Life Facilitating Conditions

Assessing probable properties of extra-terrestrial life and the chemistry capable of developing it.

Bachelor’s Thesis

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*“We are like linguists on an isolated island where only one language is spoken. We can construct general theories of language, but we have only one example to examine. It is unlikely that our understanding of language will have the generality that a mature science of human linguistics requires.”*

 Carl Sagan, The Cosmic Connection, published 1973.

# Introduction

The question of extra-terrestrial life, its existence as well as its expected forms, has fascinated humans since antiquity. For nearly all this time, the machinery of life and the complex history that formed it remained utter mysteries. With the knowledge of the day predictions about potential alien life could be made, but were often fanciful in hindsight. The ever advancing biochemical and evolutionary sciences allow us to continually fine-tune our understanding of life, its functioning and its formative history. Our views on Alien life are in turn shaped and changed by this progress. We understand life in its basic form as a complex set of chemical processes which are quite well defined for life on our own planet. However, even as our understanding of the underlying processes of life increases, our perspectives continue to be shaped exclusively by life on our own world and its single-origin nature, with a Last Universal Common Ancestor that lived several billion years ago (National Research Council, 2007). The apparently monophyletic phylogeny of all currently known life may limit our view of potential biochemistries. Recognizing that the chemical nature of life follows general principles of reactivity, solubility and catalysis to ensure functionality, life is viewed more and more as a versatile self-organising system that is not bound to the specific structures and biochemistries found in modern earthly lifeforms (Bains, 2004). This has opened the way for the new combinational field of study called Astrobiology to research the astronomically diverse questions pertaining to life in the wider universe, researching and discussing possible structures, and the biochemistry it may make use of. All this effort aims to aid detection of life in the universe, which may differ from our kind so extensively that traditional thinking might not allow for detection. In this thesis I will focus on the chemical and physical qualities of matter that allow metabolisms to spontaneously arise and support Darwinian evolution. I will look at metabolisms and structures of basic life in order to explore potentials for ‘basic’ non-earth life. Thus, the scope of this thesis specifically excludes examining more ‘advanced’ forms of (intelligent) life often discussed elsewhere, a subject which does not concern basic functionalities of life such as metabolism, is too large to cover here and remains too speculative to cover in a biochemical perspective.

In this bachelor’s thesis I will discuss several of the basic biochemical and evolutionary concepts that lie at the foundation of life’s functioning. I will begin by discussing what exactly life *is*. To do this I will first discuss an often-used definition and compare it to new astrobiological definitions. I will discuss life as a natural process possibly occurring wherever conditions in the universe are appropriate for its development. To explore these, I will use a set of concepts such as thermodynamic gradients, solvent systems to metabolise in, and some basic biochemistry that lie at the basis of life. I will explore these concepts separately and more in-depth later in the thesis.

After discussing these general conditions, I will explore the problems inherent in us (carbon based, oxygen breathing life that uses water as its solvent) attempting to make predictions about all other possible forms of life in the universe without ever actually having seen any. These “n=1” related problems can cause “terracentric” (National Research Council, 2007) or chauvinistic (Sagan, 1974) perspectives which will be discussed.

Having discussed some aspects of the question of non-terran life in the universe, I will explore a more complete set of characteristics of basic life. These are currently recognised as the main properties or concepts that facilitate the formation, functioning and/or evolution of early life (Benner, Ricardo, & Carrigan, 2004). I will first discuss properties of life which seem relatively certain such as temperature ranges consistent with chemical (covalent) bonding, liquid phase facilitated metabolisms and the limited choices for biochemical backbone materials. Less predictable are the variety of polar and a-polar solvents available to life, the need for an isolating mechanism to facilitate Darwinian evolution and the probability of a repeating genetic charge such as RNA as the basis of life, or alternatively, metabolism-first worlds.

After I’ve discussed this set of options available to life, I will then look into carbon’s role as a bio-backbone in-depth, exploring its chemistry in particular.

I will then summarise my findings briefly and discuss the implications of the information presented here for the search of simple lifeforms in our own solar system. I will conclude with several recommendations for this search in hope of assisting in this modern-day age of exploration.

# Definition of Life

In order to discuss the potentialities of life in the universe, first we must decide what we mean by ‘life’ as precisely as possible. This is not as straightforward as it may seem, and many interpretations have been put forward over the years. Common ‘list’ definitions of life usually state that life is some object or material characterised by a capacity for metabolism, growth, reaction to stimuli, reproduction, and imperfect reproduction where the imperfection is itself heritable. While this definition seems appropriate to modern earth life, the earliest and extremely simple forms of life emerging on Hadean Earth some 4 billion years ago would hardly be expected to fulfil all these characteristics. To give an example: if we imagine some proto-lifeform as a single molecule capable of synthesising itself in a primordial soup, characteristics such as growth, reaction to stimuli and a well-defined metabolism are quite absent and yet such a molecule is currently hypothesised be the original basis for later, more complex cellular lifeforms (Neveu, Kim, & Benner, 2013). Other still more exotic lifeforms might not even feature reproduction or any of the other ‘core’ traits in any way recognisable to us. Many variables, both known and as yet unknown, in the constituency and development of early life makes a dependence on any of these specific characteristics untenable.

A change in perspective is warranted. Life on earth is found wherever there is both liquid water and an energy source (Benner et al., 2004), suggesting a huge variability and adaptability to earth life’s functional chemistry. Currently we have not observed any reasons why life is uniquely suited for development only on planet Earth (Darling, 2007). Conditions appropriate to life’s flourishing may arise throughout the universe, although we have yet to find these locations. If we view life as an emergent property of matter that arises spontaneously when some key conditions are satisfied, new astrobiological definitions of life arise that are aimed at defining life in the wider universe rather than focusing on the specific traits or biochemistry of life here on earth.

In 1970 Carl Sagan wrote the article on life for Encyclopaedia Britannica which included new kinds of definitions of life (Sagan, 1970). He included a Metabolic, Physiological, Biochemical, Genetic, and Thermodynamic definition. An Autopoietic definition (meaning self-enclosing, -repairing, -maintaining) was later added by his wife and son (Sagan, 1970). These were the first definitions to discuss life in a much broader sense, viewing it as a self-contained chemical system exploiting thermodynamic gradients rather than being defined by a specific biochemistry or set of abilities. These definitions have played an important role in the modern definitions that I will discuss below.

Following this work by Sagan, in the 1990’s an internal panel at NASA convened to define life provisionally. This was done in order to aid in the detection of extra-terrestrial life via remote sensing space probes then in development. They agreed on the following wording: ‘[life is] A self-sustaining chemical system capable of Darwinian evolution’ (Joyce et al., 1994). This has become an important and widely cited working definition discussed in the literature (Bains, 2004; Benner, 2010; Cleland & Chyba, 2002; Schulze-Makuch et al., 2015). Due to its central position in the field of astrobiology, I will dissect the wording of this one-sentence definition. Below I’ve listed its parts, and I will discuss its qualities, and later; its problems.

1. ‘Self-sustaining’ – Related to the Autopoietic definition, it was included because life is inherently selfish: its prime directive is to sustain itself preferentially to all other forms of matter, and it is this quality that forms an important characteristic of life. A biochemical system that needs external intervention to retain functionality does not sustain itself, and thus does not meet the definition of life.

2. ‘Chemical’ – the most complex assemblies and interactions of atoms have so far been observed to always be based on electrostatic interactions: chemistry. Chemical interaction appears to allow for a great versatility in both form and function of matter. Any life we encounter thus seems likely to be based on chemistry. More exotic forms are not deemed impossible, but are instead intentionally left outside this definition’s scope.

3. ‘System’ – This definition applies itself to a whole system of life rather than one entity that is alive. Chosen because an individual lifeform does not form a complete or self-sustaining system by itself but is embedded in one. An example: a bacterium constantly makes new copies of itself to persist in the environment, but the one original bacterium is not the complete system. It is important to differentiate ‘Life’ from the quality of ‘being alive’. A single human for example is itself ‘alive’ but does not exemplify ‘life’ as they are not capable of sustaining themselves indefinitely or undergoing Darwinian evolution. Mates, sex, and offspring are needed to complete that system.

4. ‘Capable of’ – The distinction between being capable of Darwinian evolution and actually observing it is important. Demonstrating Darwinian evolution in the field is not critical to recognising that something is alive, and on non-geological timescales this can be impossible to observe. Thus, the system merely must be capable of it by design. The system must be judged by this capability, which implies some form of genetic material must be present and mutable. However, active mutation/selection need not be observed. This is simply a practical wording for Life-detection missions (for which the panel formulated this definition) which are severely time- and resource constrained.

5. ‘Darwinian Evolution’ – Evolution is the cornerstone of this definition of life, as it is the means by which life adapts to its surroundings. Natural selection and gradual mutation are the primary motive forces behind Evolution, which itself is the basis for the immense diversity and complexity of life we observe. Again, this term implies the presence of some form of mutable genetic code handed down generation to generation where the mutations themselves are heritable and produce differing fitness leading to natural selection.

Although lifeforms that do not fit this description are easily imagined (non-chemical, non-Darwinian)(Davies et al., 2009; Schulze-Makuch et al., 2015), they are so far removed from life as we know it that the possibility of their existence remains highly speculative. Furthermore, these forms would seem so alien to us that even if we were to come across them, we would encounter difficulties in recognising them as being alive (Davies et al., 2009). As this is a working definition put forth by a NASA panel to aid in the identification of extra-terrestrial life, these lifeforms are considered to be outside the current scope of research. However, these exceptions do demonstrate that rather than pretending to be definitive or complete, this definition of life merely attempts to be useful in our current search for alien life: it is absolutely not a definition that encompasses all potentially possible forms of life. This also serves to show just how little we know about what life in the universe may be like, a problem that will be addressed.

Many other definitions and commentaries have built on the 1994 chemical-Darwinian definition (Bains, 2004; Benner, 2010; Cleland, 2012; Cleland & Chyba, 2002; Irwin, Méndez, Fairén, & Schulze-Makuch, 2014; Ruiz-Mizaro, Peretó, & Moreno, 2004; Schulze-Makuch & Irwin, 2004; Snook, Cleland, Wolfner, & Karr, 2000). Ruiz-Mizaro, Peretó, & Moreno proposed a universal definition of living beings in 2004 as autonomous systems capable of open-ended evolution. They posit that these systems must have a set of specific characteristics. Firstly, a semi-permeable active boundary (such as a cell membrane). Secondly, an energy transduction apparatus (such as the citric acid cycle). Finally, two or more types of ‘functionally interdependent macromolecular components’ (such as DNA, RNA and Enzymes) are needed. (Ruiz-Mizaro et al., 2004). In effect, it combines the NASA definition and the autopoietic definition discussed before, with some alterations. While a fully accurate definition remains elusive, other authors have pointed out that the very definition of life itself may as yet be impossible, as there might be very fundamental problems with trying to define something as intangible as life.

# Problems with definitions of life

In trying to define life, we are immediately confronted by our limited knowledge about life in the wider scope of the universe. Since all currently known life derives from a common ancestor, life as we know it can be considered as only a single sample. Consequently, in his book “Life as we do not know it’’ Peter Ward argues for classification of all earth life under a single taxon (Ward, 2007). Non-terran biologies, such as those not based on DNA or Carbon chemistry, would then constitute other clades life. This example serves to illustrate the lack of generality in our knowledge of life, a fact that was already commented on by Carl Sagan in the 1970’s when he introduced the term Carbon Chauvinism to describe our preconceived notion that extra-terrestrial life is likely to be Carbon based like we are (Sagan, 1974).

Philosophers of science Cleland and Chyba argue that all current definitions of life face problems because any definition is connected to a supporting theory that gives it its meaning (Cleland & Chyba, 2002). In the same way that ‘Water’ cannot be defined precisely without a supporting molecular theory (allowing for a definition of water as ‘H2O’), ‘life’ cannot be defined in precise terms without a supporting biological theory of life. As we lack this ‘theory of life’, the concept of life may be inherently ambiguous. A universal non-anthropocentric theory-definition of life might not be possible at all.

Steven Benner points out that it is the implicit theories of life that we collectively hold which determine what we look for in our search for extra-terrestrial life (Benner, 2010). If we appreciate chemical metabolisms as a key feature of life, as we do now, we will exclude all lifeforms that do not exhibit chemical metabolisms from our definition. Similarly, in using the 1994 NASA working definition of life, we will automatically exclude all lifeforms that are *not* self-sustaining chemical systems capable of Darwinian evolution from being considered life, and thus from being targeted for detection. The instruments we build to detect life on mars are designed to test the theories we hold, so any form of life that does not exhibit signs of life appreciated by the theory will not have its presence noticed by these instruments. Again, the conclusion here is that anthropocentrism is inherent and unavoidable in the current stage of researching and defining life in a broader scope. In accepting that our working definition is inherently flawed, it is important to note that changing it in favour of one that includes more exotic lifeforms is not feasible at this point. This is because we currently have no evidence whatsoever that they exist (Benner et al., 2004). We must simply acquire more and more knowledge about the nature of life in the universe in order to be able to expand our working definition, which might someday lead us to construct a comprehensive Theory of Life.

Our current understanding of what life is does not appear to reflect any absolute truths, but rather a single point in a timeline of increasing understanding of the complex phenomenon of life. What we look for when we look for life is only a reflection of what our human minds currently perceive as such. This may be a very constrained set indeed, but I will accept it. In this thesis I will limit myself to exploring several potentialities of life as a self-sustaining chemical system capable of Darwinian evolution.

# Life Facilitating Conditions

To explore where life might find footholds to develop, we must understand what conditions are required for the emergence and development of life. Although our perspectives on this matter have already been shown to be terracentric, several broad requirements can still be laid down with some confidence (Benner et al., 2004). Because it is the only known example of life emerging, understanding the early Earth can help us understand how life can come into being. Current research views the Origin of Life (OoL) as a slow rise in complexity of a chemical system capable of sustaining itself in the harsh environment of early Earth. This initially very simple geochemical process gradually acquired more and more characteristics of life, leading to the very first simple lifeforms (Hays et al., 2015). Note that defining the point at which a process becomes ‘living’ is difficult, if not impossible to do, but in general the advent of life can be described as a gradual emergence of complex structure from simple abiotic chemistry. Here, I will lay down and explain the Core Concepts that are currently viewed as the basis for the functioning of life and are essential for its emergence. I have identified four main Core Concepts following literature (National Research Council, 2007) and I will then use these concepts to study a universal basic property of life more in-depth.

## Core Concepts

### 1: Thermodynamic disequilibrium

Physical and chemical processes occurring in nature only happen when energy of some form is dissipated. Imagine a river, which flows and sculpts its banks because water gains momentum from flowing down. If water were not continually inserted into the river at the beginning of its course (a high-energy state) via rain or glacial melting, it would run dry. The lake or sea at the river’s mouth is characterised by a lack of flow: a state of lowest possible energy (if it weren’t for heating and evaporation induced by sunlight: another high-energy state causing flow). Without input of some form of higher energy, be it rain, sunlight, or heat from inside the earth, these processes would eventually dissipate all energy and reach their lowest possible energy state where everything is evened out and levelled, like a dead sea. Thus a trend emerges: a flow from a high to low energy state is characterised by a dynamic process (flowing river) that can create ‘complexity’ in an environment, such as an intricately patterned river delta, while a steady-state system such as a dead sea is more evened-out or featureless, and has a low ’complexity’. We call this ’dead’ state in which no net flow of energy occurs Thermodynamic Equilibrium, and we call this measure of ‘complexity’ Entropy, where the universe moves naturally to ‘chaos’, or high entropy (Clausius, 1867). An energy flow (from low to high entropy) can reduce local entropy (river valley) and thus increase complexity. Because a net flow occurs, this flow of energy is said to be at thermodynamic disequilibrium.

Thermodynamic disequilibria are important: on earth life exists wherever there is a thermodynamic disequilibrium, and indeed all earth-life requires this disequilibrium to function (Benner et al., 2004). The steepness of the thermodynamic gradient defines the amount of flow, and thus the amount of energy harvestable, in the same way that a ball accelerates faster down a steep slope than a shallow one. Two core characteristic of life are thus that firstly: it is a highly-organised low-entropy state of matter, and secondly: that it requires a flow of energy to organise this material (Morowitz, 1968). Because places with a large net flow of energy provide the means to locally supress entropy levels, life is more likely to be found in locations with a large energy flow.

### 2: Temperature

If life needed nothing but a large energy flow to spontaneously emerge, we would expect to find most life not on planets but on stars, as stars release huge amounts of energy to lower states. However, the extremely high temperatures associated with these environments precludes a rise in complexity. The kinetic energy of individual atoms in most stars is high enough to smash any chemical structures. This is why molecules only occur in the coolest of stars (Masseron, 2015). Besides a source of energy, life as we have defined it requires an environment that facilitates a rise in complexity when given a flow of energy. This complexity can arise from chemical bonding: a ‘chemical system’. The chemical bonding allows for the formation of large, complex, and stable structures. Depending on ambient temperatures, different modes of chemical bonding suit the needs of life. Carbon-Carbon bonds are excessively stable and would be virtually unbreakable at temperatures lower than those on earth. Thus, any lifeform living at low (compared to us) temperatures based on C-C covalent bonds would find it hard to have an active metabolism due to an inability to break or form bonds. Instead, such a lifeform might make use of hydrogen bonds which are much less stable. At 300 kelvin these hydrogen bonds are so unstable that any structure built from them quickly disintegrates. However, at lower temperatures hydrogen bonds or a different polarity-based bonding might provide a similar balance between stability and reactivity as that which carbon-carbon bonds provide for Life on the relatively hot earth. Life may depend on a variety of covalent and non-covalent bonding for proper functioning depending on many factors, but note that all these bonds are chemical.

If we search for places with temperatures consistent with chemical bonding, but which still retain a large thermodynamic flow, we are quickly drawn to the space immediately surrounding stars and the planets that orbit there. Here we find plenty of energy, a range of starting material and varying temperatures which combine to create a ‘hotspot’ for diversity of matter, as evidenced by the diversity in composition, size, shape, configuration and colour of the objects that we find in both our solar system and beyond.

### 3: Fluids

A diverse supply of material in non-equilibrium state, exposed to an external energy source can generate complex geochemistry (Wilson, Atreya, Kaiser, & Mahaffy, 2016). The rate of chemical interactions can be greatly facilitated by immersion in a mobile miscible medium. This allows more interaction between molecules than in a solid, due to Brownian motion and exposure to more material through mixing. Gasses provide such a medium and could thus facilitate a rise in complexity of chemical interactions. However, macromolecules suspended in a gas will in general be heavier and tend to precipitate out of the medium. Complex chemistry based on macromolecules will thus be limited to fluids, as they offer an ideal mixture of chemical reaction potential while simultaneously suspending both substrates and products, depending on the solvent properties of the fluid. In his 2004 paper, Bains argues convincingly for chemical life as being dependent on its molecular components being suspended in a fluid medium of comparable density to that of the macromolecules (Bains, 2004). A fluid medium provides the mix of properties that allow for complex and consistent macromolecular interactions. In their 2002 paper, Whitesides and Grzybowski list a liquid in which components are free to mix and interact as a prerequisite for self-assembly of chemical components under laboratory conditions. This demonstrates the importance that fluid mediums have in the study of self-organising systems, of which life is perhaps the most profound example (Whitesides & Grzybowski, 2002). These fluid mediums can be either a liquid or a supercritical fluid. In stellar systems, liquids and supercritical fluids only occur in a select few places. Liquids occur where atmospheric or geologic pressure prevents evaporation and heat prevents freezing but both pressure and temperature remain lower than the substance’s critical point. Supercritical fluids occur at locations where temperatures and pressures exceed this critical point, often in the interior of large gaseous planets. Thus, locations featuring fluid mediums have up until now exclusively been moons and planets. Noting that liquid water is by far the most prominent and accessible fluid medium in the inner solar system beyond the surface of Earth, it is easy to see why NASA has identified water as one of the main targets in planetary exploration. Most literature currently holds the view that life is likely to be based universally on liquid water (Bains, 2004; Pace, 2001), however the opposite view, as far as I’ve found, seems to be gaining ground (Benner, 2010, 2017; Schulze-Makuch et al., 2015). Although not discussed at length in this short work, the topic of fluids and solvents as used by life is a highly complex and interesting one entirely worthy of a review on its own, and I regret not having the space to do it here.

### 4: Darwinian evolution

As essential as it is to my thesis, evolution remains difficult to define clearly. Here, I define Darwinian evolution as the long-term result of natural selection and genetic drift. Evolution can then be summed up simply as a core set of tenets:

* Individuals differ in minor traits, with the variation being heritable
* More individuals are produced as offspring than can survive to produce the next generation
* Those individuals that possess beneficial traits are more likely to reproduce and pass these traits on
* Reproductive isolation allows for separate species to arise

Darwinian Evolution is essential for the formation of complex living systems from simpler abiotic chemistry. As such, Darwinian evolution takes a central place in all current Origins of Life research. It explains how a primitive macromolecular system is capable of change, adaptation to local circumstances and long-term conservation of genetic information. Darwinian evolution is dependent on imperfect replication and can only take place if specific traits that have an effect on individual fitness are both heritable and mutable. Thus, the crux of Darwinism lies in genetics. Mutability is present in most non-living systems; however these mutations are themselves not normally heritable. A good example is an artificially grown Sodium Chlorate crystal which is crushed and seeded to form new crystals (Benner, 2017). The crystal can be said to reproduce and show varying levels of fitness, depending for example on its shape, size or internal lattice. Should a fault develop in a growing crystal, for instance through an impurity, the crystal can be said to have mutated: it carries new, extra information. This mutation however is not passed on to any subsequent ‘daughter’ crystals that are grown from it: they will grow using the original crystal lattice. The mutation is therefore not heritable: any mechanism transferring the information in the mutation from parent to daughter crystal is absent. A molecular system that *can* support heritability of mutations is thus special and forms the basis of the genetic system of life, allowing it to undergo Darwinian evolution. All known life uses one of two nucleic acid biopolymers, DNA or RNA, as its genetic system, but other genetic biopolymers are hypothesised to exist (Benner, 2017). The polyelectrolyte theory of the gene states that a repeating charge in a genetic biopolymer is a probable trait of many alternative genetic systems that operate in water (Benner, 2004) and provides an excellent framework with which to detect potential alien lifeforms.

OoL research heavily studies the early genetics of life and the structures that performed this essential service. Much remains unknown about the epoch of life before DNA became established as the near-universal standard, before the central dogma of biology even existed. Currently studied are a variety of hypotheses that seek to elucidate the functioning of life’s early genetics. The RNA World is an ageing but still highly relevant hypothetical stage in the development of life (Neveu et al., 2013). RNA is however astonishingly difficult to form abiotically, so many other ideas have been put forward to add the ‘missing link’ between abiotic chemistry and RNA (Engelhart & Hud, 2010). ‘Metabolism first’ hypotheses challenge the traditional idea of genetics-first, seeing the earliest lifeforms as self-sustaining autocatalytic chemical networks. This challenges traditional ideas of genetics as the replicator concept, at the core of most definitions of life, is absent (Vasas, Szathmáry, & Santos, 2010). TNA (Eschenmoser, 2004), and possible identities of even more primitive non-nucleic biopolymers that can exhibit genetic behaviours are also being researched (Engelhart & Hud, 2010). It is this earliest genetic system or network which can be considered somewhat of a holy grail in OoL research, even as both its identity and functioning remain utter mysteries to date.

## Carbon as a universal catalyst for life

To support the core concepts I have outlined, life needs a material capable of exhibiting a great chemical diversity and adaptability. A type of molecule that can receive and store energy, is stable over a large temperature range, is dissolvable and chemically compatible with naturally abundant liquids, and can support some form of information-preserving genetic system. This is a tall order, and so far we have only one example: Earth. All known Earth life is carbon-based (Benner, 2010). The geologic and biologic processes that have led to complex life emerging on our planet have done so based on a polymeric carbon chemistry. Carbon based life can be found anywhere on this planet where there exists both a thermodynamic disequilibrium and liquid water (Benner, 2017). Polymeric Carbon chemistry seems to afford life a massive versatility in form and function. To understand the chemical nature of extra-terrestrial life, it is imperative to understand our own first. Earth life serves as a convenient starting point, demonstrating the potency of Carbon as the central biochemical atom. Making use of a polymeric chemistry to form functional macromolecules might be a common theme in chemical life beyond earth. Here, I will discuss some reasons why earth-life uses Carbon as its backbone material and the complex chemistry it makes use of. Some potential biochemistry-supporting alternatives will be discussed afterwards.

Following literature, I have structured potential reasons for Carbon as life’s basis along 3 classes: Functional, Historical and Vestigial (see Benner et al., 2004). A functional explanation for life’s usage of Carbon could be that it is the only element that can produce a chemistry complex enough to support life. Carbon is then simply selected as the ‘best’ option. A historical explanation could state that Carbon life is one of many options available, but once life happened to emerge based on Carbon, it had no means of switching. Elements other than Carbon could potentially be better, but historical development ‘locks’ life to Carbon: it is *not* (evolutionarily) selected for. A vestigial explanation holds that selection for Carbon *did* take place at some point in the past but no longer represents an optimal solution: other options could be as viable, or even more viable. An example here could be that the widespread availability of volatile carbon compounds on the early earth made it the preferable material for life to get stated with, even though other non-carbon-based chemistries might now better be suited for complex life on earth. As with historical explanations we would again observe a sub-optimal ‘carbon lock’.

Starting with a functional explanation, Carbon’s ample versatility as a central atom in large molecules is demonstrated by the universal occurrence of complex organic chemistry beyond Earth. Many families of organic molecules have been observed in space (Kwok, 2011) and of all chemical compounds that can be spectroscopically observed in the universe, a large number are complex organic molecules (Ehrenfreund, Spaans, & Holm, 2011). Complex Carbon-containing molecules were delivered to the early Earth by the Late Heavy Bombardment which is also hypothesised to have brought in large quantities of water (Valsecchi et al., 2010). A specific category of Carbon meteorites called Carbonaceous Chondrites was probably responsible for catalysing the formation of prebiotic chemicals on the early Earth (Rotelli et al., 2016). These meteorites contain complex carbon molecules that can catalyse the reactions of simple organic molecules into many of the essential precursor molecules of life (see Rotelli et al. for more in-depth information). Carbonaceous Chondrites were formed in water-rich parts of the proto-solar system some 4-5 billion years ago and contain large quantities of both water (up to 16%) and organic molecules (Le Guillou & Brearley, 2014). As these chondrites entered the earth’s atmosphere and crashed into the surface, their internal organic ‘payloads’ were exposed to large amounts of energy in the form of heat, radiation and shockwaves which produced a huge variety of compounds. Combined with the presence of liquid water, this had the potential of kick-starting life as it seeded the early earth with an abundance of biochemical precursors and catalytically active compounds (Cooper et al., 2001). The geochemistry that was kick-started this way was likely complex, but details remain speculative. However, what is certain is that there is a huge diversity that can be ascribed to Carbon’s chemical interactions with its surroundings in the early solar system (Chyba & Sagan, 1992).

All this is despite the fact that elements such as Oxygen and Silicon are hundreds of times more abundant in the earth’s crust than Carbon, which is even less abundant than Titanium (Haxel, Hedrick, & Orris, 2002). As far as is currently known, the superior abundance of these elements did not lead to a corresponding chemical complexity on the early earth. The natural ability to form polymers that can incorporate other elements as side groups in various configurations appears to have been unique to Carbon. Carbon’s chemical flexibility as a central atom in large molecules was thus probably (and certainly remains) unrivalled by any of the more abundant elements. These reasons combine to make carbon perhaps the most intriguing element on the early earth and from a historical perspective made it by far the most likely to host the complex chemistry that would later start calling itself life (Schulze-Makuch & Irwin, 2006).

I’ve assessed that Carbon played a central and pivotal role in the early earth’s surface chemistry and was at least likely to play a role in abiogenesis, but this could be considered circular reasoning: both the reader and the author of this text are direct descendants of the products of this process. It could be chauvinistic for a Carbon-based entity to assume that Carbon is the most likely basis for its emergence. A critical examination seems in order. What is it that makes Carbon exhibit such an interesting chemistry? And having identified the reasons for this, are there alternatives? As already noted, complex organic chemistry is not a local fluke: beyond earth and the solar system, organic molecules have been detected in space, specifically in cold dense molecular clouds, protoplanetary nebulae, huge star forming regions and the Local bubble (that last one as I was writing this!) (Farhang, van Loon, Khosroshahi, Javadi, & Bailey, 2019; Ruaud et al., 2015; Vijh, Witt, & Gordon, 2004). The largest specific molecules that have been identified contain up to 4 aromatic rings (such as Pyrene) and are referred to as polycyclic aromatic hydrocarbons or PAHs. PAHs and other polymeric carbon compounds appear to be common in the local universe. PAHs are a good example of self-assembly: Pyrene for example is a large, complex 26-atom molecule, but it arises spontaneously through naturally occurring conditions. This self-assembling behaviour into large and complex polymers seems symptomatic of Carbon’s chemical behaviour throughout the universe, not just here on earth. Carbon seems to occupy a special place in the chemistry of the wider universe, facilitating complexity in many circumstances.

The chemical properties that lead to this facilitation of complexity are themselves surprisingly basic. I will discuss the most important ones here. The first is Catenation: the ability to form a polymer consisting of only Carbon atoms. Elements other than carbon can form long polymers naturally, but these are usually highly unstable or lacking in other respects. These Carbon Polymers show a high diversity due in part to Carbon’s other important characteristic: Valency. Carbon has 4 Valence electrons (4 electrons in its outer shell) which means it can form 4 covalent bonds. Being able to form this many bonds means a polymer of Carbon can have rings and side-chains. A nearly unlimited amount of branching chains and a long list of functional groups can be attached, which then allow for a huge chemical diversity (as life amply demonstrates). Similarly, Sulphur also forms stable polymers in nature: it naturally occurs as the polymer cyclo-S8, or cyclo-octa-Sulphur, a ring of 8 Sulphur atoms. However, unlike a ring of Carbon atoms, this ring of Sulphur atoms can have no other attaching groups because Sulphur atoms can only form 2 bonds (due to it having 6 valence electrons). As evidenced by its valency, Sulphur is far less likely to host complex macromolecules (by itself) despite exhibiting catenation.

In the context of biochemistry, Carbon having the potential to bond itself and 4 other atoms is only useful if those bonds have the (1) correct level of stability, (2) can be formed with a wide range of other elements and (3) are stable over a wide range of temperatures. The covalent bonds between carbon and other elements need to be strong enough to form in the first place, but weak enough to remain reactive and thus be susceptible to modification. Carbon satisfies all these demands through a combination of atomic characteristics. Due to its small size, Carbon fits into large, complex molecules. Carbon’s chemical analogues Silicon and Germanium have atomic radii of 111 and 125 picometers respectively, whereas carbon’s is only 70 picometers. This is larger than, but similar to, the radii of the other elements from the first period such as Oxygen, Nitrogen and Fluorine (50-70 pm). If carbon were any bigger, it would spatially dominate the structure of molecules consisting of a carbon backbone with functional groups attached and could reduce the space available for other biochemicals to interact with these groups.

Carbon’s average binding energies to common elements are listed below and give a good indication of why carbon forms stable bonds with such a wide range of elements. All bond energies listed are medium to high, associated with short to medium (r = 100-190 pm) bond lengths. As can be seen in the table, Carbon forms single, double, and triple bonds that are very stable with some of the most abundant elements. Carbon is one of the few elements capable of forming double or triple bonds with a wide range of elements. This allows for delocalisation of electrons through pi-orbitals in the resulting molecules, which stabilises the molecule and is a primary requirement for storing energy. Delocalised electrons allow capture of energy and lie at the basis of processes such as photosynthesis (Pace, 2001). Single bonds of excellent stability are formed with an even wider range of elements, as can be seen in the lower part of the table.

|  |  |  |
| --- | --- | --- |
| **Bond** | ***D*(kJ/mol)** | **r(pm)** |
| C-C | 346 | 154 |
| C=C | 602 | 134 |
| C≡C | 835 | 120 |
| C-O | 358 | 143 |
| C=O | 799 | 120 |
| C≡O | 1072 | 113 |
| C-N | 305 | 147 |
| C=N | 615 | 129 |
| C≡N | 887 | 116 |
| C-S | 272 | 182 |
| C=S | 573 | 160 |
| -------------- | -------------- | -------------- |
| C-H | 411 | 109 |
| C-P | 264 | 184 |
| C-Cl | 327 | 177 |
| C-F | 485 | 135 |
| C-Si | 318 | 185 |

Table 1: Common bond energies and their corresponding bond lengths. Single bonds are highlighted in red. Source: Huheey, Keiter, Keiter, & Medhi, 2006

Carbon manages to combine all these fascinating chemical properties with a high cosmic abundance. Despite being relatively rare on earth as the 15th most abundant element, it is the 4th most common element in the Milky Way at approximately 0.5% of all baryonic mass (Croswell, 1995). If the emergence of life is indeed a stochastic process as we now understand it, Carbon, as the element combining by far the most complex and diverse chemistry with universal abundance would indeed be very likely to give rise to the first lifeforms. This statement can be considered true irrespective of our own constitution, as both cosmic abundance and chemical qualities exist independently of us: they are universal qualities. Due to its unique set of characteristics, and in agreement with current literature, I believe Carbon to be a catalyst for life not just on earth, but universe-wide, wherever the conditions allow for this potential to be realised.

# Discussion

Any kind of Carbon life appears to be constrained to locales where temperatures do not exceed 250 degrees Celsius (Schulze-Makuch & Irwin, 2004). Although earth-life is known for finding ‘tricks’ to cope with high temperatures (Musto et al., 2005), 250 °C appears to be the limit (Benner, 2004). The limit appears universal because this is the point at which complex Carbon molecules become extremely reactive. Their internal kinetic energies become so large that bonding energies can be spontaneously overcome, rendering them inherently unstable. An opposite problem occurs when complex carbon chemistry is exposed to very low temperatures. At -180 °C, the ambient temperature on Saturn’s moon Titan, the bonding energies of carbon are so large that currently known biochemical reactions can only proceed on near geologic timescales. As there is a huge abundance of planets in our milky way where temperature ranges (and nearly all other planetary parameters) are thought to vary widely, are there other backbone materials that can take Carbon’s place?

Polymeric chemistry is highly complex and mostly performed under standard Earth conditions (297 K, 1 Atmosphere of pressure, negligible ionising radiation). This is an environment in which Carbon is clearly at home and its resultant chemistry complex. Much remains unknown about chemistry at highly elevated or reduced temperatures, at supercritical or extremely low pressures, in high radiation environments or in solvents other than water (and the few others we use industrially) (Lide, 1995). From an astrobiological perspective Chemistry’s current state can be likened to Earth’s oceans in that small parts of it are known very well but what lies beyond remains uncharted and enigmatic. To say that all complex chemistry has been explored as extensively as the Carbon organic family would be more than optimistic. It would be false. Thus, large, unexplored chemical ‘families’, forming complex polymers based on elements other than carbon might exist elsewhere but remain undetected (Schulze-Makuch & Irwin, 2006). Examples include polymers based on Boron, nitrogen, silicon, phosphorus, and/or sulfur (Schulze-Makuch & Irwin, 2004). Reliance on one particular element to provide a backbone might not be a necessary requirement for life: sequential chains of Boron-Nitrogen and Silicon-Oxygen are potential alternatives (Schulze-Makuch & Irwin, 2004). Boron Nitride for example can from structures analogous to Carbons’ graphite and even diamond (both cubic lattice and Lonsdaleite lattice), has water-like interactions with the common liquid ammonia and shows a potentially highly diverse chemistry at higher melting- and boiling temperatures than its carbon-based alkene and aromatic hydrocarbon analogues. Silicone is another polymer, consisting of alternating Silicon and Oxygen atoms. It is very stable as a backbone for large complex molecules and has a wide range of current applications. Such polymers are produced synthetically and are already in use, and might support their own alien biochemistries (Bains, 2004). However, they do not appear widespread in the universe and have not been detected so far. This need not be a problem as only an insignificant percentage of planets in the milky way has been found so far, and characterisation of these planets beyond orbital parameters, radius and mass has not occurred. I believe it important to leave open the possibility that on planets sporting very dissimilar conditions to Earth large sets of chemistries based on unfamiliar types of polymers could remain undiscovered, and that these chemistries could exhibit under these conditions the chemistry capable of serving as an alternative backbone for life.

# Conclusions

In this bachelor’s thesis I have tried to give a short overview of the current state of research on some topics within the field of astrobiology. I have used a definition of life that describes it as a chemical system capable of Darwinian evolution to look at the concepts and chemistries that allow matter to exhibit this highly complex behaviour. Although a complete definition of life remains elusive, the hypothetical biochemistry of non-terran life is now sufficiently understood to allow for at least somewhat accurate life detection experiments. I have sought to answer my initial question “why Carbon?’’, and in reviewing the literature, I have found a large degree of support for my assessment that Carbon is a universal catalyst of life. Carbon combines a set of structural and chemical properties that result in a unique and complex polymeric chemistry. The family of Carbon organics is unrivalled in its sheer size and the diversity of molecular functionality. This appears to be true both on and beyond the surface of the earth. Carbon Chemistry is complex on a universal scale, and thus there appears to be at least some evidence that the universe supports our natural Carbon bias. It is important to note that other, as yet undiscovered, polymeric chemistries might exist that are equally (or more) capable of being the chemical foundation upon which life may arise and evolve. Much remains unknown, waiting to be discovered. In the coming years large amounts of exoplanets will be discovered using new instruments that will, for the first time, be able to characterise exoplanet atmospheres. We are likely to learn a great deal from atmospheric compositional data which will aid significantly in the quest for discovering the first extra-terrestrial life. These are exciting times indeed.

Bachelor’s Thesis

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