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LIVING WITH THE STARS

How the human body is connected to the life cycles of the Earth, the planets, and the stars

KAREL SCHRIJVER & IRIS SCHRIJVER

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SHARON BRYAN (1943–), excerpt from "Stardust"

1

The Illusion of Permanence

Our bodies are made of the burned-out embers of stars that were released into the Galaxy in massive explosions long before gravity pulled them together to form the Earth. These remnants now comprise essentially all the material in our bodies. Most of it has been cycling through the continents, with a small amount added only recently, when comets were captured by the Earth's gravity, or when ultrafast particles ran into the atmosphere and created a shower of new particles. It is being used by all living beings on the planet. Plants capture sunlight and release oxygen even as they create food for us, humans. We live by the grace of stardust assembled by plants into nutrients that provide us with energy to grow, to move, and to think. Those light-powered plant chemicals are used to rebuild our bodies over and over during our lives. This rebuilding is so common inside our bodies that every few years the bulk of our bodies is newly created, giving us continuity merely as a shape in which most of the tissues are repeatedly replaced.

When we are asked to define ourselves ("who are you?"), we can approach this challenge in various distinct ways. We can state that we are human and can add whether we are male or female. Moreover, we can comment on our physical features, list character traits, and include certain socio-economic factors, such as whether we are single or married, have children, are employed, and, if so, in what line of work, and at what level within an organization. Some may define themselves by their status in society, by their possessions, by their accomplishments, or by their interests and relationships. Whatever descriptions we choose, they will inevitably be rough and incomplete. They will also be influenced fundamentally by the culture and by the era into which we were born.

If, instead, we consider directly what actually constitutes us, we may think of the body and of the mind, with the two often being thought of as somewhat distinct entities. Some people may introduce the metaphysical concept of a soul or of a life force. Considering, for now, only our physical bodies, it is clear that we are made up of a hierarchy of organs, tissues, cells, and molecules. Our bodies are estimated to contain the amazing number of approximately 50 trillion human cells (using the so-called short scale for large numbers as we do throughout this book, so that means 50 million times a million cells). Within the cells that shape the human body, numerous tightly regulated processes occur to keep us alive and in a healthy state. These involve a large variety of molecules, which are composed of elemental atoms. Each cell contains an average number of atoms that is approximately as large as the number of cells in the body.

We may think of our bodies as composed of "our cells", but interestingly the majority of the cells that are contained within our overall human form are not human at all: on the inside and outside surfaces of our bodies, the bacterial cells that form what is called the human microbiome outnumber human cells by approximately 10 to 1. We are, in fact, colonized by hundreds of bacterial species. Bacterial cells are much smaller than human cells, so although they outnumber our human cells they do not considerably add to our weight. These bacteria are, however, critical factors in both health and disease because they influence complex biological processes, including the regulation of our immune system and the digestion of food. The immune system helps us ward off damaging effects of the surrounding world and digestion allows us to extract the nutrients that our bodies require from the food we eat. Thus, in order to survive we actually need this symbiosis that blurs the line between "us" and our surroundings.

Apart from the physical reality that is our body, another attribute by which we often define ourselves is our age. We rarely realize just how diverse a range of aspects we could consider in giving our age. Here, as in our thinking about what makes our physical form, considerable ambiguity arises in any attempt to formulate a straightforward number. Generally speaking, and as legally defined, our age is the time elapsed since birth. Yet we often allow for other evaluations. For example, there is the age of how we feel or of the degree of maturity with which we behave. Both are heavily influenced by the culture we live in. For example, in some places we may find many a grandmother well into her 70s who thinks nothing of going for a challenging hike each day, who dresses contemporarily, and who actively pursues a variety of interests. In contrast, we may encounter women of the same age in other cultural settings who have very sedentary lifestyles and who consider themselves as having all but lived out their lives. Not envisioning a compelling future, their behavior and presentation fully reflect that perception. The flipside of this cultural difference is that old age is frequently resisted and rejected, especially in North American culture: age is something that is fought intensely, and weapons of questionable effectiveness are eagerly supplied by the beauty and biomedical industries. In some cultures, however, a ripe old age is bestowed with certain benefits, such as elder status and an inherent association with wisdom that demands respect. Thus, to some extent, age and its interpretation are mental and cultural concepts.

Another way to address the question of age is to consider our *functional* age, which is an index of an individual's performance, taking into account a combination of the chronologic, physiologic, mental, and emotional ages and is, as such, a useful indicator of aging or "senescence", more so than time since birth alone. However, it is only our chronologic age that we typically are expected to provide as the metric of how old we are when we are asked our age.

In reality, however, even the concept of chronologic age has an unavoidable ambiguity to it. When not applied to a living being, chronologic age is generally taken to mean the length of time that has elapsed since the object was first completed. That works just fine for a painting, a piece of furniture, or a book. It quickly becomes less obvious, however, for longer-lived objects, such as an old car with many replacement parts, a road that has been resurfaced or diverted several times over, or a centuries-old house with numerous additions and repairs.

So, how old are you? That deceptively simple question can be answered in very different ways. Nine months before humans are born, at the time of conception, the genetic complement of what that human will grow into is created when an egg cell and a spermatozoon merge to create the first cell of the new individual. Both the paternal and maternal components already existed separately before that, but their merging is essentially the first moment when the blueprint of that specific human being, in strictly genetic terms, is present in the universe.

From the moment of conception onward, it takes some two decades to grow into what we consider to be an adult human. The moment of birth is clearly a differentiating moment during that time frame, and, if we were houses, we could think of ourselves perhaps as "finished", as ready to live in, after our development in the womb. During the entire growth period to adulthood, however, more material is added to our bodies than they contained at birth, and this accumulation of material does not stop when we reach the legal age that confers the status of adult. Even if we do not gain weight in later decades, which most of us do not manage to entirely avoid, the body does not cease to accumulate and process material from the world around us.

The chemicals that we take into our bodies when we eat, drink, and breathe do not simply enter and leave, but may become part of us temporarily, to help power our muscles and our brain, to repair cells, or to build new ones as earlier generations die. The original cell out of which we grew has, in all likelihood, long died. Only copies of it, differentiated to perform one of the hundreds of distinct functions within the body, continue to exist, variously lasting from days to decades, all to be replaced themselves at some time during our lives.

When we think of ourselves as a composite of cells with only temporary existence, it is evident that the conventional approach of listing our age as the number of years elapsed since birth utterly belies the complexity of the processes in our bodies. These processes reflect a sophisticated regeneration and recycling machinery that is, in turn, tightly connected to our terrestrial environment and even to our cosmic one.

We are continually rebuilt out of materials that stay in our bodies perhaps for only some days or maybe for a few years. But it goes further than that: some of the vegetables and fruits that we consume today contain energy trapped from the light that left the Sun only eight minutes before it was absorbed by a plant, and only weeks before that plant was harvested. The majority of the atoms that are present in our bodies have existed for as long as the universe has; others were forged inside stars billions (that is, thousands of millions) of years after the Big Bang, yet still billions of years in the past. Some atoms were made less than a human lifetime ago by nuclear reactions in the upper layers of the Earth's atmosphere, called the stratosphere, where commercial air traffic cruises along. What we document in this book is that this much is certain about us: very, very little in our bodies has actually been part of it for as long as what we say when we state our age. All the body parts of any living organism on the planet, be it plant or animal, are continually subject to replacement and recycling.

At some level, we are all aware of the reality of impermanence. We so often say that we no longer are who we were when we were younger. That is true enough in the psychological sense in which we generally mean it. It is particularly true, however, for the material that makes up our bodies, ranging from the water that constitutes the biggest volume of our bodies—being recycled on a time scale of days to weeks—to the very foundation of our bones and our nerve tissue, components of which may take a few decades to be largely replaced. What survives all this replacement is only a shape, a pattern, a temporary collection of matter and energy assembled into a host of specific, recognizable attributes that persist, at least for much of a lifetime.

The temporary collection of matter and energy that is a human body is a relatively flawless copy of what it was hours, days, and years ago. Even our genetic material, the DNA that lies coiled in the chromosomes in the vast majority of our cells, disappears when cells die, and is replaced in a new generation of cells. As years go by, the pattern of what we visibly are does change, yet it is still familiar enough for people to be able to recognize themselves in pictures of when they were children, and to recognize one another many years after a previous encounter. In such meetings, at high school reunions, at weddings or funerals, or in chance encounters in the street, we acknowledge that we have grown older (often perceiving more change in the other than in ourselves), but features and habits are sufficiently long-lasting for us to recognize each other, even though there may be some hesitation when much time has passed between successive encounters. Fortunately, many of our memories survive over the years, although it is unlikely that what contains these memories is composed of the same molecules that first captured them.

What it comes down to is that we are intrinsically impermanent, transient, continually rebuilt, and forever changing. We are a pattern, like a cloud, a traffic jam, or a city: even as we exchange our building blocks continually with our surroundings, the overall pattern provides enough stability for us to have a sense of continuity, both with regard to our own body and personality, and with regard to those of others.

Our bodily existence, in a way, is also akin to a wave in the ocean. The wave is a pattern of motion that travels in space and time, but the water that makes a wave at any given moment resides within it only briefly. The wave moves through, but not with, the water. Or, if we were to travel with the wave, the water would appear to flow through the wave, with as much coming into it on one side as is leaving it on the other. In the case of living organisms such as we are, the analogy with the water moving through the wave is imperfect because chemical elements and compounds stay in our bodies for different amounts of time. Nevertheless, the fundamental nature of the comparison holds true: we are a composite of patterns that are shaped by the chemical components coming into us and which travel with us temporarily before they are discarded and left behind as new ones are collected and incorporated.

We may not normally apply to ourselves directly this concept of existing only as a pattern, but with advancing technology we have become quite used to thinking in abstract terms of patterns and their evolution as copies of earlier versions. We put pictures of ourselves on social networks that friends can view on screens far away, with no idea of what was the original and what the copy. We enjoy duplicates of music files or videos on devices in our homes or on those we travel with. We email messages which, when printed, become copies that are not identical to the originals, yet carry the same content. Such persistent patterns long preceded technology and in fact surround us in the natural world every day. Let us look at a few examples.

A cloud is a pattern in which water condenses from vapor into droplets. As air moves slowly through the cloud, new droplets form while earlier ones may be lost by evaporation at the cloud's edges or by raining out of the cloud base. Another example is a river. Water moves in a river from the headwaters to the final basin, commonly a sea or an ocean. New water enters all the time, so that when we sit on the river's banks we are able to look at the one pattern that we designate "the river", but that pattern is filled with different water as time goes by and changes its shape. If we were living at a much slower pace, we would be able see the evolution in the pattern that we call a forest, too: individual trees sprout, mature, and die, yet unless that forest is cut down or burned completely, successive generations of trees form the continuing essence of this living forest. Speeding up time even more, we would see the mountains change into grains of sand as erosion takes its toll, with other mountains emerging on the Earth as a consequence of geological forces. On the longest time scales that fit within the existence of our planet, we would see continents move about, fracture, erode, and reshape, subject to the conveyor-belt motions of the seafloors. Even on the exceedingly long time scale on which stars evolve, a cyclic pattern is seen: all stars that are somewhat heavier than our own star, the Sun, explode at the end of their existence, throwing most of their matter back into the galaxies within which they formed, and new stars and planets are recycled out of that stardust to hold the pattern that is their galaxy.

The undeniable truths of impermanence and of the inadequacy of any unique definition of age apply to our environment as much as to us.

For instance, in some places the Earth itself is created anew and appears to be younger even than we are. On volcanically active islands like Hawaii one can stand on volcanic rocks that are no older than a year. One can also stand on a sandy beach that has grown markedly since the previous season. In both instances, the overall land mass is reshaped as material is moved around: from deep within the Earth to its surface on a volcanic island and from a shallow sea floor to just above sea level in the example of a beach. Volcanic rock forms by the cooling of liquid magma that has cycled inside the Earth possibly ever since our planet formed. The rock that materialized when this magma reached the Earth's surface may only be hours, days, or years old. In the case of a beach, the sand grains imply a story with more pieces to it. Once upon a time a piece of solid Earth was eroded into smaller fragments, which may eventually have been packed into sandstone and then fragmented once more, over a long period of time. This may have occurred while drifting on the ocean floor or perhaps in distant desert dunes, before finally—but just as temporarily—coming to rest on a beach that warmly supports us when we enjoy a tropical sunset. In scenarios such as these, it is easy to recognize that "age" can represent any of a variety of time scales.

The face of the Earth has changed dramatically over time, even though we might think that much of what we see has been and will be there forever. Life on Earth formed several billion years ago, but mammals have been here for only something like 60 million years, rising as the dinosaurs became extinct. Humans as a genus have existed for only a few million years. Cleary, many very substantive changes have occurred over this period, as some things were lost forever while others formed for the first time. If we focus on mankind during the past few centuries, for example, we realize that, whereas technology has changed our lives dramatically, and whereas there are definitely more humans now on the planet than 100 years ago, mankind itself is like the pattern of the wave: people are born, grow up and grow old, and eventually die, but as they come and go they flow through the pattern of mankind, which maintains a much longer and larger identity.

In the case of the universe, we typically think "age" less than "ageless". Our eyes view the stars over a negligibly small time span from the perspective of our ancient universe. To them, the Galaxy is a vast, still, and steady cradle for our small planet. We readily observe the cycles of the Moon and we unavoidably live with the daily rising and setting of the Sun. Apart from these familiar motions, however, nothing seems to change. If we measure precisely enough, we can establish that the stars and the planets are moving through the firmament, but on the cursory inspection that we commonly afford the skies, the universe appears to us to be static. We usually do not stop to think that some of the stars that twinkle in the midnight sky were extinguished eons ago, their light having left the distant star perhaps thousands of years before that, still traveling toward us as the star itself exploded and vanished. Despite the universe's appearance as a timeless, permanent fixture, individual objects in space have different ages too. We can trace back the universe as a whole to moments after the Big Bang, but most of the stars, planets, and other heavenly bodies that make up the uncountable galaxies have not existed since the beginning of time. Instead, early generations have "died" while new ones have been formed.

Realizing how fluid we are and how impermanent everything around us truly is, we should think differently about the materials that we take into our bodies to quench our thirst and feed our hunger: this material does not simply flow through our gut, but is assimilated into the very structure of our bodies until, after some time, it leaves it again in some other form. Our bodies are very complex chemical machineries, as are those of all living things on this planet, but the mixture of the elements used in our chemistry simply reflects what is readily available around us in a chemically useful form and quantity. From this, it follows quite logically that the most common elements in the planetary system are the same as the most common elements in our bodies, albeit with some notable exceptions that we can easily understand.

Not only the elements in our bodies, but all processes on the Earth are directly connected to those in our solar system, to our Galaxy, and to the universe beyond. From that perspective, it becomes understandable not merely that life on Earth reflects the elemental makeup of the solar system, but that the solar system in turn reflects the elemental makeup of the Galaxy around it. Once mankind learned the true nature of stars and realized that they are vast nuclear furnaces that shape and destroy the planets around them, and when a better understanding emerged of the central role of stars in establishing the contents of the universe, it became clear that we are, indeed, stardust, in a very literal sense. Every object in the wider universe, everything around us, and everything we are, originated from stardust. Thus, we are not merely connected to the universe in some distant sense: stardust from the universe is actually flowing through us on a daily basis, and it rebuilds the stars and planets throughout the universe as much as it does our bodies, over and over again. In our everyday lives, we tend to ignore the universe beyond the Earth's atmosphere and take it for granted that the Sun steadily shines its warming light onto the planet. We do not generally ponder the many links between us and the stars, except perhaps for the links to the nearest star that we call the Sun. These links range from the Big Bang, in which the universe was formed, to the particle radiation from the Galaxy that slams into the high terrestrial stratosphere right now.

With the exception of hydrogen, which formed when the universe itself was created, almost all of the atoms in our bodies have been forged either in the deep interior of stars, or within the explosion of these stars at the ends of their existence.

One key connection between ourselves and the universe and, indeed, an essential ingredient of life, has yet to be discussed: energy. It is energy that maintains the surface of the Earth well above the cold of the ambient universe, which is a mere three degrees above absolute zero and thus hundreds of degrees below freezing. In units that we encounter more frequently, this translates into about minus 455 degrees Fahrenheit or minus 270 degrees Celsius. Without an external energy supply, life on Earth as we know it would be simply impossible. The external energy raises the Earth's temperature so that it can support plants, which, in turn, feed animals, including us.

The bulk of the energy that is available to life on our planet comes from the Sun. Only a very small fraction of the Earth's overall energy budget is liberated from the radioactive decay of stardust in the Earth's interior. This afterglow of stellar deaths deep inside the Earth manifests itself to us on the surface as geothermal or volcanic energy. This energy is primarily liberated from the decay of uranium, thorium, and potassium, which were formed as stars exploded at the ends of their lives.

Even the Sun's radiant energy is a form of stardust. The energy of the Sun's light is ultimately generated in the deep solar interior by violent nuclear collisions. Mass and energy are equivalent and exchangeable: the solar light that hits the Earth loads the equivalent of about 140,000 tons of mass onto our planet every year. Much of that load is there only briefly, because a lot of the sunlight shining down on the Earth is reflected back into space by the clouds, oceans, and land masses, but part of it is stored in plants for days or weeks and then can be processed in a great diversity of ways. It may be used to build the compounds that constitute our bodies and to power the network of metabolic reactions that we need every single moment of our lives. Or it may end up stored underground, in plant and animal material that is slowly being converted into the chemical energy stored in coal, gas, and oil.

These connections between us and the universe offer us a view of the richness and diversity of the sciences that we know as chemistry and physics, as astronomy and biology, and as geology and medical science. Understanding them in detail is daunting, but exploring them broadly—as we do in this book—enables us to see ourselves as part of the greater whole. It shows us to be entities that do not exist apart from the world around us in a hostile universe, but rather as connected to all life around us, to the planet as a whole, to the Sun, and to the stars throughout the Galaxy. To explore this multitude of connections, we travel through this general hierarchy of scales in space and in time: from cells to atoms through the biosphere, from there into the cycles of the Earth, and then to the lives of the stars, to eventually return from the Galaxy to our solar system and the diversity of its components.

Key Points: Chapter 1

- The human form comprises some 50 trillion cells. It hosts another 10 times as many bacteria, many of which are integral parts of our digestive and defense systems.
- Human bodies are intrinsically impermanent. Rather than fixed, they are more akin to a pattern or a process, although stable enough to allow a perception of continuity.
- The chemicals that we take in by eating, drinking, and breathing typically become part of us temporarily to help power our bodies, repair our tissues, and replace cells. All parts of any organism on the planet are continuously subject to replacement and recycling.
- Not just our bodies and other living organisms, but all processes on the Earth are intertwined with those in our solar system, our Galaxy, and the greater universe.
- Our chronological age does not reflect the time during which the components of our bodies have been part of them. This is also true for our environment and the universe. Although the universe appears timeless, stars and planets come and go, and therefore have a range in age, too.

- Every object in the universe, everything around us, and everything we are originated from stardust. Stardust continually flows through us, directly connecting us to the universe, rebuilding our bodies over and over again.
- **The universe is constantly in flux. Everything is impermanent and interconnected.**

Each living creature must be looked at as a microcosm—a little universe, formed of a host of self-propagating organisms, inconceivably minute and as numerous as the stars in heaven.

Charles Darwin (1809–82),
in *The variation of animals and plants under domestication, Vol. II* (1868)

The existence of forgetting has not yet been proven; all we know is that we are not capable of recollection.

Friedrich Nietzsche (1844–1900),
in *Morgenröte; Gedanken über die moralischen Vorurteile* (1881)

2

Dying to Live

The human body performs a great variety of critical functions to keep itself alive. It does so to varying degrees of ability and comfort throughout our lives, the extent of which primarily depend on our age (here defined as time since birth) and the quality of our health. Most of the functions of the human body escape our conscious awareness, so that we generally do not notice that behind the scenes our body is a beehive of activity. We also fail to recognize that, in the process of keeping us alive, our cells divide, age, grow, and die in such a way that our body is a continually changing composite of which little survives over the years, with only copies of copies of copies of cells carrying us from conception to old age.

Take the skin, for example: a living, breathing, regenerating tissue that is the largest organ of the body and that acts as a barrier between the internal organs and the environment. In adults, it encompasses about 22 square feet (2 m^2) and weighs around eight pounds (4 kg). It protects the interior of the body from injury, from harmful effects of microorganisms, and from the damaging ultraviolet rays of the Sun. It plays a role in the body's thermal regulation through the constriction or dilatation of small blood vessels, it contains nerve endings that allow us to feel touch, temperature, pain, pressure, and vibration, and it slows the loss of fluids from the body. The skin also shelters the hair follicles, which produce the hairs that cover most of the body's surface, and it provides storage for a variety of substances.

The skin, composed of several layers, ages quickly but is remarkably effective at renewing itself. In the top layer, the epidermis, most cells eventually reach the surface as the outermost layers of cells wear off. They are replaced in a time frame of roughly a month or two, in a continuous process that culminates in the loss of approximately 30,000 cells every minute throughout our lives. This translates into roughly eight pounds (4 kg) of dead material per year. Some features of our skin are, of course, more lasting. For example, we may have seemingly permanent moles and we may have scars that persist for years. These tissues, however, are not really skin. Moles are embedded within our skin but they are in fact benign growths that are typically composed of pigmented cells that do not follow the same lifecycle as true skin cells. Likewise, scars are repairs of deep cuts in our skin, but their fibrous repair tissue is organized differently than true skin, in that it lacks the typical characteristics of skin anatomy.

Another example of a cell type with a high rate of replacement is the blood cell. This type comes in two main classes. The red blood cells carry oxygen, while the white blood cells are important components of our immune system. Both cell types are predominantly produced in the bone marrow, with additional manufacturing capabilities in a few other organ systems, mainly the liver and the spleen. Subsets of blood cells are generated at the amazing pace of some 300 million per minute (this number, as many that follow, is a rough estimate and such numbers are subject to sometimes large uncertainties, while they also differ from individual to individual and from time to time). This massive output is required because of the equally high death rate of these cells. Red blood cells, much more numerous than the white blood cells, have a rather short life span: they mature in the bone marrow for a week, enter into the blood stream, and subsequently circulate in the peripheral blood stream for only four months before being trapped and destroyed in the spleen, with eventual recycling of their oxygen-carrying iron content.

Epidermal skin cells and red blood cells are just two examples of our many different cell types. In fact, every tissue turns over its cells, each at a different rate. This has been investigated using carbon-14 dating (to which we return in Chapter 8). When this dating method is applied to the DNA molecules that store our genetic identity, the life span of individual tissues in our bodies can be determined. With this technique, it has been estimated that cells in the adult human body have an average age of 7–10 years, which is far less than the average age of a human.

There are remarkable differences in tissue ages, however. Some cells exist for only a few days. These tend to be the ones that form the part of our body that is directly touched by the external world. This part is a constellation of external surfaces made up by our skin, as well as by the internal surfaces of our lungs and the digestive tract, which goes all the way from the mouth via the stomach through the gut. We are, in a simplified view, after all comparable to a doughnut or to a cored apple in which the outside world touches what we see as the external surfaces as well as what we do not generally see and then refer to as internal surfaces.

One inner part of our interface with the environment, the lining of the gut, is highly exposed to material from outside and consequently cell turnover there is correspondingly high. This rapid replacement of cells helps maintain a surface layer of cells that slough off rapidly but that collectively are essential in sustaining the physical barrier that protects us against harmful influences. Cells deeper in the intestinal tissue, which are not directly exposed, in contrast, may last upwards of 16 years.

The epithelial cells that pave the surface of the lung may exist for up to half a year before they are replaced, and some of the liver cells persist for a year or two. The muscle cells that constitute the heart typically continue to function for several decades; by the age of 50, about half of our heart cells have been replaced. Because of such substantial differences in the life span of the cells in the different tissues throughout our bodies we cannot assign an accurate age to our body, but it will be clear from the above that it takes at most a few years for most of the cells to be completely replaced, leaving in essence a copy of our "original selves" to go through successive cycles of replacement.

Because of the replacement of the contents of our cells and of the cells as a whole, in some sense we can make the case that we are always merely days, months, or years old, depending on which parts of the body we choose to focus on. The key concept is that our bodies are never stagnant and that our cells have to remain dynamic in order to stay alive. We have hundreds of different cell types, each with its own specific rate of cell turnover. Paradoxically, all this exchange and renewal serves to support what we think of as a rather persistent physical body.

All these examples of cell replacement make it clear that the vast majority of our cells are considerably younger than our chronological age. We tend to assume that nerve cells, particularly those in the brain, are with us for life after they have matured during the growth phase in childhood. This is indeed the case for some cells within the nervous system. One example is tissue in the visual cortex, the part of the brain that processes visual information and that enables us to realize what our eyes see. Carbon-14 dating has revealed that the age of these cells does indeed match our chronological age. However, findings in individual cell types should not be generalized to all cells in the nervous system. The question of how long a long-living brain cell in fact survives intact turns out to be a question of definition and remains very difficult to answer, because cells are made up of many components that are themselves continually replaced and rebuilt. For example, just the replacement of all the water in our bodies on a relatively short time scale of at most a few weeks demonstrates that the liquid contents of a cell change in a far shorter period than the lifetime of a cell, which is generally already considerably shorter than a human lifetime. Apart from water, we also need fuel to make our cells run. Brain cells, for example, thrive on the energy derived from oxidizing sugar, which consequently requires constant replenishment. Even the cell membranes, which package the cells, are maintained and replaced as needed, like fences that need mending from time to time. All these replacements occur gradually and continually. It is, therefore, difficult to accurately establish how long the entire replacement process typically takes.

Memories are also subject to impermanence: some short-term ones may never transform into long-term ones, and even those that we retain for more than a brief moment are not necessarily stable, but can be lost over time or disrupted by injury. Take, for example, the case of Henry Molaison, who has become the most intensively studied patient with memory loss in history. By the time of his death at age 82 in 2008, more than 100 researchers had studied him. He had brain damage that caused the inability to form new memories. This memory loss, called anterograde amnesia, was not for past events but for anything that happened after the brain damage. Thus, it was as if he were always experiencing almost everything for the first time. This severe condition was the unexpected side-effect of an operation done in 1953 during which neurosurgeon William Scoville removed certain parts of the brain that were thought to harbor the triggers of the grave epilepsy from which Henry Molaison was suffering. That surgery was performed because, at the time, there was no way to relieve these symptoms with medications. Although the surgery much improved the otherwise intractable epilepsy, it also resulted in profound memory loss for “H.M.”, as he was called in the scientific literature in an attempt to protect his privacy. Doctors William Scoville from Connecticut and Wilder Penfield, a cognitive neuroscience professor from Quebec, started to record and study the memory loss, and thereby formed the basis of an entirely new understanding of the intricacies of our brain and memory system. Henry Molaison, by so generously participating in numerous tests and studies, through his tragedy tremendously helped to advance brain science.

To date, no scientist has been able to capture a memory, extract it, and store it as one could an object. Yet, over the past few decades, tremendous strides have been made in our understanding of the different types of memory, the anatomic locations that are important in memory creation and storage, and how memories transition from short-term phenomena to more permanently saved forms. Memories may not be solid objects, but many are lasting and all have a biological basis in our brain. In other words, there are processes in place that maintain our memories over time, even though their biological components are subject to change as well as replacement. This is an area of very active research in which multiple hypotheses about the workings of our memory systems are being tested. Some of this work builds on previous concepts, while other work opens entirely new avenues of thinking about memory. We just do not really know yet how memory works. Nevertheless, it is fascinating to think that something as personal and ephemeral as a memory has an age and a life span, fairly analogous to what we observe with the cells in our body.

Memories can be divided into two major categories. Declarative memory reflects our common meaning of the word "memory", which includes awareness of events and facts from the past. The second category of memory covers actions or procedures learned in response to what is presented to us by our environment. Such learned actions can become quite habitual and are typically not consciously recognized but instead are stored as a more internalized memory that is, nevertheless, based on previous occurrences. It is especially this procedural, implicit type of memory that is vital for our survival.

Through observations and studies of people and animals with damage to different parts of their brains we know much about the roles and functions of such damaged areas. For example, the area of the brain that is called the hippocampus (located in the center of the skull, just above the plane of the eyes and ears) is now known to be critical for the formation and retrieval of memories. Areas of the temporal lobes on both sides of the hippocampus further shape and maintain memories. Diverse other areas of the cortex, the outer layer of our brain, are also important for memory storage and recollection. There is, then, no single "memory control-center". In fact, multiple different areas of the brain are activated when we recall complex events, such as a first night at a performance with colorful costumes and beautiful music.

Memories do undeniably have connections to particular structural components of the brain but in fact they may best be thought of as a collection of patterns rather than as separable solid objects. When viewed this way, our overall memory can be described as a system of different circuits within the brain that are updated, influenced, and regulated by our environment, which may be stimulating the system or slowing it down. External factors that affect this system include drugs, caffeine, and the amount of sleep we have had. Importantly, the memory circuits are also controlled by internal substances such as neurotransmitters that help convey messages from neuron to neuron in our brain. Neurotransmitters, in turn, are regulated by changes in gene expression and other genetic switches, as well as by what are called epigenetic influences. These are not directly obvious in our DNA but can have powerful functional effects on our genes and their products. All of these components together help us to create the initial memory and enable us to subsequently consolidate, store, and retrieve it under the influence of newly synthesized proteins and neural pathway connections.

Our brain is thus not a static organ that does not change after the initial phase of growth and development, but rather contains networks that are ever changing, being rearranged and remodeled based upon external and internal environmental influences. The synapses, which are a critical part of our neurons that facilitate communications between the cells of the nervous system, are subject to change in their shape and in their direct molecular environment. Synapses may also change in number and can be added to some areas of the brain when needed, even in adulthood, to create networks that have resilience and some redundancy. This helps to create a more lasting trace when a memory is consolidated and stored. Neuronal pathways and their communications shape our image of the world in which we live, our habits, and our persona. Somehow, memories often manage to survive, albeit subject to gradual change, even as their substrates, the cells and their chemicals that make up our bodies, are replaced piece by piece over time.

The process of cell turnover continues throughout our bodies for as long as we live, beginning in the embryonic stage as a normal part of growth and development. In fact, in these early stages, much cell death is programmed into our DNA. For a developing embryo the planned death of cells enables, for example, the separation of our fingers during limb development, as well as the proper formation of the reproductive organs when they differentiate into male or female. On a daily basis, however, even as adults, we lose billions of cells through cell death that is designed into the human system. Amazingly, every year of our lives we each seem to use, eliminate, and regenerate a cell mass that is almost as large as our body weight.

The replacement of old generations of cells by new ones is fundamental to our health: cells die in order for the body to thrive. It is an elaborate chain of events that occurs in human tissues under normal circumstances according to a programmed interplay of cell division and cell death. Dictated by this tightly regulated process of cellular proliferation on the one hand and cellular attrition on the other, cell turnover amounts to a form of self-renewal, as long as cell creation and death are balanced. This self-renewal ensures a stable, well-adjusted environment in our tissues through the purging of some cells, cell division to replace the eradicated cells, or formation of new cells that specialize their function so that they can take on the roles needed for specific tissues. Exactly how a cell is slated to die and how cells are activated to divide to produce new cells, and also what sets the rate and quantity of these actions, are scientific questions that are not yet fully answered.

In some (and perhaps in all) cases, the cells that are being eliminated somehow communicate with the surrounding cells to signal the need for an environment within that tissue that will stimulate cell division to replace dying cells. This cell division can occur in a variety of ways. When mature, specialized cells divide, they essentially make duplicates of themselves. In many instances though, cell division does not primarily originate from cells with particular functions but rather from what are called “adult stem cells” or from their descendants, which are called precursor cells. Stem cells are not-yet-specialized cells, or undifferentiated cells, that are not programmed for a specific cell-type destiny. Such cells are present in virtually all of the human organ tissues. They are called into action when needed to support the cellular environment in which they are located. Upon division, the newly created cells specialize as the specific types of cells that had to be replaced.

The notion that there are undifferentiated, unspecialized stem cells dates back just over a century, but the first description of the multipotency of these cells in normal tissues was not until 1963, by biophysicist James Till and experimental hematologist Ernest McCulloch, from Toronto. They had earlier started to collaborate on a project that aimed to find out how the human body could be protected against the effects of the atomic bomb, the threat of which occupied the minds of many at the time of the Cold War. In the course of their work they exposed mice to lethally large amounts of radiation and discovered that certain cells were capable of differentiating into any of the various types of cells we find in the blood, rather than just being programmed to follow a single predestined path. In addition, they figured out that these stem cells were capable of self-renewal. Their discoveries paved the way for stem cell research well beyond the blood system and it remains a very active area of medical research today.

Although the details of the integration of cell death and division in adult tissues remain incompletely known, it is clear that effective management of this process requires a complex series of actions that involve much more than small clusters of cells here and there, and that therefore must involve cell signaling pathways that control the larger tissue environment and possibly entire organs. The number of genes within our DNA that have been shown to be involved in coordinating this balancing act between cell birth and death continues to increase. More and more components of this process are gradually being revealed through discoveries that include interactions within the various cellular signaling pathways, and the regulation of messages that are being exchanged within cells and between cells.

Cell replacement is not only important in maintaining our body over time under normal conditions; it is also critical when tissues are in need of repair following damage through disease or injury. As we advance in age, however, our cells have a diminished capacity for self-renewal and a reduced capability of tissue regeneration. The process that is at the center of aging and that ultimately tips the balance toward cell loss is called biological aging or cellular senescence. Cellular senescence reflects a state in which cells are no longer able to adequately divide either to meet the demands of normal cell turnover or in response to damage. In this condition, an important source of tissue renewal is gradually lost: when the pool of stem cells and their offspring precursor cells fail to maintain their regenerative fitness, the very source of rejuvenation is depleted from our tissues. Interestingly, although the lack of cell division associated with cellular aging overall is detrimental, it can also be protective when it precludes the proliferation of cells that have undergone unfavorable changes that could eventually make them cancerous. Unfortunately, this mechanism of protection is only one factor in a myriad of processes: in reality, overall there is an increase in the frequency of cancer development with advancing age.

Tissues lose their regenerative potential over time as the number of senescent cells increases and the physical decline that accompanies the aging process becomes obvious. Aging, however, is not solely determined by senescent cells, but also by a general loss of function in those cells that are fully specialized and therefore no longer dividing, but that still remain capable of living. Such a loss of overall function may be tied to an impaired ability to communicate with other cells or to problems with the synchronization of a variety of cellular tasks. Moreover, aging cells release substances that influence critical cellular processes. These processes include cell growth and differentiation, the creation of new blood vessels after injury, and tissue structuring. If inappropriate chemical signals are released from senescent cells, the structure and function of other cells can be disturbed. A general response to that unfavorable state is a chronic inflammation that itself further upsets the functioning of the tissue. This type of inflammation is not caused by bacteria or by viruses, but is a negative consequence of the chemicals released by aging cells.

In addition to internal tissue dynamics, the process of aging is also considerably influenced by the environment as well as by a person's lifestyle. These effects can either accelerate or slow the effects of aging. Even under the best of circumstances, however, the rate of overall aging rapidly increases with the number of years since birth. In the end, we do not simply die of old age, as it is often said, but rather of a decline in cellular vitality, which in turn permits diseases to develop when cell damage accumulates and prevents cells from being efficiently replaced. Nevertheless, given that we do not seem to all age at the same rate, there must be individual differences. The rate at which we age and that at which age-related diseases manifest themselves are moderated by internal reactions. These reactions regulate the body's healing and the body's response to conditions that cause stress to our tissues and cells. Such conditions include internal challenges, such as process errors that cause damage to our DNA and the malfunctioning of proteins. And they include external influences, such as oxygen availability, cell nutrition, temperature, physical activity, and exposure to unhealthy chemicals and radiation.

External influences are difficult to study in a standardized way over a lifetime and new findings about the decline of overall health with advancing age have therefore often resulted in scientific or political controversy. Geneticist Edward Lewis, for example, performed