Astrobiology for a General Reader

Astrobiology for a General Reader:

A Questions and Answers Approach

By

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V. M. K. dedicates this book to the memory of her dear brother,
Vladimir Kolb.

B. C. C. dedicates this book to the memory of his beloved wife, Johanna.

TABLE OF CONTENTS

PREFACE

VMK:

Much has been written about astrobiology, for all readership levels, from popular books to highly advanced treatises on one or more topics in the field. This book is geared for the general reader who has some science background or a strong interest in science. A unique aspect of this book is that it utilizes a Q&A (Question and Answer) approach to aid the thought process and hold the interest of the reader.

The knowledge base of general readers is typically quite broad. I felt that the content of this book should not be oversimplified, but I also avoided highly detailed or overly speculative analyses. It remains for each reader to decide if this approach is successful.

The questions in this book are inspired by those that have been asked of me from beginning students and from the general audience at public presentations and various science conferences. In formulating the answers, I am drawing upon my astrobiology research, experience in teaching, and the current developments of pedagogical approaches suitable for science fields.

The strings of the related questions and answers are organized into chapters of various topics. Chapters are not equal in length, which reflects the topic of the chapter. Some topics require a more technical approach and longer explanations, while some others allow for a less extensive coverage of the main ideas.

There may be some slight overlap in the material, to enable readers to understand a chapter in which they are interested, and who may have skipped a previous chapter(s) that provided a foundation. In such cases, I have given minimum background without extensive repetition.

I have utilized many resources, such as various astrobiology references at different levels. Also, I have relied on some advanced material from two recent books for which I was the Editor and also contributed chapters:

“Astrobiology: An Evolutionary Approach” (2015), and the “Handbook of Astrobiology” (2019), as well as many different research journal articles to assure the answers are up to date.

Carefully chosen literature resources are given in the section “Further Readings.” This section starts with the general information on how to find references, followed by an abbreviated version of selected references for each chapter, arranged sequentially for each Question/Answer number. Following the abbreviated versions are the full References, arranged alphabetically. They include books, book chapters, and journal and magazine articles. These literature references acknowledge the authors of the ideas and accomplishments this book utilizes and enable the reader to further explore topics of their own interest. Selected web resources, including Wikipedia, are also given. At the end is an Index, keyed to the Answers to the Questions.

After I had finished writing about one half of this book, I was fortunate to recruit a co-author, Dr. Benton C. Clark III (Ben Clark), to contribute mostly to the chapters which deal with space missions. Ben has participated in Viking and numerous other missions and is now involved in the Mars 2020 rover mission, among others. His background in biophysics and first-hand knowledge of such missions made him an ideal co-author of this book. He also complements my own expertise, which is in the chemical aspects of astrobiology.

BCC:

The invitation by VMK to join this book adventure as a co-author reflects the development of astrobiology as a science. At the time VMK was receiving her astrobiology training in San Diego (1992-1994), the post-Viking missions were only in the planning or preparatory stages. Now, however, the astrobiologist’s dream to search for life elsewhere in our Solar System has come to fruition via significant and extremely productive new missions to Mars and other objects in our Solar System.

Thus, any astrobiology book for a general reader needs significant coverage of these endeavors. The cooperation with VMK on this book and my part to cover the space missions is truly a marriage made in heaven, since most of my life’s work was and is dedicated to such missions.

ACKNOWLEDGMENTS

The authors are thankful to Prof. Richard H. Judge for reading the manuscript and making useful comments. Vladimir Kolb provided numerous wonderful tips and suggestions for the Q&A approach.

CHAPTER 1

WHAT IS ASTROBIOLOGY?

Q 1.1 What is astrobiology?
A 1.1 Astrobiology is a field of science which studies the origin, evolution, distribution, and future of life in the universe.

Q 1.2 What are the key questions astrobiology seeks to answer?
A 1.2 Astrobiology seeks to answer questions about the origin and evolution of life on Earth, the possibility of extraterrestrial life, and the future of life on Earth and in the universe in general.

Q 1.3 What are the specific goals of astrobiology?
A 1.3 Specific goals include understanding the origin of life on Earth; study of the early life on Earth and how it interacted and evolved with the changing environment; study of the evolution of the early life on Earth to more advanced life; investigation of the environmental limits of life; exploration of the habitable environments on Earth and in our Solar System and beyond; the search for extraterrestrial life; and recognition of the signatures of life ("biosignatures") on early Earth and on other worlds. These goals are delineated also in the NASA's astrobiology roadmap.

Q 1.4 Is NASA's astrobiology roadmap the only one?
A 1.4 No. For example, a similar roadmap has been developed for astrobiology research in Europe. It just focuses more on European research and space missions.

Q 1.5 How old is the science of astrobiology?
A 1.5 "Astrobiology" became a designated scientific field in 1995, thus rather recently (it was founded by Wes Huntress at NASA). Astrobiology evolved from its predecessor, "Exobiology" (named by Joshua Lederberg in 1960), which studied the origin of life and possibility of extraterrestrial life.

Q 1.6 What are some examples of recent advances in astrobiology?
A 1.6 The examples are summarized below.

New developments in genetics and studies towards synthetic life help us understand the basic requirements for life on Earth. Improved identification of the fossils of early microbes on Earth help us nail down the beginning of life on early Earth. The search for potential biosignatures on Mars informs us about the possibility of extraterrestrial (ET) life. Advances in planetary geology, especially those resulting from space missions, point out the planetary bodies in our Solar System which may be habitable for life, based on the presence of water, energy sources, and the availability of organic materials (chemical compounds that contain carbon). Improved analysis of organic materials from space, notably in meteorites and micrometeorites, helps us understand chemistry in space. Worlds, like Mars, are promising because they provide water and all the key elements necessary for life as we know it (CHNOPS = carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur). Discovery of numerous exoplanets (those that are outside our Solar System), some of which may be habitable, extends our search for ET life to more distant worlds.

Q 1.7 But surely people explored the idea of extraterrestrial (ET) life much earlier than 1960s?
A 1.7 Yes, this is correct. Although astrobiology is a new science, it has a long history of ideas which originated in the antiquity. Thus, the debate about the possibility of ET life was carried out by the ancient Greeks and has continued up to and including modern times. However, only recently have science and technology developments enabled search for ET life via space missions, and for the ET intelligent life (ETI) through radio-astronomy to search for the signals emanating from the extraterrestrial intelligent civilizations.

Q 1.8 These scientific efforts have been so far unsuccessful in confirming either the ET life or ETI. Is this correct?
A 1.8 Yes, this is correct. The space missions, notably the Viking missions on Mars in 1976, searched for microbial life on Mars, but did not confirm its existence. The same is the case for the later missions. Likewise, the analysis of a meteorite ALH 84001 which originated from Mars and was found in Antarctica revealed interesting morphology reminiscent of the fossils of bacterial life, but the results were not convincing enough to indicate remnants of life on Mars. The search for ETI via SETI (Search for Extraterrestrial Intelligence) did not yield positive results so far, although efforts continue.

Q 1.9 Astrobiology is referred to as a "field of study" or "science", rather than a discipline. Isn't astrobiology a discipline, like chemistry or physics?
A 1.9 The question if astrobiology should be treated as a separate scientific discipline is still open to discussion, but the prevailing view is that astrobiology is a field of study rather than a discipline. The reason is that astrobiology is multidisciplinary in its contents and interdisciplinary in its execution. Although not a discipline itself, astrobiology draws upon other disciplines, subdisciplines, and specialized areas of research such as physics, chemistry, biochemistry, biology, molecular biology, microbiology, ecology, evolutionary science, geology, planetary science, astronomy, cosmology, atmospheric science, oceanography, evolutionary science, and paleontology. Furthermore, astrobiology also seeks insights from the history of science and philosophy.

Q 1.10 Is being multidisciplinary/interdisciplinary a disadvantage?
A 1.10 No, it is not a disadvantage. It is a necessity. Multidisciplinary and interdisciplinary approaches are needed to investigate complex problems which are beyond the reach of any single discipline.

Q 1.11 It seems that astrobiology covers lots of ground. What is its all-encompassing goal?
A 1.11 According to NASA, an all-encompassing goal of astrobiology is to understand cosmic evolution. Such evolution includes the following sequence: Big Bang; formation of galaxies, stars, planets, and elements including the biogenic ones; chemical evolution which led to life; pre-Cambrian biology; complex life; intelligent life; cultural evolution; civilization; science and technology; and the search for life in the universe.

Q 1.12 Who are astrobiologists, and where do they work?
A 1.12 Astrobiologists are typically trained in one of the scientific disciplines, and later they learn other disciplines which equip them to work on complex astrobiology problems. Astrobiology training is offered by selected universities, at the advanced undergraduate, graduate, or postgraduate levels. Astrobiologists often work for NASA, ESA (European Space Agency), or other space agencies, or at the universities which have astrobiology programs. They also work in industries which are involved in space missions.

Q 1.13 If I would want to become an astrobiologist, how do I do it?
A 1.13 First, one needs training in one of the scientific disciplines, such as chemistry, physics, biology, or geology, as some examples. Another

example is planetary science, which would typically require some geology background. Another example is study of the chemical composition of meteorites, which will require an analytical chemistry background. If one is interested in survival of microbes in space, one would need a microbiology background. Virtually every astrobiology problem requires a solid scientific background. Then one needs additional training on the specific astrobiology topics. This is just general guidance.

Much can be learned from specific examples, such as those described in a book "Talking About Life" by Chris Imprey, in which he presents interviews with 37 leading astrobiologists, who share how they got into the astrobiology field. For example, we find that Iris Fry was originally trained in chemistry, biochemistry, philosophy, and history of science, to become a leading philosopher on the subject of the origin and emergence of life. Steven Benner was first trained in biophysics, biochemistry, and chemistry, before he became one of the leading experts in so-called prebiotic chemistry (chemistry before life existed on Earth, and from which life emerged). Guy Consolmagno is the curator of the large meteorite collection in the Vatican. He is a Jesuit religious brother who has a strong interest in the possibility of life elsewhere in the Universe and is known for his popular astronomy books, among other contributions. Each one of the 37 interviews by Imprey are highly inspiring and will resonate with readers of various backgrounds.

CHAPTER 2

UNDERSTANDING THE CONCEPT OF LIFE WITHIN THE ASTROBIOLOGY FRAMEWORK: WHAT IS LIFE?

Q 2.1 Don't we all know what life is?
A 2.1 Not really. At some levels we do, at some other levels we do not. For example, life which is visible to the naked eye, such as plants and animals, is easily recognizable by its familiar features, such as shape, behavior, and reaction to stimulus. Microscopic and submicroscopic life forms and structures are by now familiar to most people and can be described by images of cells and their components, for example. However, life can be also described by molecular means, namely by the chemical composition of biological monomeric (monomer = single unit) building blocks, such as amino acids, sugars, and nucleic acids, and also their respective polymers (many units hooked together), such as proteins, polysaccharides, and polynucleic acids (such as RNA or DNA). Further, life can be characterized by its inner workings, such as metabolism, information and energy flow, growth, and reproduction. Life requires a high level of organization to ensure that all of the contributing parts are working together properly. Such organizational features reflect life's complexity. But all these different descriptions of characteristics of life are still not adequate for astrobiology, which requires its own definition of life.

Q *2.2 What is wrong with the already existing descriptions of life?*
A 2.2 They are Earth-centric, namely they are focused on life on Earth as we know it. While this is understandable, since this is the only life we know, it is not sufficient for astrobiology, which is concerned with the search for extraterrestrial life. While such life may or may not be the same as ours, scientists believe that the ET life should share at least some of its essential characteristics with Earthly life. Thus, astrobiologists wish to extract from the description of life on Earth its essential features, devoid as much as possible of Earth-centric specifics, and hopefully define universal life. The latter would then be appropriate also for recognizing ET life if we find it.

Q 2.3 What are the essential characteristics of the earthly life?
A 2.3 Examples include metabolism (the set of chemical processes that occur within a living organism to maintain life), presence of a boundary (such as a membrane), growth, and reproduction. Life must also have capacity for mutations (changes of the structure of the genes) which will enable its evolution via natural selection. This means the following: mutations generate modified forms of life, some of which are better able to adapt to environmental changes. Better-adapted life is naturally selected over life which cannot adapt as well. Also, life differs from inorganic objects and dead matter. These essential properties are likely shared with ET life.

Q 2.4 This seems relatively straightforward. Is there a problem?
A 2.4 Yes. One problem is the existence of various exceptions and borderline cases. One example is reproduction as the requirement for life. Some life forms, such as viruses, are not able to independently reproduce, but use the cellular machinery of their host for this purpose. This poses the question if viruses are alive. However, most recent findings show viral cooperation which in some cases verges on altruism. Such sophisticated behavior is typically attributed to life forms. Some organisms, such as mules and worker bees cannot reproduce, but are obviously alive. Some other organisms cannot reproduce on their own since they require a partner, as in the case of sexual reproduction. Even for organisms which normally can reproduce, they may be in part of a life cycle in which reproduction is not possible, such as for the babies or quite old people. Still, they are alive.

Another problem is that when essential life properties are considered, they are usually chosen such as to describe life via its lowest common denominator. Only properties which are in common to all life, from the lowest organisms, such as bacteria, to the most developed organisms, such as intelligent humans, are taken into account. Thus, if intelligence of the type humans have is included as a critical property of life, then bacteria and plants would not be alive (along with many other organisms). On the other hand, if we decide to use the entire set of characteristics of an organism as a basis of defining life, we run into a problem, since characteristics for one life form may not be applicable to another.

For example, if one describes the properties of a flower in exquisite detail, many such details are not in common with a bacterium or a bird. Thus, using phenotype (the set of observable characteristics of an organism, such as morphology or physical structure) for the purpose of defining life does not appear to be practical. This difficulty is further complicated by the influence that environment exerts on phenotype. Namely, phenotypes are determined not only by genotype (the genetic constitution of an organism, which provides the hereditary information) but also by the environmental factors. Due to such problems, although numerous attempts have been made to define life, no definition is universally accepted.

Q 2.5 Is it perhaps easier to define life by the specific chemical and physical properties of its machinery at the molecular level?
A 2.5 Not really. The problem is that specific details about the machinery of life on Earth, which uses either DNA or RNA as its genetic material, may not be the same as for the putative ET life, although they are probably related at a general level.

Q 2.6 Can you clarify this with an example?
A 2.6 Yes. As one example, Steven Benner posed a question if life could be based on chemicals which are similar but not the same (so-called "analogs") as those that life on Earth utilizes. To answer this question, he synthetized in the laboratory various analogs of important chemical compounds which are components of nucleic acids (such as DNA). The latter are critical for transfer of information and replication (the process of making a copy) at the molecular level. He has found that some laboratory-made analogs can function as the naturally occurring ones, albeit less efficiently in some cases. He hypothesized that the ET life could be based on such analogs.

Q 2.7 Could the ET life be based on silicon instead on carbon?
A 2.7 Not likely! (One should not take as truth the famous Star Trek episode "The Devil in the Dark", about the Hortas silicon-based life forms from the caves of planet Janus VI). Chemical properties and reactivities of individual atoms put a constraint upon what any type of life may or may not be based. Because of such constraints, life based on silicon is considered to not be feasible, because of unfavorable and limited reactivity of silicon as compared to carbon, which is the basis of our life on Earth. Similarly, an old argument that everything reacts with everything else, and thus we get an unlimited and unconstrained number of chemicals just by mixing them, is not correct. Some chemicals do react with each other, but many others do not due to their lack of reactivity or unfavorable thermodynamic factors. Thus, while we can only hypothesize about the characteristics of the ET life, we do know for sure that some possibilities for such a life are precluded, simply based on the laws of chemistry. This would be the case for the silicon-based life.

Q 2.8 In light of all these difficulties, how do astrobiologists define life?
A 2.8 Examples of definitions as proposed by different authors are shown below, selected from about 100 definitions of life compiled and fully referenced by Radu Popa in 2004 and expanded in 2015. In general, these definitions were constructed by first observing and analyzing properties of life on Earth, and then choosing a minimum number of critical features of life. Specifics were removed as much as possible. This makes such definitions suitable for the ET life, for which we do not know the specifics, but expect their general features to be like those on Earth. Since the definitions of life are stripped of the specifics, they may sound quite theoretical and abstract. Further, these definitions would be applicable to the life of e.g. a butterfly, but we cannot reconstruct the butterfly from the definitions alone. Our comments are shown in the parentheses after the definitions.

a) Arrhenius 2002: Life is a system capable of 1. Self-organization. 2. Self-replication; 3. Evolution through mutation; 4. Metabolism and 5. Concentrative encapsulation.
b) Baltscheffsky 1997: Life may be described as a "flow of energy, matter and information." (A very abstract definition).
c) Joyce 1994: NASA's working definition of life: Life is a self-sustained chemical system capable of undergoing Darwinian evolution. (This definition extends Darwinian evolution from organisms to chemical systems).
d) Oparin 1961: Any system capable of replication and mutation is alive.
e) Trifonov 2011: Life is self-reproduction with variations. (Similar to d).
f) Brack 2002: Life is a chemical system capable of transferring its molecular information independently (self-reproduction) and also capable of making some accidental errors to allow the system to evolve (evolution).
g) Horowitz 2002: Life is synonymous with the possession of genetic properties, i.e. the capacities for self-replication and mutation.
h) Kolb and Liesch 2008: Life is a chemical phenomenon which occurs in space and time as a succession of life forms which when combined have a potential to metabolize, reproduce, interact with the environment, including other life forms, and are subject to natural selection.
i) Kolb 2010: We propose that the life of an organism is the sum of its life forms over a period of time. We set the integral of time from the birth of the organism to its death (this would include babies to old age in case of humans).
j) Lauterbur 2002: It's alive if it can die. (The problem with this definition is that defining death is as difficult as defining life).

k) Horowitz 1986: Life is synonymous with the possession of genetic properties. Any system with the capacity to mutate freely and to reproduce its mutations must almost inevitably evolve in directions that will ensure its preservation. Given sufficient time, the system will acquire the complexity, variety and purposefulness that we recognize as alive.

l) Vilee and co-authors 1989: The characteristics that distinguish most living things from nonliving things include a precise kind of organization, a variety of chemical reactions we term metabolism, the ability to maintain an appropriate internal environment even when the external environment changes (a process referred to as homeostasis), movement, responsiveness, growth, reproduction and adaptation to environmental change.

m) Nealson 2002: Any definition of life that is useful must be measurable. We must define life in terms that can be turned into measurables, and then turn these into a strategy that can be used to search for life. So, what are these? a. structures; b. chemistry; c. replication with fidelity and d. evolution. (There is a problem in measuring evolution, as in the NASA's definition above, definition c).

Q 2.9 How are these definitions useful when we search for ET life?
A 2.9 They delineate certain essential characteristics of life on Earth which should apply also to the ET life in principle, if not in all the details.

Q 2.10 What is meant by "in principle, if not in all the details"?
A 2.10 "In principle" means that all life, including the ET life, should be able to metabolize, reproduce, extract energy from the environment, adapt to both physical and biological environments, mutate and evolve according to natural selection, and to be sequestered in some sort of a compartment. "Not in all the details" means that the chemistry does not need to be the same for the life on Earth and the ET life. For example, chemically speaking, one would need some sort of genetic system, like a DNA, which would keep and transmit the information, plus some sort of enzymatic system which would catalyze the reactions, and some sort of cell membrane. However, chemistries may differ, as long as the function stays the same. Thus, a genetic system may vary chemically, but it must be able to keep and transmit the information.

Q 2.11 This still appears quite abstract. Is there a practical guidance on how to recognize and detect the ET life?
A 2.11 Yes. Practical guidelines have been developed for the space missions in our Solar System, which seek to detect the ET life or remnants thereof. Recently, comprehensive guidelines have been formulated, which focus on detection of life by various criteria which are specific and mostly Earth-centric and are described as a "ladder of life detection". This ladder summarizes measurements seeking to find life, including searching for biosignatures. The latter are substances, phenomena, and patterns whose origin specifically requires a biological agent. Examples include complex organic matter characteristic for life; polymers with repeating charge, which could be indicative of genetic material; co-location of reductant and oxidant, which could be related to metabolism; organic materials not found in abiotic milieu; bacterial microfossils; cell-like structures in multiple stages of development, indicating reproduction; etc. Further, guidelines for detecting life on exoplanets (planets outside our Solar System) have also been developed based on what we know about life on Earth, and what can be detected via remote sensing. Examples include biosignatures that are gaseous, such as oxygen, ozone, and methane, and surface biosignatures, such as pigments that indicate photosynthesis.

In conclusion, there is a difference between *definitions* of life, which are by necessity abstract to be applicable also to the ET life, and guidelines for *detecting* the ET life, which are practical and include many specifics. There is a need for both approaches. The practical, specific guidelines are useful for detecting life that is expected to be quite similar to ours, while the abstract definitions prepare us to look for life that may be substantially different than ours.

CHAPTER 3

PHILOSOPHICALLY SPEAKING: CAN SOMETHING BE BOTH ALIVE AND NOT-ALIVE?

Q 3.1 Isn't "not-alive" the same as dead?
A 3.1 Not necessarily. "Dead" customarily refers to something which was alive but is not alive anymore. "Not-alive" makes the distinction from dead. In the context of this chapter, it is something which has some but not all the features of a living system.

Q 3.2 What is an example of this?
A 3.2 One such example is the viruses. Viruses have some, but not all the essential properties of life, according to some schools of thought. Virologist Luis Villarreal classifies viruses as belonging to a "twilight zone of life". For example, viruses have genes and evolve via natural selection, which are critical features of life, but they lack some essential characteristics of life, notably that they do not have metabolism and cannot reproduce on their own. However, viruses in their non-reproductive form (virions), thus not-alive according to the reproduction criterion, can penetrate cells of their hosts. They then become capable of reproduction with the *assistance* of their hosts, and thus they act as alive. This is only if we accept the assisted reproduction as a *bona fide* mode of reproduction, since there are precedents in other species which use it and are recognized as alive (e.g. species that use sexual reproduction and thus cannot reproduce on their own but need "assistance" of the sex partner). Thus, viruses could be classified as alive, with respect to the crucial reproduction requirement. Therefore, one could state that viruses are both alive and not-alive.

Q 3.3 The statement that viruses are both alive and not-alive is contradictory and defies common logic. Isn't is so?
A 3.3 Yes. Indeed, according to the traditional logic, which comes from Aristotle, it is impossible to *be* and *not to be* at the same time, or for both *p* and *not-p* to be true, namely that both the statement and its negations are

true. However, Aristotelian logic has been challenged with a view that there are some contradictions that are true. This is the subject of a branch of logic named dialetheism (Greek: *aletheia* = truth; *di-aletheia* = a two-way truth), proposed by Graham Priest. Classification of viruses as both alive and not-alive is possible within the dialetheism.

Q 3.4 What are some important features of dialetheism?
A 3.4 Dialetheism examines the limits such as those of the mind, thought, concepts, expressions, descriptions, and knowing. Transcendence beyond these limits may create contradictions. One of the strengths of dialetheism is that it can account for transitional phenomena in general, and the contradictions they create. A simple example that Priest gives is a case of a person leaving the room, thus transitioning between the inside and outside of the room. At some point of this process, the person will be both inside and outside the room. While the statement "a person is both inside and outside the room" appears contradictory based on Aristotelian logic, it is clearly true for this transition process, which dialetheism can treat.

Q 3.5 What are some examples of applications of dialetheism to astrobiology, other than the case of viruses?
A 3.5 There are two additional significant examples: that of the emergence of life on Earth from abiotic (not-alive) matter, and the concept of extraterrestrial life.

The example of the emergence of life on Earth: Astrobiologists believe that life on Earth has emerged from the not-alive chemical systems, which are termed abiotic (not-biotic; biotic = living) or prebiotic (before living). However, details of how the transition between abiotic and biotic occurred are not clear but include a "transition zone" in which complex abiotic systems gradually acquired some, but not all properties of life. This would be to some extent analogous to the case of viruses, which exhibit some, but not all properties of life. Just like viruses can be considered both not-alive and alive, the chemical systems in the transition zone can be looked at as both abiotic and biotic.

Dialethism also provides a fruitful approach to extraterrestrial life. We do not know if extraterrestrial life exists or not, since we have not found it yet. Thus, we do not know its properties, if it exists. In contrast, we know volumes about terrestrial life and its properties. When we envision extraterrestrial life, we cross the conceptual boundary of terrestrial life and transcend beyond it to the putative extraterrestrial life. Priest examined the limits of concepts and knowing, among other limits, and has found that these limits are boundaries which cannot be crossed, and yet we do cross them.

By conceptualizing extraterrestrial life, we cross one such boundary. If we are not aware of this problem, we may believe that our conceptualization of extraterrestrials as modeled by the earthly life is correct. Problems with the conception of alien life have been recognized by means other than dialetheism, but the latter helps us to see clearly the intrinsic problems in our thinking about this issue.

Q 3.6 What is the most important thing that we have learned from applications of dialetheism to astrobiology?
A 3.6 The most important thing is the improvement in our own way of thinking. Astrobiologists often get bogged down in an endless debate whether (1) viruses are alive or not, or (2) what is the nature of the transition from abiotic to biotic, or (3) what is the nature of extraterrestrial life. Based on dialetheism, we simply acknowledge that viruses can be considered as both alive and not alive, that the transition zone has properties of both alive and not-alive, and that in conceptualizing the extraterrestrial life we are going beyond our limits of knowledge. Dialetheism takes the mystery out of our thinking processes.

CHAPTER 4

WHAT IS SYNTHETIC LIFE?

Q 4.1 What is synthetic life? How is it important to astrobiology?
A 4.1 Synthetic life, just as the term implies, is life made artificially in the laboratory, by unnatural means. There are various levels of accomplishing this, as discussed below. The importance for astrobiology is that if we are successful in making life synthetically, then we could understand the origin of life more fully.

Q 4.2 If we make life synthetically, does it have to be like our familiar life, or could it be different?
A 4.2 In principle, it could be either. If the same, it will tell us more about our own life. If different, it would point out to variations of life, some of which may be relevant to the extraterrestrial life.

Q 4.3 Is the idea of making synthetic life new?
A 4.3 No. The ideas on how to make synthetic life span the period from antiquity to the present. The history of these ideas and various attempts to create synthetic life are critically reviewed by Phillip Ball. Selected material is presented here for illustration.

The early ideas reflected a widespread belief in the spontaneous generation of life from decaying matter, such as Aristotle's recipe on how to make vermin (insects and mice), as described in his book "On the Generation of Animals", and Virgil's method for making synthetic bees from a carcass of a dead cow which was left on a bed of thyme and cinnamon sticks. It was later shown by Louis Pasteur that life is not generated by these methods, but is instead a product of life forms already present in the decaying matter, or which infiltrated it from outside (e.g., maggots).

More ideas came about, notably by the early chemists who believed that life is the result of a particular chemical composition, and that generating life is just an exercise in getting the right mixture of ingredients. Later ideas focused on the organization of matter, since it does not suffice to get just the right mixture of ingredients; they need to be configured such to interact with each other in specific ways.

The modern era of attempts to make synthetic life are based on the discovery of the double helical structure of DNA in 1953, and the mechanism by which DNA encodes genetic information and passes it from one generation to the next. The information is encoded in a DNA molecule as a sequence of molecular building blocks (nucleotides) along the helix. The mechanism by which the information is copied during replication involves the complementary match of the basic components of nucleotides and their interaction via hydrogen bonding. This gave chemists a long awaited "instructions for life".

Q 4.4 How is the knowledge on instructions for life translated to the recipe to make synthetic life?
A 4.4 The process was gradual. It involved development of new laboratory tools and methods for modifying "the instructions for life", namely DNA. First, scientists discovered how to use natural enzymes to edit (insert, delete, or replace) one or more of a DNA's nucleotides. This discovery was the foundation of the field of genetic engineering, which started in the 1970s, and the ability to create the *recombinant* DNA. These new developments also fed directly into the flourishing field of biotechnology, with many practical applications, e.g. medical, agricultural, industrial, and environmental. The focus here is only on what is most directly relevant to the recipe for life, namely genetic engineering and recombinant DNA. These terms are briefly defined, and then the recipe for life is addressed.

Genetic engineering is a method for manipulation of an organism's genes coded in its DNA. Genes may be inserted or removed. This method can transfer the genes within and across species, thus producing new organisms.

Recombinant DNA is DNA that has been formed artificially by bringing together genetic material from various sources, including different species. This creates nucleotide sequences that are not found in the original DNA. Furthermore, DNA sequences that do not exist in nature may be created by chemical synthesis, and then incorporated into the DNA molecule.
However, the recipe for life for the new organisms produced by these techniques may not be a *legitimate* recipe.

Q 4.5 What is meant by a legitimate recipe? What is the problem? Are these new species alive or not? Or, is there another problem with them?
A 4.5 The problem, in general, is not with the new species, many of which satisfy the requirements for life. The problem lies in the process (procedures and ingredients) for producing such a life.

Q 4.6 Is the problem that the processes involved are not natural?
A 4.6 This is only a part of the problem. The antipathy and distrust towards artificial/unnatural life started in antiquity and persists to the present time. Metaphors for synthetic life that are used in the media coverage are often religiously, culturally, and emotionally charged. Scientists are said to be "playing God", or are "creators of life", or are producing "Frankenstein" organisms, which are dangerous and might escape to the environment.

Another part of the problem is deciding which processes, with their associated procedures and ingredients that are involved in the recipe for synthetic life are considered legitimate. If one starts with an alive system, and genetically engineers it into a different alive system, does it mean that life has been formed? The answer to this question is not straightforward. One possible answer could be yes since a new life has been created. Another possible answer could be that the original life has been only modified. Finally, the answer could be no, since life has not been created starting from the abiotic ingredients, such as prebiotic chemicals, which are not alive. In the latter scenario, the recipe would include various prebiotic chemicals, reactions that lead to the formation of biochemicals, and the processes which lead to the proper organization of life from these biochemicals. This is beyond reach at the present time. One of the grand challenges of synthetic life, "cooking from scratch" (a bottom-up approach), still remains.

Q 4.7 Is this then the end of the story of formulation of the recipe for life?
A 4.7 No. There is a way to break down the process for formulating the recipe, by conquering the individual steps that could eventually lead to the solution.

Q 4.8 Is there a good example for this?
A 4.8 Yes! Work by J. Craig Venter and his research group is an excellent example. These researchers aimed to reduce life to its bare essentials, which would constitute a milestone in the process of designing life from scratch. In 2016, they designed and created a synthetic cell which contained only 473 genes, which is the smallest genome of any known, independent organism. These researchers utilized techniques by which a whole genome can be built, starting from chemically synthesized nucleotides, and then transplanted it into a receptive cellular environment, resulting in a brand-new, viable, but artificial species.

Q 4.9 What is the current trend in this area?
A 4.9 It is difficult to decide since the field is rapidly evolving. Still, the goal of synthesizing the human genome from scratch seems to be the current

focus of many research groups. Such a goal, which is otherwise worthwhile, is less related to the origins of life, and thus astrobiology, than the above-described project by Venter and coworkers, in which a minimal genome cell was created.

Q 4.10 Is research related to producing synthetic life ethical? Is it regulated?
A 4.10 Such research has significant ethical issues, ranging from creation of "Frankencells" to the danger of synthetic life to natural life, from rights of humans to create synthetic life to the "rights" of such synthetic life. Following publication of Venter's work, the ethics of synthetic biology in general have been examined by The Presidential Commission for the Study of Bioethical Issues, and guidelines about such types of research have been published. It was concluded that new regulations, oversight bodies, or a moratorium on pursuing this type of research were not needed at that time. However, it was recommended that society must be vigilant about potential harms of such research and be prepared to revise the policies as needed. The moral significance of the creation of artificial life, such as concerns about playing God, and potentially undermining the special status granted to life, is also examined, with a conclusion that the creation of artificial life is not morally insignificant, but that more work needs to be done to support the view of its significance. Thus, at this time, both ethical and moral issues associated with the creation of artificial life are still in the examination phase.

CHAPTER 5

ORIGIN OF LIFE ON EARTH: WHAT IS CHEMICAL EVOLUTION, PREBIOTIC CHEMISTRY, AND THE RNA WORLD?

Q 5.1 What is the current understanding of the origin of life on Earth?
A 5.1 The major hypothesis about the origin of life on Earth, which is accepted by astrobiologists, is the so-called Oparin-Haldane hypothesis. It was proposed independently by Alexander I. Oparin in 1924 and J. B. S. Haldane in 1929. This hypothesis states that the origin of life on Earth can be understood based only on the laws of chemistry and physics. Importantly, life arose on the early Earth by a series of chemical reactions and physical processes over a *long* period of time, and under the specific conditions in the early Earth's distant past. Thus, life is a product of the chemical evolution of matter.

Q 5.2 Does this hypothesis have any experimental support?
A 5.2 Yes. Since the original proposal of the Oparin-Haldane hypothesis, experiments were performed which supported it, such as the synthesis of amino acids and other key biological precursor molecules under conditions that simulated those on the early Earth. The most famous such experiment was Stanley Miller's, in 1953. Miller, in association with Harold Urey, built a glass apparatus which consisted of a series of connected flasks and tubing, designed such as to simulate the primitive Earth's environment. Thus, one flask was filled with water, simulating the early ocean. The water could be heated for evaporation to add water vapor. Another flask contained the water vapor and the gases of methane, hydrogen, and ammonia to simulate the early Earth's atmosphere, which was believed at that time to be chemically reducing**.** In such an atmosphere oxygen is absent. The energy source was an electric spark, generated by a Tesla coil which was sparking in the "atmosphere" flask to simulate lightning as the natural energy source. Various amino acids were formed, such as glycine and alanine. Miller's experiment demonstrated that organic compounds which are central to life