two small molecules during the fermentation of glucose has almost the same sequence as the protein that catalyzes the same reaction in humans. Either only a few of the $20^{100}$ possible sequences fold in the right way to catalyze this reaction, or bacteria and humans inherited the information to make this enzyme from a common ancestor and have not changed it much ever since. The first possibility can be ruled out, because we know of proteins in archaebacteria with sequences almost completely different from those in bacteria that catalyze this reaction. They take up the proper shape to distinguish the three-carbon compound from other very similar small molecules. The archaebacterial sequence has one short run of 5 amino acids that are in the same order as a run of amino acids in the bacterial enzyme, but other similarities in the sequence are few and far between. Although the archaebacterial and bacterial sequences may be distantly related, it is clear that proteins with little similarity in sequence can catalyze the same reactions. So why are almost half the amino acids in this 248-amino acid chain identical in the enzyme in humans and the enzymes in several bacterial species? A shared ancestral sequence that has been inherited for billions of generations is the likely answer.

A comparison of the sequence of this protein—which is called triose phosphate isomerase—found in rabbits and the same protein in humans shows the two proteins are 98 percent identical. Out of the 248 amino acids in a row, only 2 in rabbits, 4 in dogs, and 1 in chimpanzees differ from the human sequence. In fact, there is no question that all mammals inherited the ability to string amino acids together in the same sequence in this enzyme. Since 159 of the amino acids in triose phosphate isomerase are in the exact same order in some plants, and over 100 amino acids are identical in some bacteria, it appears that this is an ancient sequence inherited from a cell that long ago gave rise to not only bacteria but also plants and animals. This is not the only protein inherited from a common universal ancestor: thousands of proteins appear to be shared between plants and animals, and many of them clearly had a bacterial origin. The sequences vary to a certain degree in the different organisms, but they are all very similar, and the similarity could not have arisen twice by luck alone. The chance that they are unrelated is less than 1 in $10^{50}$, a number so small that it can be safely ignored.

The evidence that all life on this planet is related goes on and on (Loomis 1988). Once life originated, it thrived, giving rise to unimaginably huge numbers of cells. Some of the progeny slowly changed and gradually produced all the diversity of life we see around us. There are several arguments that the first cells on earth were similar to the bacteria that live today. Rocks that are more than 3 billion years old show signs that they were made by deposits collected around colonies of bacteria. And there are fossil traces in other rocks of the same age that resemble strings of bacteria. Fossils of the kinds of cells that make up plants and animals first appear in rocks that are a billion years old. These cells, called eukaryotes, are characterized by being larger and carrying their chromosomes in a nuclear envelope. It is not surprising that bacteria preceded eukaryotes, since simpler cells with a single membrane on the outside would be expected to evolve before cells with a nucleus. It is likely that one of these simpler cells, which had had the world to themselves for so long, gave rise to a rare variant with internal compartments, which then shared the planet with them.

## TIME AND DESCENT

Until recently, history was told in epic tales passed on within tribes. Elders would recite the stories they had heard as children around the campfires, and their children and grandchildren would listen and pass them on years later. The stories changed as old memories faded and recent events were more vividly recalled. By the time these stories were written down, starting about three thousand years ago, the origins of the tribe were clothed in poetry and given supernatural meaning. Some of the myths and stories seemed to stretch back to the beginning of time. Tribes that traced their lineage back for five hundred or a thousand years could conceive of a distant past when all things were new. A few thousand years seemed such an immense period of time that it could include the creation of the fish of the seas, birds of the air, and beasts of the land. Beautiful creation stories were written and recited.

For a long time the tales filled the need to account for the known world and all that was in it. But travelers came with seashells found in the rocks at the tops of mountains. How could they ever have gotten there? Fossils of organisms with forms never before seen started to pile up that required fanciful additions to the creation stories. It slowly dawned on people that the earth must be much older than a few thousand years. In the nineteenth century, geologists such as Charles Lyell realized that some rocks were very old. His friend Charles Darwin took a copy of his book *Principles of Geology* on the voyage of the *Beagle* in 1831. In this book Lyell argues that slow changes in the earth had raised seafloors into mountains and then eroded them away over millions of years. In 1867 Lyell estimated the start of the Ordovician period at 240 million years ago based on the fossil record. We now know it began about 500 million years ago, but it was not a bad guess.

In 1907, Bertram Boltwood came up with a whole new way of dating rocks. He realized that radioactive uranium spontaneously decayed through a series of elements until it turned into lead. The decay was slow and continuous and provided a sort of clock. The half-life of uranium$^{238}$ could be measured, and was found to be 4.5 billion years. So the older the rocks, the more the uranium$^{238}$ would have turned into lead$^{206}$. By measuring the content of lead in uranium ore that was available, Boltwood estimated the age of the earth to be at least 2 billion years. No attempts were made to find older ore at that time. When isotope chronology techniques were applied to a dozen or so meteorites, they were all found to be 4.5 billion years old. These rocks had been in cold, deep space, where nothing happened that could affect the decay of atoms or the retention of the daughter atoms. Their atoms had been decaying since the formation of the solar system. Various independent radiometric dating procedures, including decay of rubidium$^{87}$ to strontium$^{87}$ (half-life 49 billion years) and ratios of lead isotopes, have been applied to meteorites and ancient earth rocks and found to give almost identical ages.

The oldest rocks found on the surface of the earth have been dated to 4 billion years. They are found in the Acasta Gneiss rock outcrop in western Canada near Great Slave Lake. Very few outcroppings as old as these have been found elsewhere. However, there are rocks near Warrawoona in western Australia that date from 3.5 billion years ago, and some of these contain what appear to be fossil bacteria (Knoll 2003). In the last century, as we have come to realize that life on earth is billions, not thousands, of years old, it has become clear that we must learn to think across vast expanses of time that dwarf our concepts of history. Just as we have to think small when we look into a microscope to see the tiny bacteria that crowd every puddle, we must stretch our thoughts to encompass billions of years during which evolution slowly shaped the forms of life. From the beginning, life gave rise to life. Small changes led to cells better able to cope and multiply. Evolution continued at its slow pace for billions of years. It may be humbling to think that we are at the tag end of a very long story. But what a story it is. A single line goes on for four billion years!

Heredity insures that information available in one generation is passed on to the next, and that a variant trait reappears in subsequent copies so that it can be perpetuated in the lineage.

Natural selection determines whether or not the trait spreads through the population in generations to come. This is Darwin's descent with modifications.

The information necessary to string together a specific sequence of amino acids in a protein is encoded in the sequence of another class of long polymers, the nucleic acids DNA and RNA. These molecules are long chains made from only four different subunits. The nucleosides adenosine (A), thymine (T) (uridine in RNA), guanosine (G), and cytosine (C) are bound to each other by phosphate groups linking the sugar groups that are common to them all. The information is in the specific sequence of As, Ts, Gs, and Cs. The sequence is read out in groups of three, so that each of the twenty amino acids used in proteins can be specified. What is surprising is that the readout of the code is exactly the same in archaebacteria, bacteria, and all eukaryotes. The triplet ATG encodes one of the amino acids, methionine, in the bacterium *Escherichia coli*, the Archaea *Thermoplasma volcanium*, and humans. Moreover, the first amino acid in every protein found in living cells is methionine, and the first triplet, or codon, is always ATG. The other nineteen amino acids are encoded by other combinations of three nucleosides. The mechanism for determining where to start translating a nucleic acid begins with an ATG and then translates the rest of the sequence in groups of three bases. This holds for every bacterium that has been studied, as well as every plant and animal. Because the readout is the same in all organisms, human genes can be expressed in bacteria, and bacterial genes work fine in human cells.

The universality of the code, as well as details of the shared translation process by themselves, provides convincing evidence that all life is descended from a single cell that arose billions of years ago. The code itself appears to be a historical accident and could have been very different, but once it was in place in a successful cell, it could not change, since it is used in making every protein. Any change in a codon would result in a change in the amino acid sequence wherever the amino acid was specified. No cell could survive with changes in all its proteins. So we have all stayed with the same set of codons, although the sequence of amino acids differs to some extent in our proteins. This commonality is so striking that there is no question that all life on earth is related at this fundamental level. The nature of life can be considered for archaebacteria that live at volcanic vents under the sea just as much as for birds in the air.

Many plants and bacteria don't move on their own, and so we cannot look to movement alone as a sign of life. But they all grow and divide and have been doing so for billions of years. A microbiologist does not question whether a bacterium is alive or dead. Either it can give rise to progeny or it can't. When a population of living bacteria is diluted and spread on a suitable food source, each cell will give rise to millions that pile up into a colony that can be easily seen on a Petri dish. If the population has been harmed, say by irradiation with strong ultraviolet light or with X-rays, many cells will be unable to give rise to viable progeny, and the number of colonies will be far fewer than the number of cells plated. If the irradiation is carried on for long, there may be no colonies at all because all the cells will be killed. Immediately after lethal irradiation, many of the cells will continue to metabolize nutrients, generate the chemical energy (ATP) that powers many reactions, and even make new proteins. But their nucleic acids will have been irreversibly harmed, and any progeny cells generated by a last attempt at division will not grow. They will not be able to "keep going" any longer than an inanimate piece of matter under similar circumstances.

When a bird falls dead out of the air, there is little question that it is no longer alive. However, it may stay warm for some time since its cells are still able to metabolize and generate ATP. Some muscles may twitch for a while, but soon the body will grow cold and rigor mortis will set in. Were the cells still alive when the bird first fell? If one applied the microbiologist's criterion that they could give rise to viable progeny if spread on a suitable food source in a Petri dish, they have to be considered alive. But they are bird cells and not a bird. The bird is dead.

## RANDOM MUTATIONS

The sequence of nucleosides in nucleic acids is copied before being passed on to progeny. DNA is a double-stranded helix with adenosine always found paired with thymine, and guanine found across from cytosine. Each strand has the same information, and one is the complement of the other. When they are both replicated, the information in both strands is exactly reproduced. Since only one strand directs the sequence of amino acids in proteins, there is no confusion about the code. However, if the sequence of nucleic acids in DNA were always inherited perfectly, only those proteins encoded in the first successful cell would be found in living things. Life would be restricted to bacteria-like organisms with no chance of change. However, on rare occasions, errors are made in the replication of nucleic acids that result in random changes.

The DNA replication machinery has a built-in proofreading function that immediately corrects most changes in base sequence, but about one in a million gets through. Some changes don't matter, but most are detrimental, and the cells that inherit the variants soon die out. Only a very few can provide advantages under one condition or another. Mutations result when the sequence of nucleic acid bases is not copied exactly, such as when an A is incorporated where there should be a G in the newly made strand of DNA. This error will then be propagated through the generations, unless it leads to the extinction of the line. Since each gene consists of hundreds of contiguous bases, random changes in a gene will result in random changes in the amino acid sequence of the protein it encodes. It would be like randomly changed letters in a word: "victory" might become "wictory" or "viktory" or "victori" or "cictory" or "oictory." The first three changes might still make some sense, but the last two are meaningless.

In 1943, Salvatore Luria and Max Delbruck carried out an experiment demonstrating that rare cells in a population of *Escherichia coli* were immune to a virus (Luria and Delbruck 1943). Most cells were killed by the virus, but a few (about one in a million) survived and gave rise to colonies even though they were surrounded by viruses. By diluting the population and growing small numbers of cells separately as subpopulations before adding the virus, they were able to show that the mutation in the DNA sequence appeared *before* it could do any good. In other words, before the virus was added. Only after being exposed to viruses did these rare mutations provide any advantage. It was later demonstrated that chemical mutagens increased the frequency of mutants that were subsequently shown to be resistant to viruses. The overall population was harmed by the treatment, but errors in copying the DNA in a small number of the cells made them virus resistant, and they gave rise to colonies in which all the cells were resistant. Natural selection, in the form of lethal viruses, gave the variants the ability to grow where their cousins could not.

The occurrence of rare mutants has been demonstrated in populations of many organisms, including bacteria, plants, and animals. They arise from random errors in replication of the sequence of nucleic acids. Most organisms use DNA as their hereditary material, but some viruses use RNA. Errors occur in replication of both DNA and RNA. In fact, the error rate in replicating RNA is higher as the result of having fewer proof-reading mechanisms for copies of RNA than for DNA. RNA viruses use this property to evade immune responses of their host by randomly changing surface proteins, but pay a price in efficiency. Nevertheless, RNA viruses have not gone extinct and so should be considered successful parasites.

Random mutations generated a wide variety of different bacterial strains almost as soon as cells adapted to a new environment. Some of them acquired the ability to trap sunlight and to use photosynthesis to put the third, high-energy phosphate on ATP. Others adapted to chemically rich environments such as undersea vents. For the first few billion years, they were all anaerobic because there was little or no oxygen in the air. However, a by-product of photosynthesis is molecular oxygen, which gradually filled up the atmosphere. Oxygen is highly reactive and can quickly destroy many proteins unless they are specially selected for resistance. Random mutations in some bacteria allowed them to survive in an oxygen-rich environment and use it for more efficient metabolism.

The origin of eukaryotes can be traced to a chance association between an anaerobic archaebacterium and an aerobic bacterium (Margulis and Sagan 1995). It appears that an archaebacterium engulfed a bacterium, and they set up a stable relationship in which the bacterium provided efficient metabolism and the archaebacterium provided greater accuracy of replication. Thereafter, the DNA sequences encoding oxygen-resistant proteins were passed from the bacterium to the chromosomes of the archaebacterium, and they became forever dependent on each other. All the mitochondria now working in eukaryotes are derived from the original bacterium that was engulfed.

As the oxygen level increased, so did the size of some eukaryotic cells, and they started to feed on the smaller cells around them. Natural selection must have led to an arms race, where cells grew larger so as not to be eaten and others became even bigger to continue feeding. Present-day amoebae are thousands of times larger than the bacteria they feed on and several times as big as yeast cells, which they can also engulf. Natural selection acting on the random mutations that increased size led to some truly enormous cells found among the species of slime molds and certain algae. It also led to improvements in detecting the molecules released by prey, the ability to move more rapidly and organize the cytoskeleton, and the ability to engulf and digest food. To avoid these improved predators, some cells found an advantage in sticking together after cell division, forming large colonies that were difficult to attack. This led to the multicellular organisms we are familiar with, the plants and the animals.

The similarity of amino acid sequences in enzymes catalyzing the same reaction in even the most highly diverged eukaryotes makes it very clear that they are all related. Eukaryotes could have evolved separately several times, but one line predominated early on. They are all much more closely related to each other than they are to either ancestral line, the bacterial or the archaebacterial. The degree of similarity between comparable proteins can be used to establish the hierarchy of relatedness among all living eukaryotes. When averaged over thousands of comparable proteins, those in humans have sequences that are clearly more closely related to sequences in fish than to those of the fly *Drosophila* or the mosquito *Anopheles.* Humans and fish are both vertebrates, while flies and mosquitoes are invertebrates, so this is no big surprise. On the basis of sequence comparison, we are also more closely related to plants than we are to ciliates such as *Tetrahymena*, which is related to the malarial agent *Plasmodium*

(Song et al. 2005). Yeasts diverged from the line leading to animals more recently than amoebae or plants did, but their sequences changed more rapidly for a while, perhaps because they had come on land at a time when the ultraviolet light was far stronger than it is now and the irradiation increased the rate of mutation. In any case, primary sequence analyses clearly show the close relationship of all eukaryotic organisms.

## CLEANING, WEEDING, AND HARVESTING

If the sink smells, we might pour in bleach and kill the germs. The strong chemical, sodium hypochlorite, rapidly kills bacteria and fungi and takes care of the problem. There may be billions of bacteria in the drain that are killed, but this does not concern us, because their life-forms are so different from ours that we do not relate to bacteria or fungi. Yet each of the cells that we kill was "doing something." They were exchanging material with the environment using highly evolved protein pumps embedded in their membranes and metabolizing components using enzymes that had been selected for billions of years. They replicated their DNA using the machinery that is common to all organisms, and they positioned copies in the daughter cells before dividing. They were certainly alive. However, microbial life is cheap.

Likewise, when we pull up weeds in a garden or field and throw them on a pile, we are terminating the life of these plants. We may share many of the fundamental genes with plants, but this does not stop us from keeping a tidy garden or a productive field. The weeds entered uninvited and have to be thrown out. Even when cutting down a full-grown tree, either to clear a field for planting or for firewood, we do not think about the life of the tree, since it had grown on its own with little or no help from us. To most people, plant life is cheap.

So, is it only nurtured life that we find precious? A farmer puts in long days preparing fields, planting a crop, and fertilizing the seedlings. As the crop grows, it may be protected from insects by insecticides sprayed at regular intervals. Some fields are planted with transgenic seed that has been carefully prepared to make a crystal toxin that kills nematodes which would otherwise reduce the yield. These are some of the most carefully nurtured seeds in the world, having benefited from years of intensive research and the most advanced genetic techniques. By the time the crop is harvested, it has profited from months of continuous care. The harvest is carried out with no thought to the life of the plants, only to the market price.

Many fruits and vegetables receive extraordinary individual care and nurturing. The Asian pear has been cultivated for centuries in China, Japan, and Korea and bred to produce delicious fruits. The pears are best when left to ripen on the tree, but some strains are fragile and subject to infestations. On certain farms each individual pear, while still on the tree, is wrapped in protective paper tied with a ribbon and left to ripen. Then, still wrapped, it is brought to market. The price alone indicates that it is a highly cared-for fruit. No one objects to eating a delicious pear, no matter how well nurtured.

So is it only animals that we find special? An angler pulls in salmon from the sea with little thought about the fact that they started life as eggs carefully buried by their mothers in a distant stream. The mother died shortly after, so the amount of nurturing was limited. But other salmon are farmed in ponds, where they are provided with food and fresh water, protected from predators, and generally watched over. They arrive on the dinner plate nonetheless. They may have been nurtured, but only in a commercial manner. Although fish have eyes and brains and are vertebrates like humans, they are still considered mostly as a source of food.

Until recently most humans were hunter-gatherers who lived off nuts, berries, fruits, and small animals. Wild animals were considered meat. Only in the last few thousand years have people domesticated sheep, goats, pigs, and cattle. They carefully raise and guard the animals before slaughtering them. In some societies, hunters and butchers follow a ritual of demonstrating respect to the animal before killing it, but mostly it is done with little thought about the life that is taken. The most extreme example of nurturing animals used as food may be Kobe beef, where each cow is hand raised, massaged daily, and fed beer before being brought to the slaughterhouse. Even in more normal cattle operations, cows suckle and care for their young for months, and cowboys often assist in birth, inoculate against disease, and provide plentiful food in feedlots. Then the cows and steers are turned into steaks and hamburger. Nurtured life may be precious, but we eat it every day.

## HUMAN LIFE

Humans consider humans to be special. Everyone is aware of being human and wants to be treated specially. We certainly do not want to be considered someone else's food. As children we expect to be cared for, fed, clothed, and protected by our parents and relatives. As adults we strive for a society in which everyone is treated with respect and the weaker members are provided for. Human life is considered precious.

Birth is a defining moment but not a discontinuity in the life of the individual. The genetic makeup is determined when a particular egg is fertilized by a particular sperm. If all goes well, the resulting zygote divides to generate a ball of about a hundred cells, some of which give rise to the embryo while others participate in making the placenta. These extraembryonic cells have exactly the same genes as the fetus, but they are needed only during gestation. At birth, the placenta and umbilicus are discarded with little fanfare, even though the genetic inheritance of these organs is identical to that of the newborn. It is the life of the child that we care about, rather than the cells derived from the fertilized egg. And yet society is uncomfortable about using early embryonic cells for potential medical breakthroughs.

Almost everybody is charmed by and feels protective toward a human baby. Babies are beautiful and precious to us. They have enormous potential as human beings—we know they may grow up to be musicians, politicians, or scientists and may become caring parents themselves. We want to help them on their way. If lives are in danger, babies are usually the first ones helped into the lifeboats. Babies may not know how to walk, talk, or take care of themselves, but we know they have the ability to acquire these skills. Their developing consciousness is apparent in their wide-eyed attention, although it is not clear they have yet developed a sense of self. Over the next fifteen to twenty years, they will develop into young adults who are expected to take up their tasks and responsibilities in society. They will then be held responsible for their actions while afforded certain rights.

These same human beings, if convicted of certain capital crimes, may be executed. Serial murderers are rightly considered a menace to society and are often given the death penalty. In other societies, they are locked up in carefully guarded penitentiaries to separate them from innocent people. Countries that still have the death penalty use many arguments for putting murderers to death. Some argue that is it more humane than keeping a prisoner incarcerated for life. Others consider the financial savings in terminating the sentence relatively quickly. It is argued that the death penalty is a deterrent to potential criminals, but evidence that capital punishment significantly deters those prone to violent crimes is weak or nonexistent. Support for the death penalty comes in part from a need for revenge for the horrible crime. Many people feel that the criminal must pay the ultimate price for his or her completely unacceptable behavior. Those who do not support capital punishment argue that society is doing exactly what the murderer did, taking a life. They feel that all human life is precious and should be protected, even that of a vicious murderer.

In a series of decisions in the early 1970s the United States Supreme Court limited the rights of states to impose the death penalty, which it called a violation of the Bill of Rights, which protects us against "cruel and unusual punishment." A ten-year moratorium on executions followed. However, in 1976 the decision was overturned for specified cases. Gary Gilmore was executed by firing squad in Utah in 1977. Supreme Court Justice Harry A. Blackmun had voted for the reinstatement of capital punishment in 1976, but by 1994 he concluded, "I feel morally and intellectually obligated simply to concede that the death penalty experiment has failed. I no longer shall tinker with the machinery of death."

In October 2005, the European Human Rights Organisation pressured the United States and Japan to end capital punishment. "What is at stake is the most fundamental right to life and human dignity, and this is well worth a temporary drop of a few points in opinion polls. If the United States of America and Japan, as two leading democracies in the world, would abolish the death penalty, others would follow," said the group's secretary general, Terry Davis. Over the last twenty years, 117 countries have abolished the death penalty in law or in practice.

In 1986 the United States banned execution of the mentally retarded and, in 1988, limited the right of states to execute someone who was less than sixteen years old when the crime was committed. The following year the Supreme Court ruled that states were not prohibited from sentencing those aged sixteen or seventeen to death for capital crimes. The International Covenant on Civil and Political Rights prohibits capital punishment of anyone under the age of eighteen at the time of the crime. Although the United States ratified this covenant in 1992, it reserved the right to execute juvenile offenders. While usually professing compassion for children, judges and politicians in the United States argue that juveniles should be put to death for capital crimes. When does compassion for a child end and treatment as a guilty adult begin?

Guilt or innocence aside, people have been killing each other whenever tribes have clashed. Protecting homelands by killing enemies has been glorified and encouraged. Conquering new lands by killing and intimidating previous occupants has often been made to sound heroic, especially when told by the victors. Although there is an old religious commandment not to kill, it is usually interpreted as meaning one may not kill members of the tribe; others are fair game. It appears that the preciousness of life is contextual.

Modern societies encourage peaceful interchange among their citizens and between their citizens and foreigners. Diplomacy is usually thought to be far better than war. This does not seem to stop wars, either large or small, which break out frequently and lead to the death of soldiers and noncombatants. Efforts to civilize the process, such as treating prisoners decently and ultimately repatriating them rather than torturing and killing them, continue to be made. Indiscriminate bombing of civilian targets is discouraged but still occurs when it is deemed necessary.

By the age of twenty a person has been fed, clothed, educated, and taught to be polite. What value can we put on the individual?

This question has been asked by economists, lawyers, and politicians for many years, both in and out of court. Settlements in cases of wrongful death have varied from a thousand to 5 million U.S. dollars depending on the age of the individual, the affluence of the country in which the individual resided, and the immediate circumstances. When a U.S. Marine jet inadvertently hit the cables of an aerial tramway in Italy, killing all the occupants, the families of the victims were each given $2 million dollars as compensation. When sixty innocent Afghans at a wedding were killed as their village was strafed by mistake, the survivors were given two hundred dollars for each individual killed. If we use this measure of value, then an Italian is worth ten thousand times as much as an Afghan. Obviously, the value of life should not be decided by government bureaucrats.

Economists have made calculations based on future earnings models that consider human beings as machines generating streams of income. In this model, older people are considered less valuable than those in their prime. Retired people are worth nothing. Others have tried to determine what people are willing to pay to lower the probability of imminent death. The calculation gets complicated when the quality of life is brought into the equation. While these exercises may be important to corporations faced with class action suits for willful neglect, they demean life, reducing it to a number on a check. No amount of money can replace a loved one.

## WHAT IS LIFE?

In the last century, research in biochemistry has discovered the pathways that convert sugars to fats and fats to amino acids and back and forth in an interconnected web that lets us eat what we want and still manufacture all the things we need in order to survive and grow. Plants trap sunlight and grow by taking up carbon dioxide from the air, and this happens not by magic but with specialized pigments attached to sophisticated molecular motors. We now know the proteins that make up the motors, and we know how they fit together to make ATP, which then powers all the other interconversions and reactions. Molecular biology has explained the universal mechanisms of heredity and how DNA can be copied and proofread so accurately that progeny are almost always exact copies of their ancestors. We know the code such that, when we know the sequence of bases in DNA, we know exactly which amino acids will be strung together to make this protein or that. The complexity held within a single cell is daunting but not beyond our ability to comprehend. Cell and molecular biologists who are willing to learn hundreds of reactions and general rules come to feel they know how a cell works. Mysteries still exist, but it is exciting to try to solve them.

The evidence is now solid that life has been present on earth for billions of years, and that natural selection has generated all the varied forms from descendants of the earliest cells. Very rarely, random errors were made while copying DNA, and most of these errors resulted in defective cells that soon died out. However, with billions and billions of cells all dividing and multiplying, now and then one of the variants was able to boldly go where none had gone before. Bacteria gave rise to eukaryotes with their carefully packaged chromosomes, and eukaryotes gave rise to plants and animals. While still a bacterial world, the surface became populated with multicellular organisms of all shapes and sizes.

We may consider a cell as a thing of beauty, but we do not see it as something that has to be protected at all costs. We reserve that feeling for our families, for those we have cared for and nurtured. We can admit that we are related to all living cells, but rather distantly, and we have no problem in eating a pear or cleaning the sink. People are more than just collections of cells. We value each other even as we compete with each other.

So, have we really defined life? Only in a materialistic, mechanistic sort of manner. There is so much more to life besides eating, digesting, and procreating that biochemistry and molecular biology have only scratched the surface. The real problems of life involve daily decisions about how best to get on and what is right or wrong. Some of these problems have been around forever, but others have come upon us so suddenly, as the result of recent advances in understanding cell biology and molecular genetics, that we are unprepared to respond. In the next few chapters, I consider biologically generated societal problems, explore the range of possible responses, and hold strongly felt values up to the light of recent biological understanding.

Technical improvements have made the process of in vitro fertilization an option for infertile couples who want to have children. Nevertheless, certain groups, including the Catholic Church, feel it is unnatural and oppose it on moral grounds. Islam permits in vitro fertilization but restricts it to using the sperm and eggs of a husband and wife. The technique puts the question of whether a fertilized egg is a person squarely on the Petri dish. Moreover, the process generates more embryos than are usually needed, raising the question of what should be done with them. At present, most are thrown out within a few months, but they could be used to generate embryonic stem cells with the potential to generate all the cell types of the adult body. Stem cell research holds out the possibility of being able to treat presently incurable diseases and intractable injuries. However, many countries either prohibit or severely restrict the generation of human embryonic stem cells on the grounds that a potential human life is destroyed in the process. The difference between potential and realized human life has to be clearly understood.

Therapeutic cloning, in which the nucleus from one of the patient's somatic, or body, cells is used to replace the nucleus of a human egg, is also contentious, because improvements in the technique might one day lead to personal clones that could be harvested for spare parts. However, embryos generated by somatic cell nuclear transfer (SCNT) have to be implanted in a womb to come to term, and no reputable doctor is proposing to do this at any time in the foreseeable future. SCNT techniques have been perfected in mice, and there are hundreds of clones running around in various labs. So cloning is not just a hypothetical question: it could probably be done for humans, but who would want to? I consider these and other questions in the next chapter.

Later chapters go into whether we should consider taking evolution into our own hands and design better organisms—pest-resistant crops, sheep that have useful drugs in their milk, humans free of hereditary diseases. Having sequenced the human genome, we can spot defective genes much more easily, but there are consequences to knowing too much, and this has to be taken into account. These are all aspects of human life.