The Role of Death in Life
A Multidisciplinary Examination of the Relationship between Life and Death

EDITED BY John Behr and Conor Cunningham

The relation between life and death is a subject of perennial relevance for all human beings, and indeed, the whole world and the entire universe, in as much as, according to the saying of ancient Greek philosophy, all things that come into being pass away. Yet it is also a topic of increasing complexity, for life and death now appear to be more intertwined than previously or commonly thought. Moreover, the relation between life and death is also one of increasing urgency, as through the twin phenomena of an increase in longevity unprecedented in human history and the rendering of death, dying, and the dead person all but invisible, people living in the industrialized and post-industrialized Western world of today have lost touch with the reality of death. This radically new situation, and predicament, has implications—medical, ethical, economic, philosophical, and, not least, theological—that have barely begun to be addressed. This volume gathers together essays by a distinguished and diverse group of scientists, theologians, philosophers, and health practitioners, originally presented in a symposium sponsored by the John Templeton Foundation.

“In this book, the mutual implication of death and life is demonstrated from an astronomical level, in the emergence of human life from the death of stars, to the molecular level where death enables the emergence of cellular life, through anthropological, philosophical, and theological insights, to the realm of medical care for the dying, where it is claimed that ‘only theology can save medicine.’ A profound and challenging book.”

—Andrew Louth, Professor Emeritus of Patristic and Byzantine Studies, Durham University

“How can Christians defend the place of natural death and the death consequent upon sin, while continuing to insist upon the undying character of true life as such and so the reality of resurrection? These penetrating essays by several of the leading theological thinkers of our times will powerfully help the reader to ponder these crucial matters of our contemporary mortality.”

—John Milbank
Research Professor and Director of the Centre of Theology and Philosophy, University of Nottingham

“For once, it is not a polite exaggeration to say this is a ‘unique’ book. The breadth of disciplines represented and the originality of the analysis offered make it an exceptional contribution to current debates. Anyone who thinks the dialogue between theology and the natural sciences is, at best, an exchange of uncomprehending platitudes, will have to think again in the face of these expert, challenging essays, which show that an orthodox theology of our embodied condition can be culturally transformative.”

—Rowan Williams, Master of Magdalene College, Cambridge

“A substantive, important, and provocative volume. The insights of the essays it encompasses will richly reward the reader.”

—H. Tristram Engelhardt Jr.
Professor of Philosophy, Rice University, Professor Emeritus, Baylor College of Medicine


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The Role of Death in Life
“. . . the truth will set you free” (John 8:32)

In much contemporary discourse, Pilate’s question has been taken to mark the absolute boundary of human thought. Beyond this boundary, it is often suggested, is an intellectual hinterland into which we must not venture. This terrain is an agnosticism of thought: because truth cannot be possessed, it must not be spoken. Thus, it is argued that the defenders of “truth” in our day are often traffickers in ideology, merchants of counterfeits, or anti-liberal. They are, because it is somewhat taken for granted that Nietzsche’s word is final: truth is the domain of tyranny.

Is this indeed the case, or might another vision of truth offer itself? The ancient Greeks named the love of wisdom as *philia*, or friendship. The one who would become wise, they argued, would be a “friend of truth.” For both philosophy and theology might be conceived as schools in the friendship of truth, as a kind of relation. For like friendship, truth is as much discovered as it is made. If truth is then so elusive, if its domain is *terra incognita*, perhaps this is because it arrives to us—unannounced—as gift, as a person, and not some thing.

The aim of the Veritas book series is to publish incisive and original current scholarly work that inhabits “the between” and “the beyond” of theology and philosophy. These volumes will all share a common aspiration to transcend the institutional divorce in which these two disciplines often find themselves, and to engage questions of pressing concern to both philosophers and theologians in such a way as to reinvigorate both disciplines with a kind of interdisciplinary desire, often so absent in contemporary academe. In a word, these volumes represent collective efforts in the befriending of truth, doing so beyond the simulacra of pretend tolerance, the violent, yet insipid reasoning of liberalism that asks with Pilate, “What is truth?”—expecting a consensus of non-commitment; one that encourages the commodification of the mind, now sedated by the civil service of career, ministered by the frightened patrons of position.

The series will therefore consist of two "wings": (1) original monographs; and (2) essay collections on a range of topics in theology and philosophy. The latter will principally be the products of the annual conferences of the Centre of Theology and Philosophy (www.theologyphilosophycentre.co.uk).

Conor Cunningham and Eric Austin Lee, *Series editors*
The Role of Death in Life

A Multidisciplinary Examination
of the Relationship between Life and Death

edited by

JOHN BEHR and
CONOR CUNNINGHAM

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PERSPECTIVES FROM
ASTRONOMY, CHEMISTRY,
AND BIOLOGY
This essay discusses our present understanding of the origin of many of the ninety-two naturally occurring chemical elements in the Periodic Table of the Elements, of which the Solar System and all known forms of life consist. We will see that the early Universe essentially contained only hydrogen and helium, the two lightest elements. The creation story of relatively heavy elements such as the carbon in our cells, the oxygen that we breathe, the calcium in our bones, and the iron in our blood, is arguably one of the most beautiful and profound realizations in the history of science. It is a powerful example, on grand scales, of the role of life in death and vice versa: without the birth of stars, and without their subsequent death, especially the violent final explosion that some of them experience, new stars and planetary systems having an enriched proportion of heavy elements would not have been created, the rocky and water-covered Earth.

1. For a general overview of astronomy, including most of the astronomical concepts discussed here (and a very large number of beautiful photographs, including many of those shown in my oral presentation), see the introductory college textbook by Pasachoff and Filippenko, The Cosmos. This work also contains an extensive list of useful references and suggestions for further reading. A set of ninety-six richly illustrated video lectures covering much of introductory astronomy is that of Filippenko, Understanding the Universe. A higher-level college textbook that includes more advanced physics concepts is that of Carroll and Ostlie, An Introduction to Modern Astrophysics. For an older, but still relevant, classic, see Shu, The Physical Universe.
would not exist, and we would not be here discussing these issues. When we as sentient beings contemplate our cosmic origins, the following eloquent phrase provides a concise summary: “We are made of star-stuff.”

The Elements of Life

Let me first consider the main constituents of life on Earth, with humans (the focus of this collection of essays) being fairly representative. About 93 percent of our body mass (i.e., percent by weight) consists of only three chemical elements: oxygen (65 percent), carbon (18 percent), and hydrogen (10 percent). Adding just three more brings the total to nearly 99 percent: nitrogen (3 percent), calcium (1.5 percent), and phosphorus (1.2 percent). (In plants and other organisms lacking skeletons, sulfur replaces calcium in the top six elements.) By number of atoms (i.e., atomic percent) instead of weight, the corresponding amounts in humans are even more impressive: hydrogen (63 percent), oxygen (24 percent), and carbon (12 percent) account for almost 99 percent, with small contributions from nitrogen (0.58 percent), calcium (0.24 percent), and phosphorus (0.14 percent). Hydrogen and oxygen are dominant because humans consist largely of water: 53 percent by weight for the average adult.

If we examine the relative abundances of elements by number in our Solar System, including the Sun, which has most of the mass, we see that hydrogen is by far the most common, as in humans. Helium is the second most abundant, but it doesn't combine with other atoms, so it is not surprising that humans don't contain helium. Oxygen and carbon are the next most abundant among the non-inert elements, and they are numbers two and three in humans as well. So we are made of the most common chemically active elements in the Solar System.

But life does not consist of just the top six elements listed above. About eighteen additional elements are of critical importance. Although five of them (sulfur, potassium, sodium, chlorine, and magnesium) constitute most of the remaining 0.1 percent by atomic percent, the others should not

2. This saying is often attributed to the astronomer and science advocate, Carl Sagan, *The Cosmic Connection*. However, Sagan certainly did not discover the concept, and it had long been stated in a similar way, or even nearly verbatim, e.g., Watson, “Astronomy”; W. E. Barton, quoted in an advertisement in the *Evening News* (Sault Ste. Marie, Michigan), January 24, 1921, 2, column 3; Garbedian “The Star Stuff that is Man,” SM1, quoting astronomer Harlow Shapley.

be forgotten. Iron, the most abundant of the “trace elements” in the human body, is necessary for the hemoglobin in red blood cells, while zinc and copper are needed in some proteins, and the thyroid gland uses iodine in the production of hormones that regulate the metabolism. There are some small differences between plants and animals; for example, some types of plants do not require sodium, yet all animals need it.

From where did all of these elements arise, so necessary for life as we know it? Were they present from the very birth of the Universe? The answer is no: various physical processes produced them, as I shall now describe.

**In the Beginning**

Modern cosmologists, who study of the structure and evolution of the Universe as a whole, now have a rather detailed, self-consistent, and observationally supported story regarding the past history of the Universe, starting from a tiny fraction of a second after the moment of creation. This “big-bang theory” postulates that the Universe began in a very hot, dense state about 13.8 billion years ago, and it has been expanding, cooling, and becoming less dense ever since. During the expansion, space itself is created, rather than material objects flying through a preexisting space; thus, the big bang was not really an “explosion” in the conventional sense, like a bomb, and there is no unique center within the spatial dimensions physically accessible to us.

When the Universe was less than one millionth of a second old and its temperature was higher than about ten trillion kelvin (10^{13} K), there was equilibrium between particles, antiparticles, and photons (packets or quanta of light): specifically, quarks and antiquarks annihilated each other, forming photons, and vice versa. But through a process not yet fully understood, a slight excess (one part per billion) of quarks over antiquarks was produced, and this eventually gave rise to neutrons and protons, “baryons” that each consist of three bound quarks. Initially there were somewhat more protons (simple hydrogen nuclei) than neutrons because protons are slightly less massive. Also, starting about one second after the big bang, neutrons began to systematically decay into protons and electrons, thereby producing a greater deficit of neutrons compared with protons. At this time, the temperature was about ten billion kelvin (10^{10} K), and collisions between baryons were too violent for them to stick together. Moreover, it
was still so hot that electrons roamed freely, not bound to protons as in neutral atoms.

But by an age of one hundred seconds, the Universe had cooled to a temperature of "only" about one billion K \( (10^9 \text{ K}) \).\(^4\) Collisions between baryons were not as violent, sometimes resulting in particles bound together by the "strong nuclear force." As a first step, a proton and a neutron could bind together to form a deuteron, a heavy "isotope" or type of hydrogen.\(^5\) Two deuterons could subsequently fuse together and form a light isotope of helium (He-3, with two protons and one neutron) plus a free neutron. He-3 and a deuteron could then fuse to produce the normal isotope, He-4 (with two protons and two neutrons), and a proton. Since protons outnumbered neutrons by a ratio of 7/1 at the time of such interactions, about 25 percent of the mass ended up as He-4, with most of the rest (75 percent) remaining as protons (H nuclei). A tiny bit of lithium, containing three protons and four neutrons (Li-7), was also produced.

Nuclei heavier than lithium (with the exception of a trace of beryllium-7) were not created during the big bang because the Universe was expanding and cooling rapidly; by an age of just ten minutes, the density and temperature had dropped so much that the process of "primordial nucleosynthesis" (the formation of the lightest nuclei through nuclear fusion) had ceased. In particular, the isotope of beryllium having four protons and four neutrons (Be-8) is unstable, decaying very shortly after its creation, and this caused a bottleneck in the fusion process; there was no easy way to reach carbon (with six protons and six neutrons). The Universe was left with plenty of H and He nuclei, a smidgen of Li, a trace quantity of Be-7, and no other nuclei. Eventually, when the Universe cooled to a temperature of about 3000 K around 380,000 years after the big bang, these nuclei combined with free electrons and formed neutral atoms, primarily of H and He. Although life on Earth relies on that primordial hydrogen, we need other mechanisms to produce the additional necessary elements. This is where stars and the way they generate their energy come into the picture.

\(^4\) If one thinks of hell as having ponds of boiling sulfur at a temperature of 718 K \( \approx 1000 \text{ K} \), then the Universe was still about a million times hotter than hell at this time!

\(^5\) Cosmologists sometimes joke that the study of deuterons is known as Deuteronomy.
Star Formation and Energy Generation

We live in the Milky Way Galaxy, a gigantic, gravitationally bound collection of several hundred billion stars that might look similar to other large spiral galaxies. It is roughly one hundred thousand light years across and only about one thousand light years thick. If we were above the disk, we would easily see spiral arms. But the Sun is within the thin disk, about twenty-six thousand light years from the center of the Galaxy. An all-sky photograph clearly shows the disk, as well as the central bulge of stars. When we look along the plane of the disk, we see many stars compared with other directions; this forms the band of light called the Milky Way that can be viewed on a clear, dark night.

In the Milky Way Galaxy, we see many examples of giant clouds of gas and dust (tiny solid grains) in the “interstellar medium,” the space between the stars; a good example is the beautiful Trifid nebula in the constellation Sagittarius. In the sword of Orion, the great hunter, one finds the Orion Nebula, another excellent example. If a cloud grows to a sufficiently large mass, or if it gets dense enough, it can become gravitationally unstable; its own self-gravity causes it to collapse inward, as has occurred in the Orion Nebula. During the collapse, it begins to fragment into many smaller sub-units called protostars. As the density increases, collisions between the particles cause the gas to heat up and the pressure rises, thereby slowing each protostar’s collapse.

Further contraction occurs more gradually, but gravitational energy is still being released and the temperature continues to rise. Eventually, when the central temperature of a protostar becomes sufficiently high (typically above four million K, but about fifteen million K in the Sun’s core), nuclear reactions begin and we say that a star is born. In general, stars are produced in clusters that originated from the same initial cloud of gas and dust. Light from powerful, massive stars blows away excess gas; a star cluster remains. Presumably, our own Sun was formed in a cluster about 4.6 billion years ago, but the Sun and other stars gradually escaped from the cluster.

The energy released from a star is exactly balanced by nuclear reactions in its core; thus, there is no reason for further gravitational contraction and the star achieves mechanical equilibrium. A given star maintains roughly the same size and has a roughly constant intrinsic brightness (luminosity) for most of its normal life (technically, while it is a “main-sequence star”), though both the size and especially the luminosity are larger for more-massive stars. Typical stellar masses range from about 8 percent of the Sun’s
mass to roughly fifty solar masses, but most stars are less massive than the Sun and the very massive ones are extremely rare.

In the Sun, as in other main-sequence stars, the gases in the core are so hot that atoms are ionized; the electrons have been stripped away from the nuclei. Energy is produced by fusion of hydrogen nuclei to helium nuclei: four protons come together in a series of reactions, forming a single helium nucleus consisting of two protons and two neutrons (hence, two of the protons turned into neutrons along the way, though this detail need not concern us here). The specific sequence of reactions depends on the temperature of the core and therefore on the mass of the star, but the end result is the same: helium is produced, and it has a slightly lower mass (by 0.7 percent) than the original four protons that went into making it. That mass difference \( m \), when multiplied by the square of the speed of light \( c^2 \), accounts for the energy release through Einstein’s famous formula, \( E = mc^2 \). The Sun shines by fusing about six hundred billion kilograms of hydrogen to helium each second, yet there is so much hydrogen in the central region that this process can continue for a total of about ten billion years. The Sun is now a middle-aged star, about halfway through its normal main-sequence life.

What will happen as the Sun ages beyond about ten billion years, when the core consists mostly of helium nuclei? Over the next two billion years, the story will unfold as follows. Helium nuclei will be unable to undergo fusion because of the electric repulsion between them. Thus, the helium core will lose energy to surrounding layers and slowly contract under the force of gravity. But this contraction will heat up a surrounding layer of hydrogen that is still fusing to helium, thereby increasing the rate of fusion, eventually by a factor of one hundred or more. The Sun will become much more powerful (luminous), and its outer envelope of gases will expand outward and cool down. The Sun will be a “red giant” at this stage: a very luminous and bloated, but relatively cool and hence reddish-looking, star that will literally fry anything that remains on Earth’s surface.

**Stellar Nucleosynthesis beyond Helium**

During the next stage of the Sun’s life, heavier elements will be produced. As the helium core in the future red-giant Sun contracts, it will also gradually become hotter. When the temperature reaches about one hundred million K, a new process of nuclear fusion will begin: three helium nuclei
made of star-stuff

Can fuse together, forming a nucleus of carbon and releasing energy in the process. Moreover, a carbon nucleus can fuse with another helium nucleus, forming oxygen and releasing additional energy. This previously happened in other, similar stars as well. We are starting to see the creation of elements necessary for life on Earth!

After about a million years of helium fusion, a carbon-oxygen core will form in the Sun’s center. It will not be sufficiently hot to undergo nuclear fusion; carbon and oxygen nuclei have so much positive charge that the electric repulsion is too great to overcome in a relatively low-mass star like the Sun. The carbon-oxygen core will thus contract, releasing energy and heating up the helium-fusing and hydrogen-fusing layers that surround it. This will accelerate fusion in these layers, causing the Sun to bloat into an even larger red giant.

At this point, the outer layers of gas will be only tenuously bound to the Sun, and atoms of gas will be blown outward in the form of a solar wind. More importantly, a recurring instability will abruptly eject parts of the outer envelope in what I like to call a “cosmic burp.” High-energy light coming from the hot, exposed stellar surface will ionize the slowly expanding gases, causing them to glow. The result will a “planetary nebula,” named this way because eighteenth- and nineteenth-century astronomers thought the disks of light resemble planets. They are very beautiful objects, but each one appears different in detail, so we don’t know exactly what our own Sun’s planetary nebula will look like.

The central star in a planetary nebula gradually becomes a dense carbon-oxygen “white dwarf”—a retired star that shines only because it radiates its life savings of stored energy, not because it is actively fusing light elements into heavier ones. A good example is Sirius B, the faint companion of the brightest star in the sky; it is roughly the size of Earth, but having a mass comparable to that of the Sun, it is very dense. For stars that are initially less massive than about 0.45 solar masses, the white dwarfs consist of helium, because carbon and oxygen were not formed. But for stars that are between about eight and ten solar masses, carbon can fuse to form a core of oxygen, neon, and magnesium, so that the corresponding white dwarf consists of these elements.

The gases in a planetary nebula are slightly enriched in heavy elements because part of the material from the core (mostly carbon and oxygen) mixed outward into the atmosphere of the star prior to the formation of the planetary nebula. Also, in somewhat more massive stars, nitrogen can
be formed as a byproduct of H-to-He fusion. Finally, even heavier elements can be formed during the second red-giant stage through what is called the slow-neutron-capture process (the “s-process”), and they too can be ejected during the planetary nebula stage.

This s-process is quite interesting. It starts with an existing iron nucleus (twenty-six protons), or some other heavy nucleus from a previous supernova explosion (to be discussed below). This nucleus absorbs free neutrons from its surroundings one by one, though at a relatively slow rate. Between the capture of two consecutive neutrons, often (but not always) a neutron in the nucleus will decay into a proton and other particles (a process called “beta decay”), thereby creating the element having the next higher atomic number (number of protons). The process can continue all the way up to the element bismuth, which has eighty-three protons, and it is responsible for roughly half of the isotopes of elements between iron and bismuth. Strong evidence for the s-process was found in 1952, when the radioactive element technetium (which lasts roughly ten million years) was discovered in the outer atmospheres of certain types of stars that were billions of years old. The technetium could not have been present when the stars were born, and it was unlikely to have been produced deep in the cores where most of the fusion powering the stars was taking place.

In any case, the ejection of chemically enriched gases during the planetary nebula stage represents an important step in the process by which stellar death gradually increases the concentration of elements heavier than H and He in the interstellar medium.

**Supernovae: A Key to Our Existence**

Though normal stars produce some of the heavy elements in the Periodic Table, a crucial component comes from exploding stars (supernovae). Only a small minority of stars explode violently at the end of their lives, becoming millions or billions of times more powerful than the Sun, but those that do are crucial to our existence: they create many of the heavy elements and eject them into space, making them available as raw material for the formation of new stars, planetary systems, and ultimately life. This, again, illuminates the role of life in death and, more profoundly, the role of death in life.

There are two main types of supernovae. The progenitors of “core-collapse supernovae” (technically, Type II, Ib, and Ic supernovae based on
observational distinctions) are stars more massive than about ten solar masses near the end of their lives. They bloat out to become red supergiants, a good example of which is Betelgeuse in the constellation Orion. They gradually build up successively heavier elements in their core. The ashes of one set of nuclear reactions become the fuel for the next set—H fuses to He; He fuses to C and O; C fuses to O, Ne, and Mg; O fuses to Si and S; Si and S fuse to Fe (iron). An iron core eventually forms, but it becomes too massive and collapses; protons combine with electrons to form neutrons, and the result is an extremely dense “neutron star.” This core collapse initiates a titanic explosion of the surrounding layers, flinging out the previously made layers of C, O, Mg, and other “intermediate-mass elements.” It also fuses and ejects additional elements such as calcium, and especially nickel which radioactively decays to cobalt and finally to iron.

Another breed is known as “thermonuclear supernovae,” often referred to as Type Ia supernovae for historical reasons. Here, a carbon-oxygen white dwarf becomes unstable and undergoes a runaway chain of thermonuclear reactions, completely obliterating itself in the process. Carbon fuses to heavier elements, and about half the star’s mass becomes radioactive nickel, which then decays to cobalt and eventually iron. Exactly how the white dwarf reaches the unstable mass is still unclear: either it steals gas from a relatively normal companion star, or perhaps two white dwarfs in a binary system spiral toward each other and merge. In any case, many elements up to iron are produced by such stellar deaths and ejected into the interstellar medium.

Let me also mention the heaviest elements, including most isotopes of gold, silver, and platinum. Though in general not necessary for life as we know it, they are still of interest, and they are much used by humans. Such elements form through the rapid-neutron-capture process (the “r-process”). In the r-process, there are so many available free neutrons that quite a few get captured in quick succession before any neutron in the nucleus decays to a proton. This can produce neutron-rich isotopes, as well as all elements heavier than bismuth, through uranium. The site of the r-process has not yet been definitively confirmed, though core-collapse supernovae produce a great number of free neutrons and are thus a good candidate. Also, recent calculations show that merging pairs of neutron stars might be prime candidates for the r-process. Again, stellar death is involved, directly or indirectly.
We have compelling evidence that supernovae do indeed produce heavy elements and eject them into space. Spectroscopic studies of supernova remnants, the expanding debris of fatal stellar explosions, reveal heavy elements in such great quantities that they could not have been present in the original stars; we know of no stars having similar abundances. Moreover, studies of the particularly nearby, spectacular Supernova 1987A (whose light was first detected in on February 23, 1987) revealed the presence of short-lived radioactive nuclei that could not have been present in the 10-million-year-old star prior to the explosion. The explosion itself must have produced these nuclei!

The Chemical Evolution of Galaxies and the Formation of Life

So what happens when some stars violently explode, or when most others gently eject their outer envelopes of gases? Well, in both cases, but especially in supernovae, the gases are chemically enriched. They go flying out into space, becoming part of the interstellar medium. For example, we see supernova remnants at various stages of expansion and dilution: the relatively compact Crab Nebula is the remains of a supernova that was seen by Chinese astronomers in the year 1054 CE, whereas the Vela supernova remnant has an age of several tens of thousands of years. The rapidly moving gases are generally trapped within the galaxy by the galaxy’s overall gravitational pull, so most of the newly formed heavy elements are retained. Gradually the gases encounter other clouds of gas, either preexisting in the galaxy or the remnants of other dying stars, and they coalesce, forming progressively larger clouds. Some of these clouds eventually grow sufficiently big that they become gravitationally unstable and collapse, forming a new cluster of stars. In other cases, a nearby supernova explosion might compress the cloud, thereby initiating collapse and the formation of new stars. This is yet another example of how, in the cosmos, death can be an important precursor to life.

In any case, new generations of stars are born and die, and the chemical enrichment process continues. Over time, certain clouds of gas become so abundant in heavy elements that rocky, Earth-like planets can form in the disks of debris surrounding newborn stars. We have long known that this happened in our Solar System, and we now also know that such planets are common around other stars as well. In particular, the spectacular
Kepler mission has recently discovered a few thousand planets, most of which are just two or three times the size of Earth and many of which are probably rocky. Planetary systems broadly similar to ours abound.

On Earth, through a process not yet understood, molecules of ever-increasing complexity formed and eventually combined to create the simplest living cell, the common ancestor to bacteria and archaea at the beginning of the tree of life. Gradually, again through a complex series of steps that are still not well explained, prokaryotes (cells without a nucleus) evolved to eukaryotes, and then to creatures of progressively greater complexity, culminating with humans—sentient beings who can think about and study the Universe, in a quest to understand their origins.

Studying the emergence and evolution of life on Earth is one of the greatest challenges of modern science. It is an exciting field, full of exploration and opportunity, and I’m confident that someday we will learn the answers. But at least we already know the origin of the raw materials for life, the chemical elements of which we consist: hydrogen came from the big bang, and stars produced the rest through a repeated process of life, death, and rebirth. Stellar life allows chemical elements to be created, and stellar death creates additional elements and liberates all of them into space, leading to the formation of new stars, planets, and ultimately life. We are, indeed, made of star-stuff.

6. Excellent books on the origin and evolution of life include those of Zubay, Origins of Life on Earth; Davies, The Origin of Life; and Cowan History of Life.
A Biochemical Perspective on the Origin of Life and Death

Luc Jaeger

This paper is dedicated to Saint Albert the Great, patron saint of scientists and Saint Thomas Aquinas, patron saint of universities and students.

From a biochemical perspective, the process of life cannot be separated from the notion of death. As such, we can consider the origin of biological life to be at the origin of biological death. It is however necessary to clarify what life and death really mean at a biochemical level of integration. This essay will first explore the physico-chemical characteristics of the biopolymers on which life is presently based on. By considering cellular life as an informational process, we will then show that the process of life is intimately connected to the process of death through bottom-up and top-down causal effects. Top-down causation (TDC) by information control and adaptive selection are at the root of converging forces that shape the evolution of living bio-systems from the simplest to the most complex levels. Living systems can be defined as self-reproducing systems that function via TDC by information control and adaptive selection. Consequently, Darwinian evolutionary processes in cells are not only ruled from the bottom-up but also by organizational principles that impose necessary constraints from the top-down and determine the survival (life) or elimination (death) of cellular
bio-systems. This can be seen as resulting from the ability of informational biopolymers to be eliminated (or die) and to be selected (or live).

**Definitions of Life at an Organic Level**

From a naturalistic, scientific point of view, there is presently a significant body of research suggesting the emergence of the properties of animate, living matter (or organic life) from inanimate, non-living matter.\(^1\) The abiogenesis of life implies continuity between physics, chemistry, and biology and their natural laws. It also strongly suggests that the emergence and development of organic life are dependent on processes and conditions that are probably not unique to Earth. Despite agreements on the abiogenesis of life, an unequivocal definition of life at an organic level is still a matter of debate. Most scientists will agree that living systems are characterized by autonomous properties, homeostasis, self-organization, physical boundaries, the existence of a metabolism (anabolism and catabolism), growth, reproduction, and the ability to adapt in response of the environment (evolution).\(^2\) What raises issues is the formulation of a minimalist definition of organic life that establishes a clear distinction between inanimate and animate matters. Among the abiogenic definitions of life, many share the notion that cellular life is associated to the emerging properties of a replicating informational molecular system able to mutate.\(^3\) However, while informational self-replication is an essential property for life, this alone might not be sufficient. For instance, viruses, which seem to fit this notion, are not considered by many as truly alive because of their inability to fabricate by themselves their own proteins. More inclusive definitions attempt to define organic living systems as autopoietic systems (from the Greek \( \alpha\υτ\(\text{ό}(auto) \), meaning “self”, and \( \πο\ι\(\text{ης}(poiesis) \), meaning “creation”) by emphasizing that: “a living system is a system capable of self-production

and self-maintenance through a regenerative network of processes which takes place within a boundary of its own making and regenerates itself through cognitive or adaptive interactions with the medium.  

An essential characteristic of organic life that is often overlooked in these definitions is regulation. The ability to control self-reproduction and self-maintenance through regulatory feedback loops is likely to be one of the most fundamental properties of life as it is through regulation that cognitive or adaptive interactions can take place within a network of processes. Albeit not explicitly stating it, the autopoietic definition of organic life is the only one to suggest implicitly the need of regulatory controls in life.

The scientific investigation of the origin of life does not necessarily have to settle on a specific definition of organic life. A clear distinction between living and non-living matter becomes more and more elusive as researchers investigate the possible bridges that link chemistry to biology. For the chemist, it might never be possible to identify the specific point in time when the physico-chemical world led to the biological world. Moreover, it might also be extremely difficult to decipher at which stage a chemical system becomes truly alive. Nevertheless, identification of the set of properties that characterize modern day living-matter (life) from non-living matter is far from being useless. For instance, by looking at the properties of biological molecules, much can be learned to understand the necessary transitions and driving forces that led to the emergence of life.

One aspect that contributes to the difficulty in defining life at an organic level is that it is a process rather than a pure substance. Life is a process out of thermodynamic equilibrium, and for death, the process can be seen as a return to thermodynamic equilibrium. As such, the life process has been described as a dynamic kinetics state of matter; the fitness of living systems is therefore “dynamic kinetics stability” rather than “thermodynamic stability.” This characteristic of life is particularly well emphasized by the universal chemical constituents of all modern living systems: nucleic acids (RNA and DNA), proteins, polysaccharides, and lipids.

5. Cf. Szostak, “Attempts to Define Life Do Not Help to Understand the Origin of Life.”
Informational Biopolymers of Life (and Death)

All living systems on earth are essentially based on the chemical elements C, H, O, N, P, and S, which are among the most abundant elements produced by the stars (this is especially the case for C, H, O, N). Because of their reactivity and abundance in the universe, these chemical elements are at the foundation of organic chemistry and are particularly suited for building up chemical compounds of greater structural complexity. Behind the fact that these elements are characterized by well-defined set of physical and chemical properties, one can see a probabilistic determinism for the genesis of a diversity of reactive compounds by combination of these fundamental elements. For instance, small compounds like hydrogen cyanide (HCN) and formaldehyde (HCHO) are able to form quite spontaneously from C, H, O, N, and have been detected even in the interstellar space. Their chemical reactivity in prebiotic conditions can lead to the formation of amino-acids, bases, sugars, and polycarbon chains. Polymerization of activated forms of these building blocks can potentially lead to the emergence of nucleic acids, proteins, polysaccharides, and lipids. Because RNA can carry functional information (recognition, catalytic, and regulatory functions) as well as genetic information (able to be replicated), RNA was proposed to be the key polymer on which life developed. This led to the notion of an old “RNA world” at the origin of the present modern RNA worlds. While the prebiotic synthesis of the RNA building blocks, or nucleotides, have been considered much more challenging than the one of the protein building blocks, or amino acids, recent developments in prebiotic chemistry

indicate highly plausible chemical routes towards the production of nucleotides and amino acids as well as their enrichment in prebiotic conditions. Moreover, several plausible scenarios suggest that chemical polymerization of activated nucleotides can occur in water, in presence of mineral surfaces or lipid vesicles. If the likelihood of generating informational and stable biopolymers is a key argument for sustaining the abiogenic origin of life, often overlooked is the fact that these biopolymers can also hydrolyze back to their building block units (Table 1).

Amino Acids in a 1958 Miller H2S-rich Spark Discharge Experiment.


Table 1: Half-life ($t_{1/2}$) of biopolymers at 25°C and 100°C. The half-life of a molecule is a measure of the time for which half of the molecules still remain intact. It is also the time at which half of the molecules are degraded. On the right side the table, the stability ($t_{1/2}$ per cleavage event) is given for various biopolymers containing a specified number of bonds. (a) coronavirus PTGEV: porcine transmissible gastroenteritis virus; (b) E. coli genome is double stranded.

Informational biopolymers result from a process of prebiotic chemical selection that likely favored the emergence of cyclic, dynamic chemical networks in aqueous medium. In order to build up dynamic kinetics stability, slow degradation of the first biopolymers into small building block units is therefore as important as the polymerization reactions leading to their formation. Theoretically, open systems that produce in a continuous fashion the chemical building blocks of the first biopolymers can potentially develop into self-replicating systems with exponential growth. However, if these polymers were to be based on very highly stable covalent bond linkages, these chemical systems would not be well suited for regulation (and

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<table>
<thead>
<tr>
<th>reaction</th>
<th>bond $t_{1/2}$</th>
<th>number of bonds per polymer</th>
<th>$t_{1/2}$ per cleavage event</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25°C</td>
<td>100°C</td>
<td></td>
</tr>
<tr>
<td>RNA hydrolysis</td>
<td>4 years</td>
<td>1.3 weeks</td>
<td>1.3 hours</td>
</tr>
<tr>
<td>protein hydrolysis</td>
<td>400 years</td>
<td>5.5 weeks</td>
<td>4 years</td>
</tr>
<tr>
<td>DNA hydrolysis</td>
<td>140000 years</td>
<td>1144 weeks</td>
<td>4 years</td>
</tr>
<tr>
<td>polysaccharide hydrolysis</td>
<td>4700000 years</td>
<td>8320 weeks</td>
<td>47 years</td>
</tr>
</tbody>
</table>

15. Adapted from Wolfenden and Snider, “The Depth of Chemical Time and the Power of Enzymes as Catalysts.”
the emergence of metabolism\textsuperscript{16}). Without continuous chemical supplies of building blocks, such type of chemical systems can quickly result in the formation of homogeneous thermodynamically stable materials rather than a kinetically stable state of matter. The ability of degradable biopolymers is therefore an important feature of kinetic stability and therefore, of living systems. Through their own hydrolytic degradation, old biopolymers can contribute to the supply of fresh building blocks that can be used for generating new biopolymers that allow the system to self-regenerate but also to evolve. Based on the chemical stability (towards hydrolysis) of the covalent linkage joining two adjacent biopolymer units, RNA is the biopolymer with the highest chemical instability of its backbone, followed by proteins, DNA and polysaccharides (Table 1).\textsuperscript{17} As such, it is an ideal informational medium for enabling regulation. Interestingly, in modern day biology, the half-life of the RNA bond linkage is still compatible with the survival of RNA viral genome of up to $\sim$30000 nucleotides (nts). In an RNA world taking advantage of RNA as the sole support of the genetic information and with catalytic functions performed by RNA molecules and small peptides, a genome of this length should have likely been able to encode most, if not all, basic functions necessary to sustain the first living cells. Additionally, it is also likely that the chemical stability of an RNA-based genome can be increased by additional molecular factors protecting the RNA from degradation, as is the case for viral RNA. Considering that a bacteria like \textit{E. coli}, divides every twenty minutes with a genome one hundred times bigger, a primitive living cellular system based on a 30000 nts genome replicating one hundred times more slowly than the one of \textit{E. coli} would still have a fairly high probability to survive intact and evolve. In summary, it is because of its ability to hydrolyze within a certain chemical regime that RNA is likely to be one of the best polymers for originating cyclic, kinetically stable networks, even in the absence of enzymatically-catalyzed reactions. With the fitness being “dynamic kinetics stability” rather than “thermodynamic stability,”\textsuperscript{18} we can speculate that the establishment of cyclic kinetically stable networks based on RNA molecules would have favored kinetic coupling between RNA replication and the catabolic reactions associated to the primitive metabolism, responsible for the sustained production and

\textsuperscript{16} Cf. Wagner, Pross, and Tannenbaum, “Selection Advantage of Metabolic over Non-Metabolic Replicators.”

\textsuperscript{17} Cf. Wolfenden and Snider, “The Depth of Chemical Time.”

\textsuperscript{18} Cf. Pross, “On the Emergence of Biological Complexity.”
regeneration of nucleotides building blocks. A key feature in the emergence of these networks was likely the emergence of regulatory feedback loops. It is only at a later stage that DNA would have become an alternative support of the genetic information, offering not only an increased chemical stability of the backbone by substituting ribose by deoxyribose, but also an increased stability of the stored genetic information by substituting uracil by thymine: by contrast to RNA, substituting genomic uracil with genomic thymine at the level of DNA allowed repair of uracil resulting from the hydrolytic decay of cytosine. Therefore, behind the emergence of DNA, one can see a complex set of enzymatic reactions that eliminated and repaired the two most likely hydrolytic reactions taking place in RNA polymers and limiting RNA as a universal support of the genetic information in living systems. This led to cyclic kinetically stable networks with greater informational contents. Nevertheless, in our modern biological world, RNA remains the support of the genetic information of many viruses. Moreover, RNA is still extensively used in all living organisms for carrying catalytic, regulatory and structural functions in cells. For instance, more than 90 percent of the human DNA genome is transcribed into RNA. As such, eukaryotic (and bacterial) cells are presently being recognized as having genomes working as RNA rather than DNA.

Based on the above considerations, it is because of the ability of informational polymers to degrade or “die” that living systems may have emerged from chemistry.

From Informational Biopolymers to Cellular Life

Biopolymers are molecular information and as such, they have functional meanings. Interestingly, the regulation of the phenotypic expression of particular biopolymers (and consequently their meanings) becomes only possible through the controlled production and degradation of these biopolymers. Therefore, it is because of the controlled half-life (or death) of a biopolymer that the functional meaning of the operations performed at the level of a cell can change in order to maintain dynamic kinetics stability with respect of changes and cues in the environment. As such, it is because of the degradation (or death) of specific biomolecules that a more global functional meaning can be reached by a cell or a “living” dynamic kinetics state. Therefore, living systems (objects) are built up from processes that involve an upward movement of matter leading to the regulated production of molecules of increasing complexity (anabolism) and that is associated to a downward movement of matter leading to the controlled degradation, elimination or destruction of these complex molecules into more elementary building blocks (catabolism).

Another important aspect is the process of selection of biomolecular and cellular information carried by informational biopolymers. Through natural selection, some kind of biological information present within a space of possibilities dies to the benefit of another kind of biological information that is retained (Table 2). Interestingly, information selection is defined by a semiotic relation, in which the selected element becomes a sign of the input. While this is evidently true when the selected element is connected to the initial information, the selected element can also be a sign of things that are not obvious consequences of the input, especially when certain items are taken to be a sign of the needed element (able to satisfy the goal). For example, when considering a continuous physico-chemical process from inanimate to animate matter, the animate matter resulting from the natural selection process says something about the input information, the inanimate matter, and becomes a sign for the initial non-selected information. In the context of evolution, the process of information selection led to a limited variety of biopolymers on which all living systems are based (Table 2). Analysis of these biopolymers and their properties is

23. Cf. Auletta, Ellis, and Jaeger, “Top-Down Causation by Information Control: From a Philosophical Problem to a Scientific Research Programme.”
24. Ibid.
therefore indicative on possible chemical and biochemical constraints that led to their emergence. Furthermore, biochemical and biological investigations can offer possible explanations for the transitions from proto-cells to modern cells and cellular organisms.

**Table 2**

<table>
<thead>
<tr>
<th>discipline</th>
<th>source of variety, space of possibility</th>
<th>information flow</th>
<th>selection</th>
<th>reduced information</th>
</tr>
</thead>
<tbody>
<tr>
<td>prebiotic chemistry, organic chemistry</td>
<td>organic chemicals (C,H,O,N,S,P)</td>
<td>chemical selection</td>
<td>autonomous chemical metabolism, biopolymers, lipids</td>
<td></td>
</tr>
<tr>
<td>polymer chemistry, biochemistry</td>
<td>biopolymers, self-sustained chemical metabolism, lipids</td>
<td>biochemical selection</td>
<td>informational biopolymers, enzymes (DNA, RNA, proteins), vesicles</td>
<td></td>
</tr>
<tr>
<td>biochemistry, synthetic biology, cell biology</td>
<td>proto-cells</td>
<td>cellular selection</td>
<td>cells, organisms (Bacteria, Archaea, Eukaryotes)</td>
<td></td>
</tr>
<tr>
<td>biology</td>
<td>cells, organisms</td>
<td>natural selection</td>
<td>tree of life</td>
<td></td>
</tr>
<tr>
<td>(...)</td>
<td>(...)</td>
<td>(...)</td>
<td>(...)</td>
<td></td>
</tr>
<tr>
<td>anthropology, sociology, economics, politics, etc</td>
<td>man</td>
<td>cultural, social and political selection</td>
<td>human culture and societies</td>
<td></td>
</tr>
<tr>
<td>theology</td>
<td>human population</td>
<td>super-natural selection</td>
<td>“Christ-like” human, love</td>
<td></td>
</tr>
</tbody>
</table>

**Table 2: Information selection, life and death.** In the schematic on the top, large input information is a source of variety or a space of possibility that initiates an informational process that is concluded when selection is accomplished. During this process, while some informational elements are selected, others are eliminated. In any information exchange, the selection is at the end, not at the start. This selection delineates a semiotic relation in which the output says something about the input.

25. Adapted from Figure 6 in Ibid,