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A Fresh Start on the Problem of the Origin of Life[1]

1.1 Introduction

In 2014 a remarkable, counterintuitive discovery was made by chemical engineers that oil droplets in water, if cooled slowly, departed from their expected spherical shape (like oil drops in shaken Italian salad dressing), instead forming flat polygons with sharp corners [1.85] [1.157] [1.345] (Chapter 3, Figures 2, 3)[2]. On coming across this work during my eclectic reading as a theoretical biologist, I grew very excited, contacted the authors, and proposed that they had found a missing link in attempts to explain the origin of life, a paper on which some of them joined me [1.126]. It led to a broader book on the origin of life edited by Stoyan Smoukov [1.347]. This book, the one in your hands or computer, includes and updates our joint efforts, adds some new ideas, and guesstimates the distribution of polygonal phenotypes in Archaea at 41% of species (Chapter 15). Some of the other chapters have coauthors, who are acknowledged in those chapters[3]. Revised chapters published elsewhere are indicated by [Chapter n] in their titles in the reference lists.

This book aims to present and justify new approaches to the origin of life. It counters the common notion that a consensus has already been reached, and reviews many of the ideas of others, emphasizing those that have been "forgotten" because they don't fit that consensus (Chapter 11).

Life had long been divided into three Domains, the Eukaryotes, like us, whose cells contain a nucleus, and two distinct kinds of prokaryotes, which do not: the familiar Bacteria and the relatively recently discovered Archaea [1.405]. Archaea are prokaryotes that most people don't pay attention to, because unlike many of the Bacteria, they apparently don't attack us as pathogens [1.49], although plenty reside on our skin [1.290] and in our cavities ([1.73] [1.337] producing methane flatuance. They are in the salted, fermented fish we eat [1.67], and in table salt and salt deposits [1.143] [1.280] [1.319] [1.326] and many other places (Chapter 12). Some of the Archaea are flat polygons during at least part of their

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[1] Thanks to Frank Trixler for helpful comments.

[2] Vesicles collapsing in artificial pores also flatten [1.307], which may be useful for experimentally investigating the crowded "cytoplasm" that results. Chapter citations are to this book.

[3] Salient papers by me, sometimes with coauthors, are reprinted here as separate chapters, with the source cited in the chapter title. Significant deletions to minimize repetitions, or additions, usually updates, are indicated by []. As they are in the order written, and some previously published, I have avoided the temptation to revise them so as to rewrite history. Thus. there are some progression of ideas. Typos are fixed. Figures and Tables are renumbered and cross-referenced instead of duplicated. Note that each chapter has its own reference list, so some references are duplicated. Citations are easily searchable in the electronic version. This saves rewriting, shows our development of ideas, and makes much of this book already peer reviewed. Pronouns are not changed.

Richard Gordon. Origin of Life via Archaea: Shaped Droplets to Archaea First, with a Compendium of Archaea Micrographs, (1–32) © 2024 Scrivener Publishing LLC

life cycle. If this connection, from nonliving shaped droplets to living Archaea, is real, we have literally seen how the abiotic world might have produced life, at least, start and finish. There may have been a fourth domain: it is often surmised that LUCA (Last Universal Common Ancestor) gave rise to both Archaea and Bacteria, but apparently is no longer with us. LUCA was a speculated intermediate at best. Here I propose that LUCA was the first Archaea. Thus, this book supports the Archaea First hypothesis (Chapter 9), insofar as one can reconstruct what happened in history.

Possible advantages of flattening of a protocell/protobiont (optimistically "the goal to understand the process appears well within reach" [1.399]) include:

1. crowded prebiotic "cytoplasm", possibly accelerating reactions and keeping extended polymers in a network rather than crumpling [1.39], which may produce jamming states [1.93], and alter polymer conformations [1.387];
2. catalysis "within or on the surface of the membranes" [1.383];
3. greater surface to volume ratio, allowing more exchange with the environment;
4. if the exterior surface is hydrophobic, the vesicles may float at the air/water interface, as diatoms do [1.137];
5. potential for three internal surface environments for lipid molecules and/or embedded hydrophobic peptides: polygon planes, edges and corners;
6. if diurnal shape changes occur between spherical vesicle (the presumed shape [1.399] and flat shapes, this may allow PCR-like (Polymerization Chain Reacations) cycles and reshuffling of vesicle components [1.313];
7. 2D flows within the protocell or along its edges [1.153] [1.196];
8. stabilization of shape when peptides are incorporated into the protocell membrane (Chapter 7);
9. more surface area if adhered to a mineral that provides a local gradient or adhered organic molecules, such as amino acids, peptides or nucleotides [1.129] [1.246] [1.248] [1.411] [1.412] [1.414] [1.415];
10. "hedge betting" needed to best survive meteorite bombardment [1.381] (cf. [1.160] [1.277] [1.278] [1.374]), which may explain why, as we shall see (Chapter 19), in many Archaea species flat, polygonal phenotypes are rare.

A possible disadvantage of the flat, polygonal shape is behavior or adhesion to surfaces in flowing water (cf. [1.146] [1.274]). In most species, polygonal phenotypes are rare (Chapter 19), but no studies comparing them to "normal" rod or coccoid phenotypes have been undertaken.

Let me elaborate on possible roles of a crowded cytoplasm, which has been suggested as essential to the origin of life [1.352]. Small solutes are severely restricted in mobility [1.273], possibly accounting for the "memory" discussed in Chapter 11. Insofar as there is any catalytic activity present in the prebiotic cytoplasm, nascent metabolism can transfer intermediates from one catalyst to another without the need for diffusion through the aqueous phase [1.273], presaging enzyme complexes [1.223] [1.390] and microcompartmentation [1.54] [1.89] [1.202] [1.203] [1.386]. There may be an optimum balance even prebiotically between catalysis and diffusion [1.135] [1.378]. Fluctuations in crowding, in our case diurnal, may be of importance [1.343], solve the problem of the origin of the crowded cytoplasm [1.4] and cause spatial rearrangement of the protocell contents that possibly lead to phase separations [1.364] and osmotic effects [1.53]. The compaction of DNA at later prebiotic stages may be caused by crowding [1.77]. Diffusion within the membrane may also be hampered as the membrane becomes crowded with peptides and PAHs (polyaromatic hydrocarbons) [1.147] (cf. Chapter 8). The action of any catalysts present may depend on water fluctuations [1.249]. The creation of a crowded synthetic protocell has been a problem [1.9], especially given the common presumption that prebiotic vesicles were spherical [1.211] [1.213] [1.355] (Figure 4.16, Chapter 4). For a review of molecular crowding from the physical chemistry point of view of the origin of life, see [1.354]. Cf. [1.30] [1.352] [1.353].

If we consider the volume of one flat Archaea cell (Figure 4.3C) of mean thickness $t = 0.204$ μm and cross section length of 7.36 μm, using Equation 4.3 of Chapter 4, assuming $r = 7.36/2 = 3.68$μm, the volume of the cell swollen to a sphere would be:

$$V_s = (4/3)\pi\left(\sqrt{2}r\right)^3$$

while the flat volume is:

$$V_f = t\pi r^2$$

which yields:

$$V_s/V_f = (4/3)(r/t)\left(\sqrt{2}\right)^3 = 3.77r/t$$

which comes to a diurnal fluctuation in volume of 68×. Whether or not this occurs in extant Archaea, which do swell to spheres under various circumstances (both spherical and polygonal phenotypes, as *Halobacterium marismortui* (Chapter 14), salt inclusions [1.99]), and if so, how they cope with it, appears to be unexplored (cf. [1.7] [1.26] [1.247] [1.394]). Community may matter [1.210].

An alternative to the notion of a crowded cytoplasm is recognition of the geographic heterogeneity of the early Earth, providing "prebiotic chemical refugia" where "... certain chemical elements were accumulated in higher proportion than expected, facilitating the production of basic building blocks for biomolecules" [1.291] (Figure 1.1).

There has been a huge speculative and experimental effort to understand the origin of life, over 17,000 papers via a Web of Science search "origin of life" OR abiogenesis OR prebiotic (All Fields), including over 2000 reviews[4]. The same search in Google Books has over 4 million hits, and Google Scholar has 374,000 hits. Just one publisher, World Scientific Press, lists 78,870 books or book chapters on origin of life. Even just a search for "Archaea" yields over 22,000 chapters in [1.395], over 26,000 publications in Web of Science and over 339,000 results in Google Scholar, compared to 763,000 and 4.2 million, respectively, for Bacteria. I have to trust that my sampling of the literature is reasonable. Any bias is probably for more recent literature, which arrives almost daily. The rapid growth in the literature is apparent

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[4] Unfortunately, "prebiotic" is also often used to mean "probiotic", so these reference numbers may be overestimates.

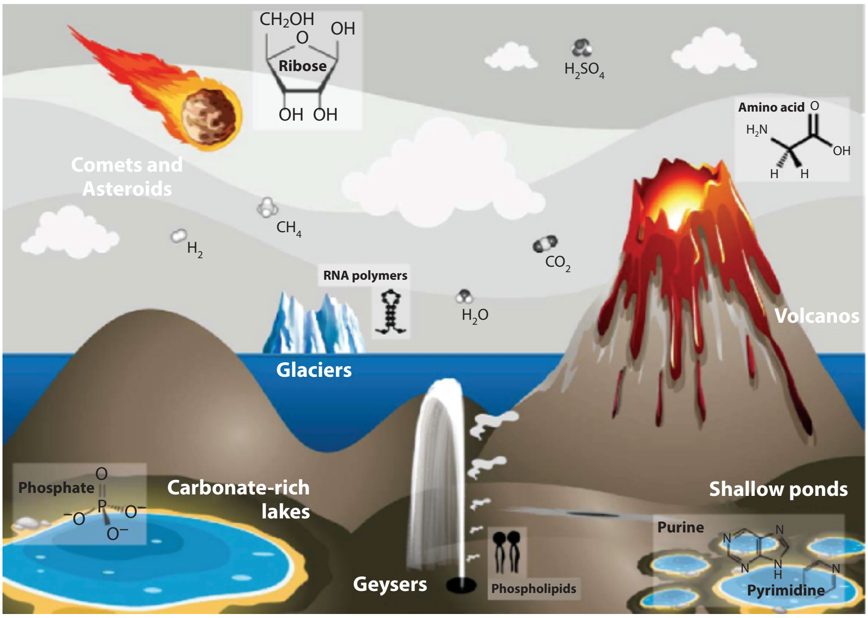

Figure 1.1 "<Figure 1> Examples of prebiotic chemical refugia. Each of the most important compounds necessary to build biological molecules agglomerates at specific chemical environments in prebiotic Earth, such as: ribose, coming from comets and found in their craters [1.189] [1.238]; glyceraldehyde, coming from comets, became ribose under alkaline conditions by the formose reaction [1.148]; nucleobases could also come from meteorites [1.43] or they could be formed in solutions of water, ice, and urea under ultraviolet irradiation of acetylene in anoxia [1.243], but also in wet–dry cycles around shallow ponds [1.27]. Phosphates could be produced in carbonate-rich lakes [1.368]. Amino acids could be produced simply precipitating from atmosphere [1.251], in volcanos [1.162] or in meteorites [1.44]. Phospholipids are supposed to be formed in hydrothermal pools like geysers [1.66] [1.204], volcanos [1.271] or craters or iron meteorites [1.276]. Glaciers may have allowed the production of nucleotides, amino acids [1.195], and the replication of small RNA polymers [1.289]" [1.291] SN. We have added endoreic lakes [1.127] (Chapter 7).

from a slightly earlier account [1.40]. If I cite a lot more than is normal, it's because there is a lot to cite. However, for those who wish to probe further I give the number of references in Web of Science as WOS followed by their accession number at the time of writing, for all Archaea species (Chapter 14). Note ISI = WOS = Web of Science, PMID = PubMed. Some topics have enough ideas to warrant separate books[5]. "This is a very young field with just a few hundred scientists worldwide doing most of the work" [1.81] perhaps underestimates the efforts of over a century. While many disciplines are involved, there has been a call to add people studying artificial life [1.321] (cf. [1.123]). The field is old enough to attract historians and philosophers [1.222] who recommend that "scholars in the humanities and social sciences" join in. It certainly has its share of "visible scientists" [1.119] [1.120], most of whom are probably represented here, some of whom suggest the problem of the origin of life is nearly solved [1.362] [1.363].

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[5] I thank the librarians of Wayne State University and the University of Manitoba for their vast efforts at making papers and chapters available.

There are so many excellent ideas that they would fill volumes. Thus, except for my possible contributions, I can cite but a relatively few of those I came across, producing in Chapter 11 what might be considered just a guide into the literature, without playing favorites amongst the richness of ideas. So, while I may sometimes provide "too much information" (pc: our kids), keep in mind that I nevertheless cover but a small fraction of the literature, and am disturbed by the focus of many on one hypothesis and one place for the origin of life. The possibilities are vast. This is not the time to come to a consensus (cf. [1.177]). Instead of burdening the reader with another "Just So" [1.173] story of the origin of life, I regard my considerations as an introduction to the vast literature on the origin of life, even though only a relatively small sampling can be mentioned. Undoubtedly some great ideas have been missed, but I leave that task to an artificial intelligence with huge patience and greater lifetime. I have occasionally followed up some papers using the forward search feature of Web of Science, but this often led to an overwhelming 50 to 100 additional papers. The reader with a particular interest is advised to do the same. Each paper listed in the Web of Science points to its references and later papers that cite it. Thus the reader can easily dig further into past references up until the present.

With many authors not mentioning the polygonal nature of occasional individual Archaea that I see in their micrographs, there may be some bias in my sampling. In the spirit of William Bateson we must "treasure our exceptions" [1.22] [1.58]. But for balance I do present the many micrographed Archaea that show no signs of polygonal phenotypes in Chapter 14, in some cases because they were not looked for.

While Archaea are estimated to form 20-40% of the prokaryotes on Earth [1.112] [1.397], they are only represented by the above figures in 7.5% to 25% of the literature. We may have a lot to learn about our possible Archaea ancestors. They are components of rarely seen ecosystems (Figure 1.2). Archaea are in and on us, and in most habitats (Chapter 12). Many are "extremophiles" [1.317].

1.2 Physics vs Chemistry as Explanations for the Origin of Life

> "...progress in molecular biology has steadily undefined the chemical basis for life" [1.101].

Many people assume that the origin of life is a problem in chemistry. Statements such as "The process by which chemistry can give rise to biology remains one of the biggest mysteries in contemporary science" [1.5] may miss the mark by presuming that the nature of the solution is already known (cf. [1.180]). This viewpoint has nearly a two-century history, going back to the first synthesis of an "organic" compound, urea, in 1828 [1.241]. For example, the RNA First (RNA World) model is widely touted [1.27] [1.62] [1.150] [1.182] [1.190] [1.215] [1.224] and critiqued [1.31] [1.37] [1.158] [1.165] [1.182] [1.272] [1.285] [1.327] [1.333] [1.334] [1.335], and the problem of how self-reproducing RNA got encapsulated into a protocell has hardly been touched upon [1.50] [1.51] [1.172] [1.279] [1.288] [1.310] [1.311] [1.410]. [Encapsulated RNA may "evolve" more rapidly [1.185] [1.329], especially in flattened, shaped droplets. Fluid flow in flat vesicles, spherical, or flattened round or polygonal, has not been investigated. Cf. [1.25] [1.33], even though molecular crowding has been considered in regards to the origin of life [1.46] [1.76] [1.136] [1.157] [1.336] [1.353].] The chemistry approach often uses pure chemicals, not a condition expected on early Earth [1.80].

Figure 1.2 "Microbial pinnacles" found at the bottom of Lake Vanda, Antarctica [1.12] [1.358] include Bacteria, cyanobacteria and Archaea [1.320]. NASA CC.[6] Cf. [1.91].

Three classes of protocells are presently being investigated: synthetic cells, minimal cells, and mixed abiotic/biological [1.331]. All three approaches may prove useful in testing some of the ideas developed here.

I intend to approach the problem by combining biological properties of life with the physical and chemical state in which life is presumed to originate in the early days of our planet. I hope that by this combined approached inspired by polygonal droplets we can try to help solve the age-old problem of how life originated. Some broad views are summarized in Figure 1.3.

A few attempts have been made to bring physics into the origin of life problem [1.6] [1.47] [1.61] [1.82] [1.101] [1.116] [1.121] [1.152] [1.181] [1.212] [1.228] [1.229] [1.385]. Since a cell is small in most cases nowadays[7], and presumably, at the origin of life, we are dealing with the physics of small things, "mesophysics", in a field now often referred to as "Soft Science" with its own journal [1.302] and webinar series [1.68]. Astrophysics at all levels is often invoked, and I will indicate many such instances. An example of an unexplored phenomenon possibly relevant to the origin of life is that at critical concentrations of colloids, which might occasionally occur in vesicles (Chapter 8), concentration fluctuations are limited, giving rise to emergent phenomena [1.103], perhaps going beyond autocatalysis. Another is the role of phase separation in enhancing self-assembly [1.132]. In any case, despite the chemistry bias, we need to keep our minds open as we try to contribute to solving "the most profound unsolved problem in biology... the origin of life itself" [1.71].

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[6] Permissions have been granted by the: American Chemical Society "ACS", American Microbiology Society "AMS", American Physical Society "APS", Creative Commons Attribution License "CC", Creative Commons BY "CB", Creative Commons Noncommercial License, "CN", Elsevier "EL", Frontiers "FR", John Wiley & Sons "JW", MDPI, "MI", Microbiology Society "MS", Public Library of Science "PLoS", Public Domain "PD", Royal Society of Chemistry "RSC", Proceedings of the National Academy of Sciences of the United States of America "PNAS", Standards in Genomic Sciences "SGS", Springer Nature "SN", World Scientific Publishing "WSP". Figure and Table numbers cited that are in other publications are designated by <Figure 1>, <Table 2>, etc., to clearly distinguish them from Figure and Table numbers in this book.

[7] Exceptions include giant Bacteria [1.340] and giant diatoms [1.409] *Phycomyces* [1.104], acellular slime molds [1.269], syncytial nerves [1.42], syncytial muscles [1.84], syncytial seaweeds (<Figure 52> in [1.122]) and early insect embryos [1.201].

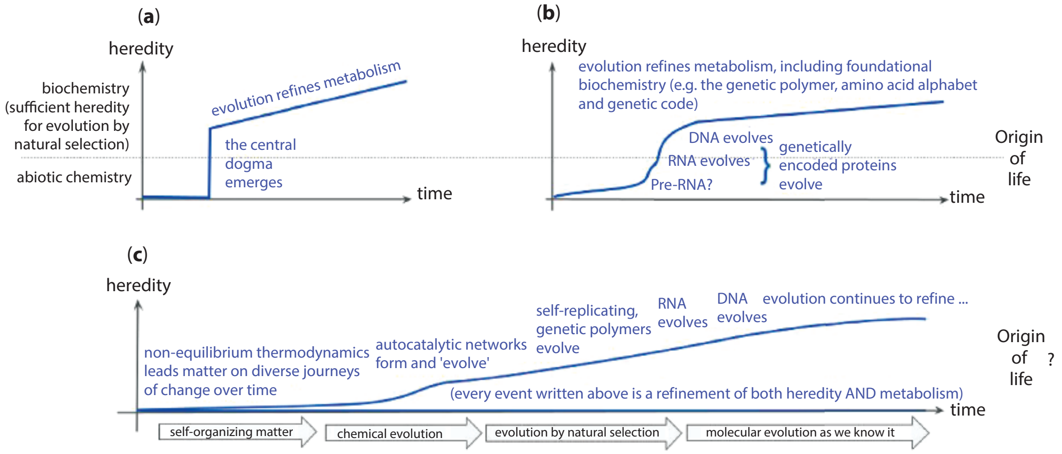

Figure 1.3 "<Figure 1> An evolving view of life's origins: from discontinuity to continuity" [1.101] Royal Society CC. These are three overall views of prebiotic accomplishment of heredity of increasing subtlety. Note that vesicles are not invoked. The sudden "and there was life" approach (<*a*>) is invoked in [1.183] and Chapters 6 and 8.

Some are trying to narrow the setting for an origin of life on Earth [1.306]. As life appears to exist in most habitats on the present Earth, we will not dwell on this problem, nor on the definitions of habitability [1.242].

1.3 The Improbability of Life

Life is impossible [1.3]. We have been told this ever since the structure of proteins and DNA was reduced to sequences of amino acids or nucleic acids. This argument, based on an assumed independence of which amino acid or nucleotide comes next in prebiotic polymerizations, is the basis for much Intelligent Design (ID) or creationist argumentation: if life is improbable [1.3], something must have stepped in to overcome its low probability. For example, the probability of random assembly of 200 amino acids into one specific protein molecule is $1/20^{200} \approx 10^{-260}$ [1.325] (cf. [1.3] [1.20] [1.131] and counterargument [1.124]). Science stops nowadays when the Grand Wizard [1.24] is invoked, despite its roots in religion and continuing interest in the relationships between science and religion [1.111] [1.125] [1.170] [1.244] [1.357], including in astrobiology [1.18] [1.52] [1.59] [1.161] [1.230] [1.281]. In [1.2] Paul Davies repeats the creationist improbability argument but juxtaposes it with the view that there is a "life-principle", a part of physics yet to be discovered. There has been a more than a century search for such physics [1.90].

But there is more to life than linear sequences of monomers in polymers. It has a four-dimensional structure, an ever-changing relationship of parts. Chains of amino acids wind themselves up in space or are assisted in doing so by chaperone [1.194] [1.216] [1.314] or other molecules, and some are not functional until they do so. While some changes in their sequences reduce or destroy functionality, many changes are compatible with or alter function [1.17] [1.261] [1.349]. Granted we have not yet solved the puzzle of the origin of life, here I will explore the rich set of possibilities that arise from looking at the structure of life, including some of the physics of life.

The "proof of the pudding" will be when a living organism, so to speak, crawls out of a test tube. The time and resources needed are well beyond my limitations.

There is a long history of scientists finding analogies to living organisms in physical and chemical phenomena [1.188], to which my effort adds. While the current paradigm is that life is "nothing but" a complex organization (a machine) of nonliving components, touted as a major accomplishment of science [1.188], it has also led to a new despotism in the current world, in which this viewpoint is projected to all aspects of humanity. So, while I am contributing to the paradigm with what I hope is a fresh look at the unsolved problem of the origin of life, I do not claim that it solves the outstanding issues of consciousness, free will, and human rights, all of which don't fit. It is not that I don't appreciate these problems, but prefer to practice "The Art of the Soluble" [1.236] [1.237], for instance, reducing an approach to consciousness to the embryological beginnings of the brain [1.372]. The only alternatives to abiogenesis, that life somehow arose from nonlife, are those promulgated by most religions, or that life always existed as a cosmic phenomenon, along with the whole Universe [1.149], and thus requires no further explanation.

The story of eukaryogenesis [1.220] [1.226] [1.250], the origin and evolution of organisms whose cells have nuclei, is fascinating and full of puzzles to be solved. Archaea played a role [1.86] [1.100] [1.140] [1.176] [1.200] [1.205] [1.260] [1.350] [1.351] [1.408] [1.416] [1.417]. Similarly, I will not delve into the ecology of Archaea [1.144], chemotaxis [1.106], etc. Here I go 2 billion years more back, to the origin of life itself.

The study of the origin of life is much like the search for extraterrestrial life: much speculation, by many people hopeful to make the breakthrough, but to date, with nothing certain or repeatable found. The origin of life is worse than astrobiology, because unlike tools like telescopes, rockets, rovers, sample returns and the cosmic time delays for light from distant bodies to reach us, we have no time machine to send us back to our start. So, it is all guesswork, unless our ability to look at earlier galaxies is someday also accompanied by much higher resolution [1.297]. At least within the Milky Way Galaxy, this is somewhat plausible using the Sun as a gravitational lens [1.371]. But then the Milky Way is "only" 87000 light years across [1.398]. Compared to the age of the universe, 13.7 billion years [1.262], this is only 0.0006%. Nevertheless, progress has been made, such as detection of a planet in another galaxy [1.87] and the ability to observe the disks of dust and debris forming planets [1.316] postulated by Immanuel Kant [1.166]. Perhaps someday we'll be able to watch the origin of life on other planets. Star formation is an ongoing process, and we observe the formation of many protoplanetary disks. Thus, despite pessimism: "..., the Universe does not seem to be teeming with life" [1.56], we are obviously at the beginning of a quest, rather than its conclusion. The current debate over whether we should continue with our thrust of civilization or destroy it, is important in understanding the roles of astrobiology [1.312] [1.418]. Wars are fought over such philosophical issues.

Thus, the best we can do for now in "studying" the origin of life is to collect pieces, like pieces of a jigsaw puzzle, and see if they fit together (cf. [1.34] [1.352]). There are many definitions of "life" [1.384] which have been widely discussed [1.1] [1.8] [1.10] [1.13] [1.14] [1.15] [1.16] [1.19] [1.23] [1.29] [1.32] [1.35] [1.38] [1.41] [1.45] [1.57] [1.60] [1.63] [1.64] [1.65] [1.69] [1.70] [1.72] [1.74] [1.78] [1.79] [1.83] [1.88] [1.92] [1.94] [1.95] [1.96] [1.97] [1.98] [1.102] [1.105] [1.107] [1.108] [1.110] [1.113] [1.114] [1.115] [1.117] [1.128] [1.130]

[1.133] [1.138] [1.139] [1.145] [1.154] [1.155] [1.156] [1.159] [1.163] [1.167] [1.168] [1.169] [1.171] [1.174] [1.175] [1.178] [1.179] [1.184] [1.186] [1.191] [1.192] [1.198] [1.199] [1.206] [1.207] [1.208] [1.209] [1.214] [1.218] [1.219] [1.221] [1.222] [1.225] [1.231] [1.233] [1.234] [1.239] [1.240] [1.253] [1.254] [1.255] [1.256] [1.258] [1.259] [1.264] [1.266] [1.268] [1.270] [1.275] [1.282] [1.283] [1.293] [1.294] [1.296] [1.300] [1.301] [1.303] [1.304] [1.305] [1.308] [1.309] [1.318] [1.322] [1.323] [1.324] [1.330] [1.332] [1.338] [1.339] [1.341] [1.344] [1.346] [1.348] [1.356] [1.359] [1.360] [1.361] [1.366] [1.367] [1.373] [1.377] [1.379] [1.380] [1.382] [1.384] [1.388] [1.389] [1.391] [1.392] [1.393] [1.396] [1.400] [1.401] [1.402] [1.403] [1.404] [1.413], and for which I will take some liberties. The similitude of shaped droplets and polygonal Archaea is analogous to finding the pieces of a puzzle that frame the picture to be constructed. So, the function of this book is to outline this possible framework and jolt the reader into awareness of the plethora of scholarship related to the origin of life, providing puzzle pieces to fill it in. Our previous, edited book was on *Conflicting Models for the Origin of Life* [1.347] (Cf. [1.287]). There is a temptation to focus on certain conceptions of what might have happened. So, while I will present a new, plausible framework, I also point to some of the vast efforts of others thinking about this puzzle. Except for my own work around the edges, I hope that this book provides a guide to the literature, and keeps minds open.

From attending many webinars, there appears to be a consensus forming that life started in sea vents as an RNA World and then acquired membranes [1.292]. The reasons for this appear to be:

1. sea vents, recently discovered, provide energy gradients [1.36] [1.186] [1.187];
2. sea vents can catalyze amino acids;
3. some RNAs can self-reproduce [1.197];
4. many extraterrestrial subsurface oceans have been deduced via fly-bys, and perhaps have their own sea vents [1.21] [1.28] [1.48] [1.75] [1.109] [1.118] [1.142] [1.164] [1.193] [1.245] [1.257] [1.267] [1.284] [1.286] [1.295] [1.298] [1.299] [1.328] [1.342] [1.365] [1.369] [1.375] [1.376] [1.406] [1.407];
5. plans for exploration of these other Solar System seas are afoot [1.48] [1.55] [1.109] [1.134] [1.217] [1.227] [1.232] [1.265] [1.284].
6. the discoveries of water on Mars (Part 1, Chapter 11) and the Moon [1.11] [1.141] [1.151] [1.263] [1.315] [1.370] may also contribute to this Ocean Worlds perspective.

Another source of energy from the ocean for the origin of life might be the gradients at the very surface of the ocean, called the "ocean skin" [1.235] [1.252].

I hope to broaden the reader's considerations by not only elaborating on the Lipid World first, but also presenting the vast range of alternative ideas, whether they are compatible with my suggestions or the more popular sea vents or neither.

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