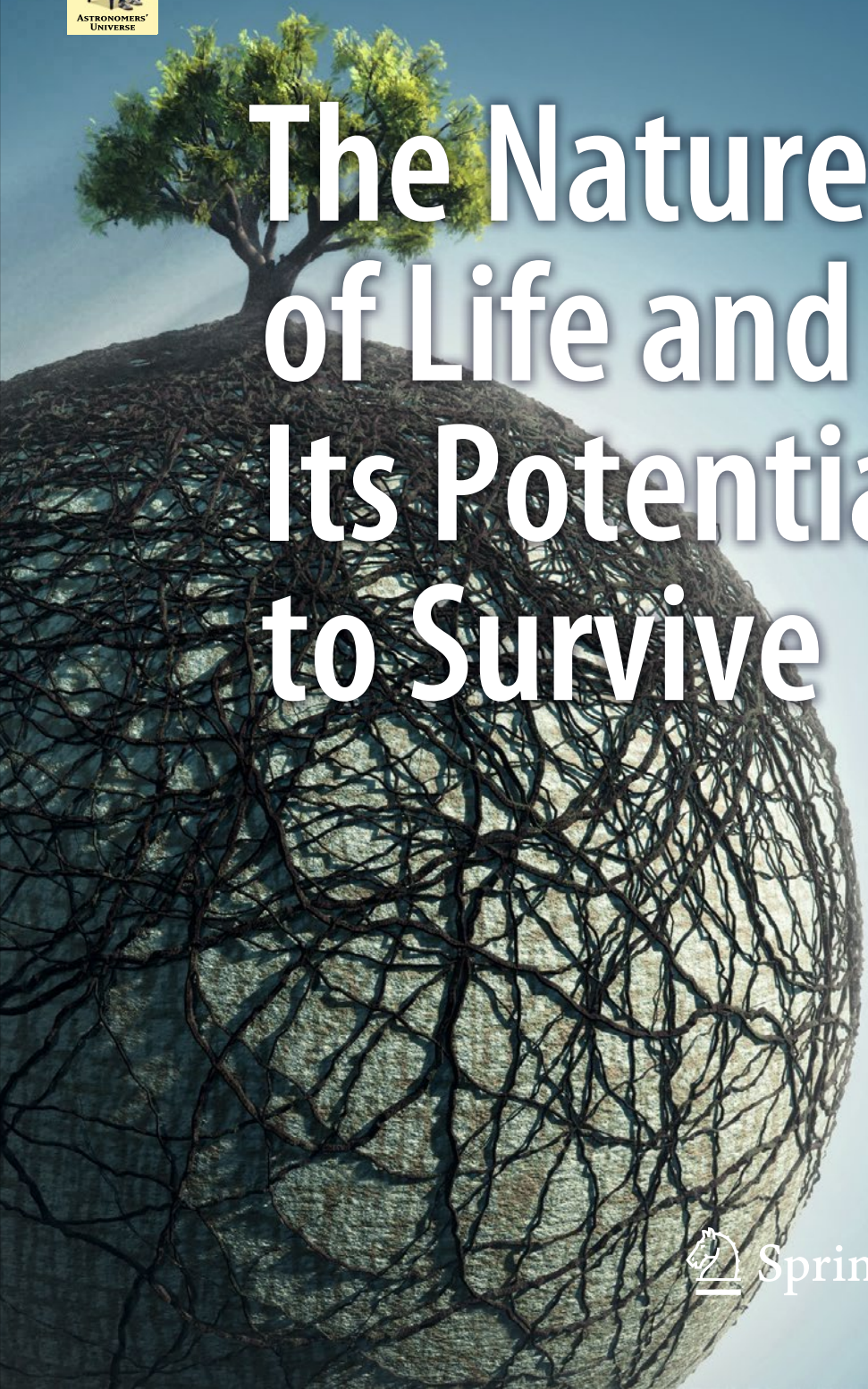
David S. Stevenson

The Nature of Life and Its Potential to Survive



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ISSN 1614-659X ISSN 2197-6651 (electronic)
Astronomers' Universe
ISBN 978-3-319-52910-3 ISBN 978-3-319-52911-0 (eBook)
DOI 10.1007/978-3-319-52911-0

Library of Congress Control Number: 2017932377

Printed on acid-free paper

This Springer imprint is published by Springer Nature
The registered company is Springer International Publishing AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

This book is for my wonderful wife, Nikki, without whom this work would not have been possible. Her encouragement and ideas have kept the development of this book in motion and made me consider possibilities that would not have otherwise come to mind. I am a very lucky man.

Preface

Why is life so tenacious? After all, we find it in virtually every environment Earth can provide. Life occupies every niche within each broad canvas of rainforest, clinging to the sides of branches high in the canopy; or lurking under the frozen topsoil of Antarctica's dry valleys. Life is found in acidic hot springs and alkaline Rift Valley lakes. Life seems boundless.

This book explores the nature of life on Earth and questions whether we can extrapolate its terrestrial characteristics to life elsewhere in the universe. Here, we assume life is universal, but is this a valid proposition? Is Earth somehow unique in the cosmos—and from our anthropomorphic viewpoint—is intelligent life so incredibly improbable that Fermi's paradox may be addressed with an affirmative, "Yes, we are alone"?

In *The Nature and Potential of Life*, we attempt to apply what we know about terrestrial life and extraterrestrial chemistry to extrapolate biology to other worlds, both those we know and those we imagine. Although there must by definition be speculation, these idlings of the mind are underpinned with solid chemistry and physics. By the end of this book, we aim to demonstrate that not only is extraterrestrial life a certainty in the universe but that intelligent life will, by necessity, arise on particular planets.

We conclude our adventure with an exploration of the planets we have already encountered and those we only imagine at present. Within this fold come the tidally locked worlds of the red dwarfs; these are likely to be the most numerous habitable worlds in the cosmos. The question we consider is whether such worlds, habitable for a broad range of living things, will ever host complex life, and life that may, like ours, ponder its own existence. Moreover, can life survive the rigors of its environment? Can the universe ever sterilize a planet with a single asteroid strike or a nearby supernova? As we set about terraforming our world into something

a lot less habitable than nature intended, will there ever come a moment when humanity brings about its own extinction?

The Nature and Potential of Life considers biology in all its complexity, but by grounding it within a solid chemical and physical framework we describe and develop a rigorous set of tools we can use as we probe ever deeper into the cosmos. The book is by definition multidisciplinary in nature, but irrespective of your background, whether scientist, layman, or student, you will find something about life that you may not have considered before. Enjoy.

Nottingham, UK David S. Stevenson

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About the Author

David S. Stevenson completed a Ph.D. in molecular genetics from the Department of Genetics at the University of Cambridge (Hughes Hall College) in 1994. Since then he has worked as a plant molecular biologist, before transferring to teaching at a successful academy in Nottinghamshire. Aside from biology and applied science, he received qualifications in astronomy, planetary science and earth sciences. Since 2013, he has published four books with Springer—*Extreme Explosions*; *Under a Crimson Sun*; *The Complex Lives of Star Clusters*; and in 2016 *The Exo-Weather Report.* The astronomy magazines, *Popular Astronomy*, *Astronomy*, and *Sky & Telescope*, have also published a number of his articles. A further book on planetary geology will be completed in 2017.

Most recently, Stevenson published a meteorology article demonstrating the successful prediction of winter weather patterns in the UK up to six months in advance of winter—ahead of the Met Office publication in *Nature Geoscience.* Further peer-review publications covering aspects of planetary science and evolution are in preparation.

The author lives in Nottingham with his wife, Nikki, and family, without which, he says, none of this would be possible.

1. What Is Life?

Introduction

On the face of it what life *is* seems fairly obvious. If you think about humans, their pet animals or an animal on a farm, then you know that living things run around, breathe, are conscious (we like to think to varying extents) and are very much tangible things.

What about plants? Well, they don't move much at all; they aren't warm and fluffy and they almost certainly don't think much. However, they are quite big, they grow and they reproduce when given the chance. Bacteria? Hmm, well, they reproduce but are very small. They don't breathe as far as we can see, but then again, neither do plants. Fungi? Well, aside from their popularity at parties,[1] fungi spend most of their time looking like a mass of tendrils that extend through whatever substance they are growing on. Here, they secrete digestive juices to dissolve the material on which they are growing. They aren't able to move; they don't think and don't appear to breathe. Yet, as far as we are concerned, they are alive.

How, then, do we define what a living thing is? Why is a cat alive, but a lump of granite not? Why is a *Yersinia pestis* bacterium living but not a crystal of sodium chloride?

Well, you might say living things are complicated, and non-living things are not. Certainly, a bacterium is made up of trillions of components, comprised of tens of thousands of enzymes, molecules of fat and carbohydrate, molecules called nucleic acids (which include DNA, or deoxyribonucleic acid) and quintillions of molecules of water and other simple substances. A rock, by contrast is made up of repeated crystals of silicates and other minerals. However, look more closely and things become more complex. Take granite. It contains quite a variety of minerals: four

[1] Why did the mushroom go to the party? Because he was a fungi.

D.S. Stevenson, *The Nature of Life and Its Potential to Survive*,
Astronomers' Universe, DOI 10.1007/978-3-319-52911-0_1

core silicates—quartz, alkali feldspar, an iron-containing mineral called amphibole and another called mica. These silicates contain silicon and oxygen, with a number of other elements, such as sodium, aluminum and potassium. Silicates are fairly large molecules containing hundreds to tens of thousands of atoms arranged in long chains, much like the molecules we associate with life. And, like the molecules of life, these "reproduce" by making copies of themselves.

What, then, separates bacteria from lumps of granite? This chapter explores the boundaries between what is alive and what is not. Hopefully, by the end of it, your idea that there is a sharp divide between the living and the non-living will have blurred somewhat. You'll then be on your way to discovering why life is so adept at surviving in such a wide variety of environments.

Beyond the Six Kingdoms

Biologists divide living things into six categories, known as kingdoms: Animalia (animals); plantae (plants); fungi (yeasts and mushrooms); protists (complex but single-celled organisms) and the "bacteria." Until relatively recently these bacteria were a homogenous group of single-celled organisms that were utterly distinct from the other four groups but were otherwise viewed as rather similar.

In the 1970s Carl Woese challenged this assertion, basing his contention on the idea that the prevailing view of the bacterial world was flawed. Woese observed rather different kinds of chemistry in two distinct camps of single-celled "bacterial" life. Further analysis of the DNA of multitudes of these "bacteria" clearly vindicated Woese's view: the "bacteria"—those microscopic single-celled organisms—were in fact two distinct kingdoms. In the end the distinction should have been relatively obvious. Woese had realized that those bacteria that lived in the world's harshest environments were so different from their more commonplace counterparts that they really could not be one and the same kingdom. Thus the "bacteria" fall into two broad groups: the Archaea and the Prokaryotes.

In general the prokaryotes include those bacteria that we are most familiar with—those that inhabit our bodies, our immediate environment and most of the world around us. The Archaea, by contrast, occupy the world's most challenging or peculiar environments, such as hot, acidic springs; alkaline lakes; the gastric chambers of cattle; or very saline environments, such as the Salton Sea. It may, therefore, be all the more surprising that the group of "bacteria" that is most closely related to us is the most peculiar. Figure 1.1 illustrates this. Indeed, some recent analysis suggests that we eukaryotes may just be complicated archaea.

In terms of their underlying biology, all living things on Earth share common features. They all have DNA as their genetic material. This is their genome. They all use proteins to form their internal and external structures and carry out the bulk of the chemical processing that cells need to keep themselves intact and productive. Cells also use RNA for a limited but critical repertoire of core chemical reactions, such as the synthesis of proteins and to convey information from DNA to protein.

Beyond this are the viruses, which you may or may not decide qualify as living things. For now, we can regard them as a seventh domain in biology, one populated by a very diverse group of entities that parasitize cells and are otherwise unable to reproduce without the help of the cells they infect. Viruses may have a genome made of DNA or RNA, and some like to use both, depending on which stage of their life cycle you are looking at. Many viruses are really rather complex. The T-even phages have relatively few genes, but structurally would not seem out of place as NASA spacecraft. Others, such as the Pox viruses, have a fairly simple structure, but have genes that number close to or greater than those found in simple bacteria. Thus, the lines are a little blurred between bacteria and viruses, even at this point.

Does this help us answer the question of what constitutes life? Well, no. The more you look the muddier the waters become. If, however, we restrict our thoughts to those organisms that are cellular—that is, made up of one or more cells, then living things can be thought of as cellular structures that contain the information needed to sustain their own survival. This is a woolly explanation and is a serious attempt to avoid any conflict.

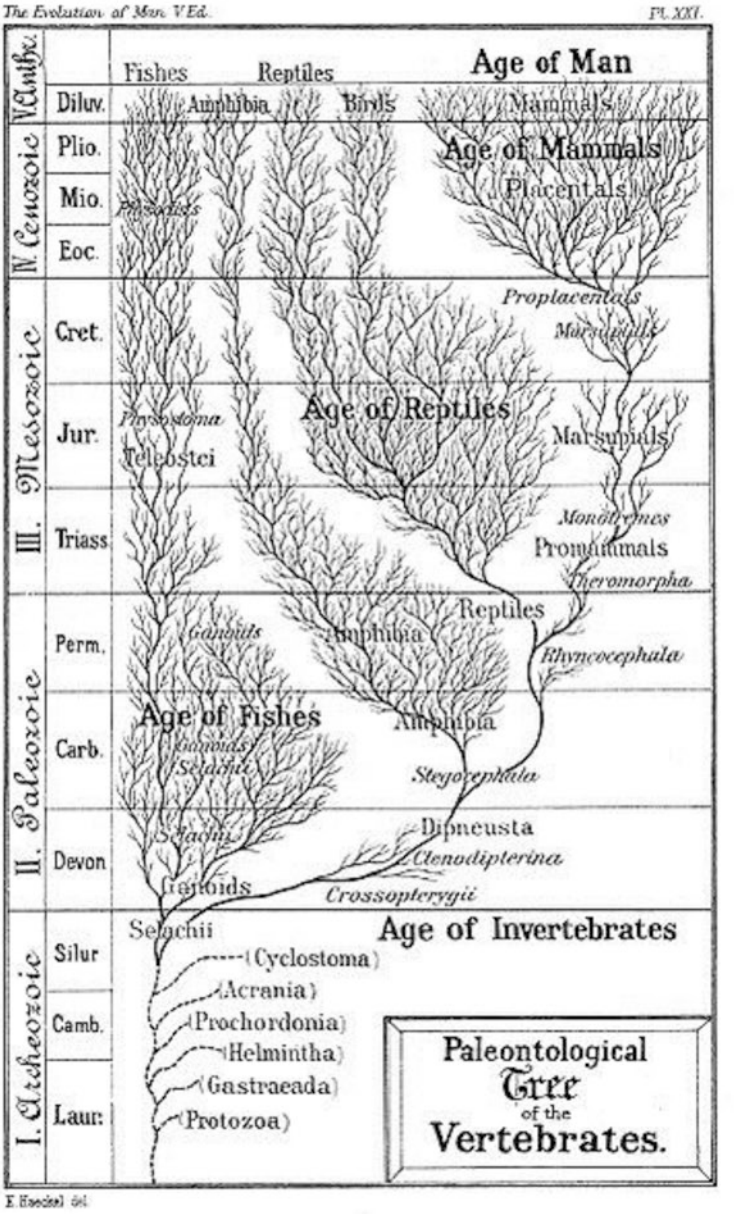

Fig. 1.1 This lovely reproduction of German biologist Ernst Haeckel's "Tree of Life" was produced in 1879. It graphically illustrates how living organisms originate from smaller branches that ultimately converge in a single trunk

Think of it, if you will, as a compromise between the contrasting behaviors of organisms such as plants and animals and the common, underlying physical structures that comprise them.

Would this cover all life in the universe, or even all life that has ever existed on Earth? Well, probably not. Think about it. With the exception of viruses, cells comprise distinct zones, even those we like to regard as primitive (the bacteria and archaea). The interior of the cell may be subdivided into compartments in all types of organism. But this is perhaps most obvious in the eukaryotes, which have clear sub-cellular compartments, each taking care of a different cellular function. However, the most obvious distinction between what is cell and what is not is provided by the outer cellular membrane, often called the plasma membrane. We'd happily state that the region outside of this divide is definitely not alive. However, inside, we would have no problem considering the region living.

What then of the earliest life on Earth, which was almost certainly not cellular? The membrane that separates the interior and exterior of the cell is comprised of a complex array of proteins and specialized fats, called phospholipids. These would not have existed on the early Earth. Therefore, it is thought that nature provided inorganic cages that compartmentalized early life to some extent. Life was, therefore, not bound in quite the same way, and living things permeated materials rather than lived within them. More on this in Chap. 5, but consider for now that not all living things may have cells, at least not in the way terrestrial life has at present.

How else might terrestrial life's cellular design affect it? In most complex organisms, cells take on specific fates or destinies, dependent on which genes are active within them. For example in humankind there are three broad groups of blood cells: red blood cells, white blood cells and the platelets, which are fragments of a larger predecessor cell called a megakaryocyte. There are around 200 kinds of specialized cell in the human body, outside the central nervous system, with another 200 possible types of neurons, lurking within it. In these complex organisms some cells are involved in reproduction while the rest work to keep the organisms, as a whole, alive.

Thus while few of the cells that fungi, animals and plants have could survive and pass on their genetic information on their own, they can function together to ensure the survival of the

organism as a whole. This requires a tremendous amount of organization and cooperation that has taken 4 billion years to evolve. Internally, each cell also has its own machinery that keeps it alive and allows it, where relevant, to communicate with other cells around it. The real marvel of biology is the manner in which life is a balance of the cell's biological prerogative to survive, and the need for it to support, actively, the organism as a whole.

Within the cell, there are a number of features common to all life on Earth. For example, all cells carry out the process of respiration, where glucose or another substances are oxidized (Chap. 2). This process may or may not involve oxygen gas, but all of these processes, no matter what cell in which they occur, generates a useful chemical store of energy biologists call ATP, or adenosine triphosphate (Fig. 1.2). The chemical energy in this molecule is then used to keep the cell viable, allow it to reproduce and communicate with its surroundings.

Multicellular organisms are composed of at least a few hundred cells. Each of these cells is "born" from predecessors through one or more processes of cell division. The vast majority of cells are able to reproduce through a process called mitosis (Chap. 2). Here, cells copy their genetic material and then divide. The resulting cells are identical to one another and the cell from they came. This makes these cells clones of one another. In multicellular organisms a few cells are allowed the privilege of dividing by

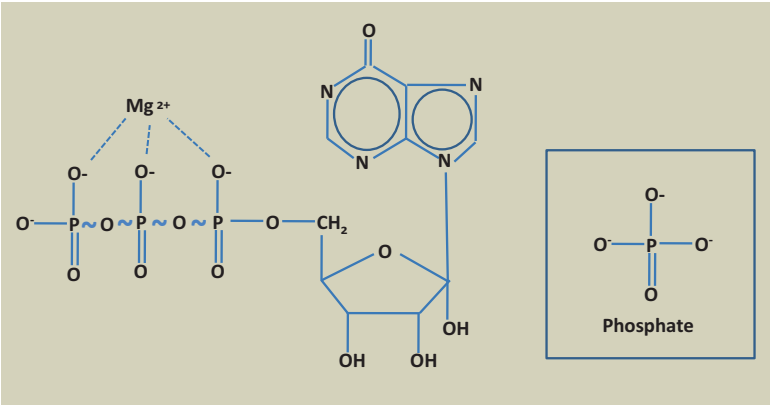

Fig. 1.2 The structure of ATP. Energy is stored in the chemical bonds that link the phosphate groups together. These are shown by wiggles rather than straight lines. The negatively charged phosphates are stabilized by a positively charged magnesium ion

another process called meiosis. Here, the cells copy their genetic material as before, but then divide twice. This leaves each of the four cells that are made with only half the original amount of DNA. This is important because these cells are the gametes—the cells that will come together from different parents through the process of sexual reproduction. Through some nifty genetic footwork the DNA in these cells is also jumbled about so that each cell has a distinct combination of genes. Through these processes—and the random fusion of different gametes during sex—new and amazing forms of the organism can come about. We call these differences variation.

Although only the fungi, protists, animals and plants enjoy the process of sexual reproduction, the prokaryotes and the archaea have some nifty genetic moves of their own that allow them to pass on variation from one generation to another. Some of these are downright devious, and we'll look at them in more detail in Chap. 2.

For now, we might assume that terrestrial and, therefore, *all* life, is cellular, i.e., made up of cells that pass on their information from one generation to another. This is simple, succinct—and quite possibly wrong.

How Do Our Genes Work?

Genes have very specific structures. If that wasn't the case they wouldn't work. How they came to be organized this way is one of the key issues in understanding early evolution, for every organism organizes its own DNA in a very similar way and operates its instructions in a similar manner (Fig. 1.3). Chromosomes are the broad unit of the genome of an organism. These are long molecules of DNA that may be linear or, in most bacteria, circular. Along these stretches of DNA are sequences we call genes. In prokaryotes and archaea these lie fairly close together, with little DNA lying between them. In most eukaryotes, however, the genes are scattered like so many islands and archipelagos in the vast Pacific Ocean (Fig. 1.4). Large sections of DNA do not appear to code for anything. However, in these vast, apparently empty, stretches there are sequences that eukaryotes use to operate their genes. There are also a lot of other DNA sequences that make molecules of RNA that the cell uses to control how it works.

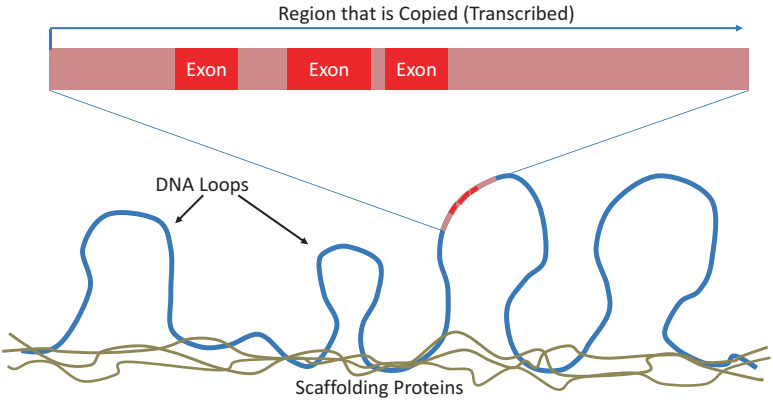

Fig. 1.3 The structure of eukaryote genes. DNA is coiled around proteins called histones (not shown). These coils are then organized into loops, bound within a structure called a chromosome. Genes form short regions within these larger loops, which are often arranged into organizational clusters

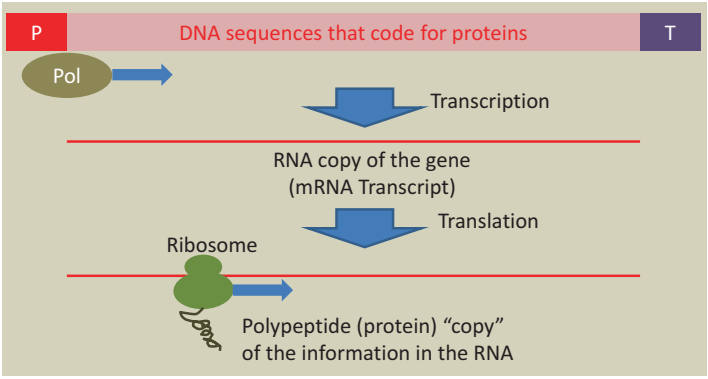

Fig. 1.4 Terrestrial cells store information in DNA. Information is transferred to another molecule (messenger or mRNA) through the process of transcription. These "transcripts" are edited to remove sections of RNA from between the exons, called introns (see Fig. 1.3) and information is translated into a different language, built from amino acids. This happens in the ribosome

Protein machines, called RNA polymerases, read genes. There are several different types of these, all reading different kinds of genes. However, they all do essentially the same thing: make an RNA copy of DNA. This RNA copy is known as a transcript, and it operates in much the same way as a copy of text from a book. Although the transcript may be modified in some organisms, essentially it is a faithful copy of the instructions laid down in the DNA.

Once the transcript is made, another machine, called a ribosome, interprets the information. For although DNA and RNA use essentially the same language, proteins—the workhorses of the cell—are a completely different script. RNA and DNA have a language made up of four simple repeating units called nucleotides. However, proteins are assembled from amino acids, and there are twenty or so of these.

How the ribosome goes about translating the information is something of a molecular marvel. To put it simply, the ribosome reads the information on the transcript in groups of three letters and inserts an appropriate amino acid into the growing protein molecule. We look at this in more detail in Chap. 3. Thus, although the language is very different, the ribosome effectively makes a protein copy of the transcript.

Now, it isn't really that simple. The genetic code for amino acids is such that, in many cases, there are multiple codes for each of the twenty amino acids. So, were you to try and work backwards from protein to RNA or DNA, you would get an imprecise version of the original information. Imagine having several synonyms for one word, if you don't know the synonym you can reconstruct the original sentence. You can get something like it, but not a precise version. In many ways, the ribosome has the toughest job in the cell. It has to interpret one code precisely and recreate another molecule with a completely different one based on that original sequence of information. That makes it a very complex machine, indeed. How it came about is a matter of fierce debate and will be discussed somewhat more in Chap. 3.

The Shifting Landscape of Our Genes

Many of us like to think of ourselves as a divine creation, perfect and made in God's image. Now, God may well exist and have made us in some vast experiment, but irrespective of belief, we are far from perfect. Humanity, and living organisms in general, are messy. Their genome—the total genetic content of their cells—is hardly made in a functional manner, at least not at a superficial glance. Human, plant and indeed all eukaryote DNA is a jumble of genes, defunct copies of genes, bits of duplicated DNA sequence,

and an array of bits of bacterial and viral DNA sequences. Indeed, only around 2–3% of our DNA codes for the cell's workhorse molecule, protein. Meanwhile 50% or thereabouts is made up of pieces of DNA that can move around, called transposons. Quite frankly, it is a bit of a mess to look at.

Yeast has a fairly compact 13.5-million-letter long genome, encoding 5800 genes. Of the total length of DNA, approximately half of it codes for proteins. Similarly, the fruit fly, Drosophila, has roughly half the number of genes that we have—approximately 14,000. These are snuggly fitted into a genome consisting of 165 million letters. Turning our attention to plants, *Arabidopsis* has a genome that is approximately 125 million letters long. It contains a similar number of genes to us (around 25,000), even though our genome is 24 times larger. Maize has approximately 32,000 genes, scattered over ten chromosomes, but its genome is marginally smaller than ours, with a total size of around 2500 million letters, compared to our 3200 million. Therefore, there is no direct correlation between the number of genes in a eukaryote and the size of its genome. Eukaryotes have rather randomly piled on genome weight. Differences may be more a matter of chance events than evolutionary "design."[2] Meanwhile, prokaryotes are really rather functional biological machines with fairly streamlined genomes.

What makes humans distinct from say a mouse or a chicken is the way its 24,000–25,500 genes work and how they cooperate with one another. Human genes are organized in part so that clusters of genes are regulated in functional groups in a manner dictated by the cell's environment or instructions that have been handed down to it. Other genes may appear to be scattered; however, they share common sequences of DNA that allow them to function in the same sort of way, or the same sorts of tissues. In many cases, genes are clustered, so that the whole business of coordinating their actions is easier.

For example, we have two proteins that combine to form the oxygen-carrying molecule we call hemoglobin. In adults, hemoglobin is produced only in those bone marrow cells that will eventually form red blood cells. Although one of these genes (called the alpha) sits largely on its own, there is a whole group of related genes (beta, delta, gamma, epsilon and zeta) that are clustered

[2] By "design" I do not mean intelligent design which is a scientifically abhorrent concept.

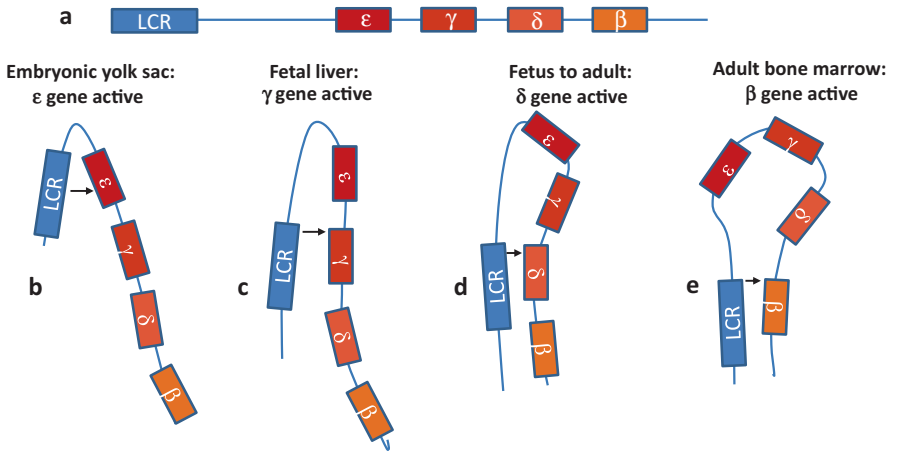

Fig. 1.5 The beta globin gene family. This cluster (**a**) of closely related genes lies on chromosome 11 in humans. Each colored box (ε, γ, δ, and β) represents one gene, which fires up (is expressed) at different times in human development. Each gene is switched on by looping it to a region of DNA called the locus control region (LCR)

along chromosome 11. This beta family produces half the molecules in a hemoglobin protein. This is a neat trick, for within this cluster of genes there is one that works when we are an embryo (epsilon), one (gamma) that work near to the time of birth and one that only functions as the principle beta family protein after birth (beta). They all share a common molecular switch on the neighboring DNA that determines which gene works at which time (Fig. 1.5). By clustering these related genes together, the cell ensures that they can be switched on and off at the appropriate time. Other genes that control development of the organism as a whole—genes that determine where legs, antennae (in insects) and other structures—are often clustered in a similar way.

Within this mêlée of genes and alleged junk there are some interesting surprises, and this brings us to the "seventh" kingdom of life, the viruses.

Genes on the Move

Genes are far from immutable. As we gather more and more information about the sequences of our genetic code we can see how organisms are related, how organisms have evolved from

one another, and also how their genomes have evolved in kind. Perhaps one of biology's greatest mysteries is how the DNA has become organized over time. As well as the kinds of overt structural organizations that are described above, there is an additional wealth of other structural features. These are crucial to the function of the genes that are embedded in the cell's chromosomes, much like islands in the sea of DNA.

Of these there are two broad groups of structures, one of which might seem rather alien. Although the bulk of our DNA is content to stay put, there are large numbers of structures within the eukaryote and prokaryote chromosomes called transposons. These sequences of DNA can make copies of themselves and move from location to location—hence the name transposon, derived from the word *transpose*, or to move.

There are a variety of different transposable elements in cells. Some move by a straightforward cut and paste mechanism, others make a copy of themselves before they move the copy to a new location. Still others make an RNA copy of the DNA sequence, which is then reverse transcribed—a DNA copy of the RNA is produced—and it is this DNA copy of the RNA copy of the DNA that is inserted into a new location. That all organisms and some viruses have transposons hidden within them testifies to the ancient nature of these mobile DNA pieces. It is thought that they originated near the beginning of life itself. Sure, more have evolved since, but the underlying principle dates back to the origin of RNA and DNA as genetic material in our cells and every other cell.

It is here, in the world of mobile DNA, that we begin to blur the edges of what is alive and what is not. What constitutes life? Some of these transposons are distinctly independent entities, or at least display some of the facets of life—movement, sensitivity, nutrition, reproduction and evolution. For, although most transposons are restricted to an existence within the cells in which they were "born," others are able to move from cell to cell. In prokaryotes and archaea this can happen when transposons jump into invading viruses, adding their genetic material to that of the virus. Other pieces of DNA, called plasmids, can also collect transposons and move them to new locations. This is particularly relevant for us because many of these transposons host antibiotic resistance genes that are mobilized from cell to cell. The ability to move

genes from location to location underpins the spread of antibiotic resistance in many species of bacteria. Such resistance is often carried on pieces of mobile DNA .

Where we humans do extremely foolish things, such as use antibiotics to boost the growth of farm animals rather than restrict their use to killing our pathogens, we invite natural selection to do its worst. Most antibiotics come from microbes. Bacteria and fungi use them to kill competitors, but this requires that they also have their own resistance genes. Otherwise they would kill themselves when they made their antibiotic. Therefore, nature is set up to help us and hinder us in equal measure. Use an antibiotic too widely, or use it in isolation, and we encourage the survival and reproduction of those bacteria that allow them to hold the resistance gene, or encourage the spread of rare microbes that carry mutations that allow survive. Worse still, most antibiotic resistance genes are carried on those mobile pieces of DNA, the transposons, and these transposons may be loaded within other mobile pieces of DNA called plasmids. All of these pieces can move from cell to cell and species to species, taking the antibiotic resistance gene, or genes, with them. Our generic use of antibiotics merely enhances the spread of these resistance genes. Where they confer an advantage to the cell, the cell that has them will survive and pass on its cargo of mobile and other DNA when antibiotics are present. Those that don't, perish. That is all there is to natural selection.

With antibiotics used to fatten up farm animals we are squandering a vital resource and perhaps setting ourselves up for a grand catastrophe in the future. At the time of writing, the power of the final—last resort—antibiotic had just been overcome by one variety of bacteria in the feces of farm animals in China. Given mass transport of humans, commodities and farm products it will only be 3 years before many life-threatening infections become untreatable with our current range of antibiotics. What a waste.

More generally, when transposons move from location to location they can disrupt the function of genes by splitting them in two. Indeed, many years ago researchers used this property to identify the function of genes in the plants *Arabidopis* and maize. It has been used extensively by others to identify genes in pretty much every organism you can imagine.

One might, then naively, assume that these pieces of mobile DNA were bad—passing their cargo of genes from location to location, cell to cell, and on occasion, from organism to organism. However, natural selection is the mother of invention. As well as allowing some cells to gain new features, such as antibiotic resistance genes, transposons can also rearrange the regulatory pieces of genes that control how they work. This property has given mammals one of their core characteristics: the ability to feed their young.

All female mammals lactate, or produce milk. This is a fairly odd feature in animals. Think about it. Females secrete a watery solution of proteins and fats and that is the only food their young can digest for several weeks or months. No other class of organism does this. Other animals—reptiles, insects, amphibians and the others—all are able to digest food obtained from their environment, such as leaves. Mammals have specialized organs, which we call breasts in humans and udders in most other mammals. In turn, these only produce milk after a successful pregnancy has advanced to a late stage and in its immediate aftermath. As with nearly everything on the mammalian front, the monotremes, such as the duck-billed platypus, have a halfway house. They do not develop "breasts" or equivalent structures. Instead, they secrete milk from their abdomens, effectively from sweat glands, indicating how the process came about. Monotremes aside, the nearest organisms you can find in the animal kingdom that also produce food from their bodies are scaly bugs. These invertebrates produce a nectar-like solution that they feed the ants that protect them from predators.

The secretion of milk requires an instruction that signals the glands responsible to do so only at the correct time. This is a hormone called prolactin. In primates and many other mammals there is one copy of this gene, but it codes for two different functions. One coded form of the gene controls the production of milk, and this form of prolactin is secreted from the pituitary gland. The other coded form is active and produces prolactin in tissues, such as the lining of the uterus. Here, it appears to be essential for the success of pregnancy. It turns out that the instructions that direct the second uterine function are contained within transposons that are inserted close to one end of the prolactin gene. Different trans-

posons are inserted into this part of the gene in different mammals. However, by doing so, each transposon has inserted a new set of instructions that have helped revolutionize mammalian life on Earth. For without the insertion of these pieces of mobile DNA, humans and many other mammals would not be able to maintain successful pregnancies.

If we describe transposons as pieces of DNA that can copy themselves but, by and large, stay within the cells in which they originate, we can conveniently separate them from the viruses. Again, these can be descriptively reduced to pieces of genetic material that can copy themselves. Now, in both instances "copy themselves" is a little bit of a misnomer. Strictly speaking it means that the machinery within the cell that they inhabit can be usurped to copy them. They can't copy themselves without outside help.

Now, viruses are simply a step up the ladder. They are mobile pieces of genetic material that, in this case, can jump between cells rather than simply within the chromosomes of the cell they begin in. There are a huge variety of viruses out there in the world. Some have DNA genomes, some have RNA. Some kill the cells they infect, others simply corrupt the cell and steal its resources to finance their own replication. Some viruses insert copies of their genetic material into the chromosomes of the host cell, while many more simply pretend they are part of the cell's genome and get copied by proxy.

Eukaryote viruses tend to manipulate the infected cell without directly killing it. Death is often a secondary consequence of the indirect damage they cause, rather than as a direct result of a frontal assault. Viruses that infect bacterial cells almost always kill their host cell when they replicate. The difference in strategy is a consequence of the structure of the cell. Bacteria have an outer wall, and this must be disrupted to let the progeny viruses out. When this happens, the cell takes in water, swells up and bursts. Bacterial viruses also tend to chop up the cell's genetic material to release resources that it can use. Meanwhile, eukaryote viruses convince the cell to manufacture what it needs and tend to block the cell carrying out its normal functions.

Beyond this, the viruses are also of key importance in evolutionary terms. For while many viruses cause much suffering to the organisms they infect, viruses are also agents of innovation. This

is most obvious in bacteria—the prokaryotes. In most cases, as we've stated, infection is followed within 30 min or so by death; however, it is not always this way. To get an idea of how the different paths emerge it is worth taking a quick peek at how infection unfolds.

Imagine that you are a single-celled organism, perhaps an *E.coli* bacterium on a human's skin or a cyanobacterium in the oceans. You're going about your daily life, metabolizing this and that when along comes a virus. It attaches to your cell wall and then begins to drill a hole through it. Once the passageway has been opened, the virus injects its cargo of genes, much like a nurse administering a vaccination. In most instances, within a few minutes, you've had your life put on hold while the virus gets your cellular machinery to construct a set of enzymes. These specialized proteins then fatally set about chopping up your chromosome into handy sized pieces, while your cell's machinery makes hundreds of copies of the invading virus. Less than 30 min after the virus punched a hole through your cell wall and membrane, you explode, scattering the newly born viruses into what was your surroundings. This process is called lysis, and, let's face it, it is a bit grim.

However, not every cell faces this fate. A very small minority of viruses infect a cell that, for want of a better expression, is not very happy. Maybe it does not have sufficient nutrients to reproduce, or perhaps there is some sort of toxin present in the cell's surroundings. In such a situation it is not in the virus's best interest to get the cell to manufacture more copies of the virus. Reproduction may be weak or impossible, and this would likely allow the cell to stop the virus in its tracks with one of the defensive systems that exist in the cell. Therefore, the virus switches to a new mode of operation. Using a surprisingly simple set of biological switches, the virus can sense the cell's distress. Now, not wishing to add to the woes of the cell, the virus holds off committing its host cell to its ruinous path, and it sits tight in the cell. The virus thus becomes part of the cell. This process is called lysogeny. In this state, the virus only gets its genetic material copied when the cell duplicates its own DNA. Typically, the viral DNA is inserted into the DNA of the cell (into its chromosome), so that the process of replication affects the virus as well as the cell.

However, should things improve in the cell the virus can sense the change in cellular fortunes and change tack once more, killing the cell and spreading to infect new host cells. There is a catch, though. Any mutation that affects the ability of the virus to escape will allow the virus's genes to become a permanent addition to those of the cell. Through this mechanism bacteria can gain genes from other cells. Although this process is quite rare, it does happen.

Now, if you imagine that the chance of this happening are about as likely to win the lottery, then yes, you'd be right. Indeed, lottery odds are better by a factor of about 100–1000. Only one in every few hundred million to few billion cells gets to keep the virus that has infected it. Poor odds, maybe, for the individual cell, but with over one billion bacteria per milliliter of sewage, in reality, that's rather a lot of possibilities for the population as a whole. In the oceans, there are millions to hundreds of millions of bacteria per milliliter of seawater. On your skin there are at least a few hundred thousand bacteria per square centimeter—even if you wash fairly often. In your digestive tract there are trillions of bacteria, all of them vying for your body's waste. Therefore, overall, there are many opportunities in nature for bacteria to acquire and transmit genes. This is where evolution through natural selection is often misunderstood.

People think of organisms in isolation. Small numbers are easier to handle than large ones. If there was more chance of a bad event—such as a gene disruption—happening than a good one, surely all organisms would suffer deleterious events and succumb. If this were true, evolution would be a dead duck. However, we aren't talking about one man becoming the Hulk. We're talking about a billion organisms each experiencing its own singular event. Some are bad and the organism suffers, while some are good and the organism benefits. Most, incidentally, have no effect whatsoever. On a population scale, evolution is perfectly reasonable. Evolution is not reasonable on the scale of an individual—except when we consider cancer. To these singular topics, we will return in Chaps. 4 and 9, when we look at natural selection and its consequences in more detail.

Do viruses provide any benefit to humans or are viruses all bad for us? Well, for the most part viruses do not confer any real