Chapter 2
Definition of Life

The definition of life is a long-standing debate with no broadly accepted scientific consensus (Kolb 2007). The underlying problem in defining life is twofold. The first is that living systems use compounds that are abundant in the surrounding environment, and processes that are not intrinsically different from reactions that occur abiologically. There does not appear to exist a single characteristic property that is both intrinsic and unique to life. Rather we have to argue that life meets certain standards, or that it qualifies by the collective presence of a certain set of characteristics.

The second problem in defining life is linguistic. Life, grammatically, is a noun, which therefore calls for definition in terms of other nouns. Yet life is much more like a verb than a noun—more a process than an entity. Defining life is analogous to defining wind. Wind is air in motion, a state of being. The molecules of wind are the same as those of air, but their dynamic state is their defining characteristic.

Margulis and Sagan (1995), in their book whose title, *What is Life?*, honors the legacy of Schrödinger's (1944) earlier attempt to modernize the definition of life, resort to a multifaceted poetic characterization rather than a concise definition:

> Life is planetary exuberance, a solar phenomenon. It is the astronomically local transmutation of Earth's air, water, and sun into cells. It is an intricate pattern of growth and death, dispatch and retrenchment, transformation and decay. Life is the single expanding organization connected through Darwinian time to the first bacteria and through Vernadskian space to all citizens of the biosphere. Life . . . is a whirling nexus of growing, fusing, and dying beings. It is matter gone wild, capable of choosing its own direction in order to indefinitely forestall the inevitable moment of thermodynamic equilibrium—death.

While there is much truth and an admirable degree of esthetic appeal to the characterization of life embodied in the passage above, such a definition is too florid and imprecise to guide the search for life on other worlds. A pithier and more objective definition is needed, to make the recognition of the living state as unambiguous as possible whenever and wherever it may be encountered in the Universe.

Life can certainly be defined through a collection of properties, but the search for life wherever it occurs depends ultimately on an ability to recognize individual

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entities with the properties of being alive, as distinct from their non-living surroundings. And, while life is like the wind in its pervasive distribution, it differs from wind in having finite boundaries. The challenge of defining life in the context of a cosmic biology, therefore, is to specify the defining characteristics of a dynamic process that occurs within discrete boundaries that set the process apart from its environment. While our everyday experience with life on Earth makes the distinction between the living and non-living for the most part unambiguous, a consideration of life on other worlds, where conditions may be different, and/or where life may have evolved from its inorganic precedents to a lesser degree, requires us to formulate a more formal and objective definition for life.

An added challenge to defining life is the rise of artificial intelligence in conjunction with the accelerating development of autonomous robots. Any comprehensive, generic definition of life must now incorporate the prospect of mechanical, or fabricated, forms of life that satisfy all the requirements of naturally evolved organisms. Henceforth in this book, we will occasionally be distinguishing between ***biological*** life, which consists of naturally evolved, self-replicating metabolic systems, and ***mechanical*** life, which is composed of self-propagating, fabricated structures that function through mechanical rather than metabolic manipulations. To the extent that either form meets the generic criteria for a “living entity,” they will be considered to be a form of life.

2.1 Problems with Common Assumptions About the Nature of Life

Historically, and still in popular usage, life has tended to be defined in terms of its dynamic features. Thus, the Random House dictionary (1987) defines life as a collection of characteristics and processes, such as metabolism, growth, reproduction and adaptation to the environment. This form of definition is generally followed by some biology textbooks (Campbell 1996; Raven and Johnson 1999), while others—tacitly admitting the difficulty of defining life—refer instead to its “unifying principles” (Curtis and Barnes 1986) or its “emergent properties” (Purves et al. 1998). The weakness in defining life as a collection of attributes is that any given attribute fails the exclusivity test—examples of entities that clearly are not alive can be found that exhibit one or more of these traits. The following examples will illustrate the point.

The consumption or transformation of energy is a central point in all traditional definitions of life. Energy metabolism in its most basic form consists of a collection of chemical reactions that yield energy by electron transfer. The central metabolism most often exploits the electrophilicity of carbon doubly bonded to nitrogen ($C=N$) or oxygen ($C=O$) or the electrophilicity of phosphorous doubly bonded to oxygen ($P=O$) (NRC 2007). Living organisms obtain energy from light by photosynthesis or by other electron transfer reactions associated with chemolithotrophy (extracting energy from non-biological molecules) or chemoorganotrophy (extracting energy from molecules synthesized by other living organisms). However, inorganic analogs of these processes are well known. Electrons can be lifted into higher energy levels by various forms of energy, such as heat or ultraviolet radiation. When the electrons fall back to their lower energy levels, the energy difference between these levels is released. When ions absorb energy and release it again in the form of light, this is known as luminescence. Phosphorescence and fluorescence are special cases of luminescence and describe the phenomenon of continued emission of light after irradiation is terminated. Common minerals with the property of luminescence include gypsum and calcite. Another possibility for storing energy in the form of heat is seen in clay minerals with interlayer sites. The interlayer water and OH-groups are suitable for storing heat energy due to their high heat capacity. Thus, nonliving substances can transfer external energy into energy-yielding transitions that under some circumstances can be maintained as potential energy, just as living organisms do (Schulze-Makuch 2002).

Another traditionally regarded property of life is growth. But just as cells grow in favorable environments with nutrients available, inorganic crystals can grow so long as ion sources and favorable surroundings are provided. Furthermore, just as the development of living organisms follows a regulated trajectory, so does the process of local surface reversibility regulate the course of silicate or metal oxide crystals that grow in aqueous solutions (Cairns-Smith 1982).

A third traditionally defined property of life is reproduction, which entails both multiplication of form and transmission of information. The visible consequence of reproduction in living organisms is the multiplication of individuals into offspring of like form and function. Mineral crystals do not reproduce in a biological sense, but when they reach a certain size they break apart along their cleavage planes. This is clearly a form of multiplication. The consequence of biological reproduction is also the transmission of information. Biological information is stored in the one-dimensional form of a linear code (DNA, RNA), that, at the functional level, is translated into the three-dimensional structure of proteins. Prior to multiplication, the one-dimensional genetic code is copied, and complete sets of the code are transmitted to each of the two daughter cells that originate from binary fission. An analogous process occurs in minerals, where information may be stored in the two-dimensional lattice of a crystal plane. If a mineral has a strong preference for cleaving across the direction of growth and in the plane in which the information is held (Cairns-Smith 1982), the information can be reproduced. Note that in contrast to living cells, information can be stored in multiple layers in a crystal. However, copying this type of three-dimensional information would be very challenging. Another important question is whether the stored information has actual meaning. We know that DNA has meaning because of the expressed segments of DNA (exons) that are read by the molecular machinery of the cell and translated into functional molecules. However, there is no obvious way of assessing whether any ion patterns in minerals have a meaning in terms of functional utility (Fig. 2.1).

Another hallmark of life is said to be adaptation to the environment. Short term adaptation can be achieved by an individual organism in a transient and reversible

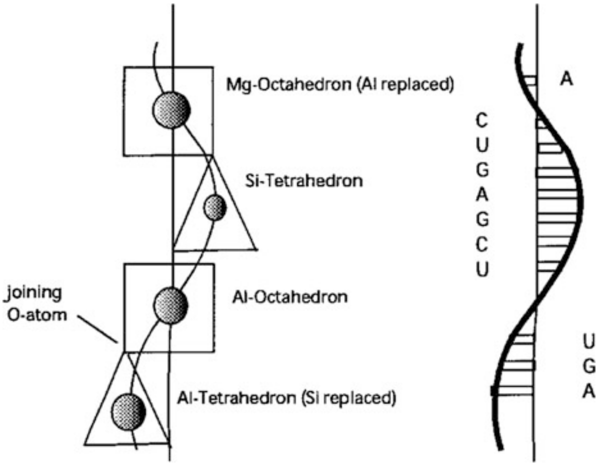

Fig. 2.1 Spiral structure of (**a**) amesite-2H_2 and (**b**) RNA, two-dimensional and schematic. As the nucleotide sequence in RNA codes for information, so could in principle the cation order in amesite

way, such as enzyme induction, in which cells produce enzymes specific to a particular substrate only when that substrate is present. Other examples include the adjustment of microbial size to nutrient conditions, or the movement of a cell to a nutrient source or away from toxic substances. However, clay minerals can also adapt to their surroundings. The most common adaptation for clays with interlayer sites is their response to water availability. If the outside environment is dry, water is released from the interlayer to surroundings; if the outside environment is wet, water is adsorbed into the interlayer.

Long term adaptation is achieved by collective organisms through time by the essentially irreversible mechanism of natural selection. An analogous process occurs in clays, which over time can accommodate different ions at ion exchange sites that will affect the lattice structure during clay mineral formation. Also, where chemical weathering is prevalent, as in the tropics, clays can develop an outer, weather-resistant layer of aluminum oxide or silicate. Changes in mineralogy can also occur depending on the ion source and change in the environment. Dehydration reactions involving water molecules or hydroxyl ions lead in general to a structural change. In extreme cases, one clay mineral can transform into another. For example, gibbsite can transform into boehmite because of an alternation of dry and wet periods (Boulange et al. 1997).

As indicated above, good analogies can be found for each of the traditional criteria for living systems in the inorganic world, specifically for clay minerals and metal oxides. A summary is provided in Table 2.1. While we are not aware of any specific minerals that display all four characteristics, there is no reason conceptually to assume that a mineral fitting the sum of all the criteria cannot exist.

At the biological edge of the interface between the living and non-living world, viruses present a similar case in reverse. By the traditional definition viruses are not considered living entities because they cannot reproduce and grow by themselves and do not metabolize. Nevertheless, they possess a genetic code that enables them to reproduce and direct a limited amount of metabolism inside another living cell.

Table 2.1 Properties of biological organisms, comparing organic mechanisms with inorganic parallel

Property	Basic requirement	Organic mechanism	Inorganic parallel
Metabolism	Energy obtained from electron transfer	Various types of biochemical pathways including photosynthesis Energy storage as ATP or GTP	Energy uptake via heat or light, elevation of electrons to higher energy bands, where they absorb energy at specific frequencies. Energy storage by luminescence or at interlayers of clay minerals due to high heat capacity of water and OH-groups
Growth	Increase in size of single unit	Cell growth as long as nutrients are available and environmental conditions are favorable until reproduction occurs. Self-organizing as development proceeds, errors corrected by enzymes	Crystal growth as long as favorable environmental conditions prevail and a sufficient ion source is present. Local surface reversibility makes it possible to correct certain mistakes during the growth of silicate or metal oxide crystals from aqueous solution
Reproduction	Multiplication of information	Various mechanisms of reproduction (most commonly by binary fission). The genetic code is duplicated and preserved through successive generations.	Crystals commonly cleave during growth. If a mineral has a strong preference for cleaving across the direction of growth and in the plane in which the information is held, new “individuals” may form and each of the new “individuals” may expose the information on the new surface (Cairns-Smith 1982)
Adaptation to environment	Compensation for, reaction to, and development of new abilities in response to various types of environmental changes	Genetic adaptation over time through mutations, transposition of genetic material, transformation, conjugation, and transduction. Homeostatic adaptation within individuals: movement to nutrient source, cellular shrinkage or formation of spores in nutrient-poor environment, enzyme induction	Adaptation through changes in mineralogy due to changes in ion and environmental source (including transformation from one (clay) mineral to another in extreme cases). Adaptation within individuals: Adaptation to outside environment via water release or adsorption in interlayer (clay minerals), development of outer, weathering-resistant layers such as Al_2O_3 or silicate layers in tropical soils

Modified from Schulze-Makuch (2002)

They thus fulfill the traditional criteria only part of the time and under special circumstances. At best, by the traditional definition, they could be considered to be "reversibly alive." Since viruses presumably evolved from bacteria that clearly are alive, do they represent a case in which a living entity has been transformed to a non-living state by natural selection? Alternatively, viruses might have been the evolutionary precursors of the three domains of life (Archaea, Bacteria, and Eukarya), as suggested by Forterre (2006), or they might have evolved from a plasmid that evaded a cell (Erdmann et al. 2017). Either way, where would we draw the line between life and non-life? If we accept the proposition that viruses are not alive, how would we consider parasitic organisms or bacterial spores? Parasites cannot grow by themselves either and spores remain in dormant stages with no dynamic biological attributes until they become active under favorable environmental conditions. Thus, if we consider parasites or bacterial spores to be alive, the logical consequence would be to consider viruses alive as well.

In summary, the traditional definition of life on close examination fails to distinguish consistently between the living and the non-living world (Table 2.1). Since biology and mineralogy have both been characterized extensively on Earth, the distinction between the two is not difficult to make on our home planet. Notwithstanding the semantic ambiguities, we generally know life (or non-life) when we see it. But the definition matters more when we leave the familiar context of Earth, and encounter more exotic conditions and environments where dynamic phenomena may exist with which we are unfamiliar. In that context, semantic ambiguities become conceptual stumbling blocks and observational obstructions. For that reason, we need a definition of life that more effectively and precisely captures the fundamental essence of the phenomenon for which we are searching.

2.2 Historical Views on the Definition of Life

From the earliest days of mechanistic thinking (the Greek philosophers, in the Western tradition), but particularly with the abandonment of vitalism in the nineteenth century, life increasingly became recognized as a state or process, in which otherwise non-living matter and energy acquire dynamic properties that generate a state of disequilibrium distinct from its non-living surroundings.

With scientific acceptance of the theory of evolution came the derivative notion of the origin of life from non-living precursors. As formal theories about this process were advanced (Haldane 1954; Oparin 1938), and evidence consistent with a plausible mechanism were reported (Miller 1953), the need became apparent for a definition that distinguishes between living and non-living states, since that boundary (at least in concept) had to be crossed at some point in the past. As the concepts of thermodynamics became formalized in the nineteenth century, the low entropy state of living entities came to be appreciated as one of their most fundamental characteristics. Because of the need to distinguish between a collection of molecules that is alive and a collection of the same molecules that is not, researchers have increasingly focused on the highly ordered state of the components of living systems, and of the energy flow required to maintain that order (Schrödinger 1944; Brillouin 1956; Morowitz 1968; Neubauer 2012; Chaisson 2013). The thermodynamic improbability of the living state has become one of its defining features.

The ability of living systems to reproduce themselves has always been one of the clearest distinctions between living and non-living systems. Up until the twentieth century, self-organization and reproduction remained as mysterious as they were distinctive. However, advances in genetics (Morgan 1915), biochemistry (Chargaff et al. 1951; Lwoff 1962), and molecular biology (Crick 1968; Watson and Crick 1953) elucidated the chemical basis of information storage and transfer in living systems, the extremely high information content of macromolecules, and the role they play in perpetuating the form and function of specific living systems. The encoding and transmission of information that enables self-assembly and reproduction have become collectively another indispensable feature of all contemporary definitions of life.

Two additional concepts have had a strong influence on modern definitions of life. The first is the contention that an essential criterion for life is the capacity for evolutionary change over extended periods of time. The second is that life is a global, as opposed to a local phenomenon.

2.3 Modern Definitions of Life

The modern attempt to redefine life in a more sophisticated way dates from Schrödinger's (1944) introduction of physical aspects such as energy states and entropy as the essence of what it means to be alive. A similar theme was developed later by Szent-Györgyi (1972). Moreno et al. (1990) focused on the autonomous nature of life by describing it as an autonomous system capable of self-reproduction and evolution. Maturana and Varela (1981) also emphasized the process of self-maintenance, or "autopoiesis", as the fundamental essence of life. Lwoff (1962) and Banathy (1998) emphasized the information processing properties of life, while Dyson (1999) in a similar vein defined life as a material system that can acquire, store, process, and use information to organize its activities.

Some authors have striven for a comprehensive definition that focuses more on the continuity of life through time. Monod (1971), for instance, combined the ecological, thermodynamic, and bioinformatic properties of life, but added the ambiguous concept of teleonomy (apparent purposefulness in living organisms). Another effort at comprehensiveness is the proposal of Koshland (2002) for seven pillars of life, which he designated as a program, improvisation, compartmentalization, energy, regeneration, adaptability, and seclusion.

Since all living forms operate within the constraints of environmental conditions and limitations, some authors have tried to incorporate an ecological perspective into their definitions. For instance, Feinberg and Shapiro (1980) proposed to redefine life as the fundamental activity of a biosphere—a highly ordered system of matter and energy characterized by complex cycles that maintain or gradually increase the order of the system through an exchange of energy with its environment.

These admirable attempts to include an ecological perspective illustrate one of the problems that has bedeviled historical attempts to define life: namely, the confusion between life as a process with a history, and the features of matter that constitute the state of being alive at a given moment in time. While almost all definitions of life refer in some way to reproduction as an essential feature, at a given moment an organism may be alive but not reproducing. Similarly, some authors insist that the capacity for Darwinian evolution is an essential feature of life, yet any single organism during its lifetime is clearly not undergoing evolution. Mix (2015) acknowledged the difficulty of finding a precise definition of life and suggested the use of provisional definitions such as *Darwin lif*e (exhibiting evolution by natural selection), *Haldane life* (exhibiting metabolism and maintenance), and *Woese life* (possessing small subunit rRNA). However, as previously outlined, clay minerals and crystals also fulfill a subset of the parameters usually attributed to life and thus may be mistakenly labeled as alive. Thus, the condition of "being alive" needs to be distinguished from the "properties of a living system." The distinction is more than a semantic technicality, if the search for life on other worlds depends on the definition of what is being searched for. While ultimately we must know that what we discover is a "living system" capable of self-perpetuation, at the moment when we first encounter it, we need more precise and practical criteria for judging whether or not it is "alive."

The current tendency is to focus on two essential characteristics of the living state: its consumption of energy to maintain thermodynamic disequilibrium, and its ability to replicate form and function indefinitely through time. More controversial but often incorporated into modern definitions is the capacity for evolution and the interdependent nature of living systems, extrapolated in the extreme to a global extent. Finally, the need to define life in a way that incorporates forms of mechanical life that meet the same criteria as biological organisms has become apparent. Each of these considerations will be evaluated in turn.

2.4 Thermodynamic Criteria

Once it is accepted that the living state maintains a high degree of order (low entropy) that persists in disequilibrium with its environment, thermodynamic considerations mandate that energy be provided to maintain that order. Nearly all modern definitions of life incorporate the assumption of a highly ordered state that degrades energy (consumes enthalpy) as a means of resisting the spontaneous tendency toward disorganization (increasing entropy) required by the 2nd Law of Thermodynamics.

Biological life on Earth has evolved in such a way that energy is drawn from complex molecules with high free energy content, through a series of reactions that capture the release of energy as the complex molecules are broken down to simpler compounds with lower free energy contents. Photoautotrophs and chemolithoautotrophs manufacture their own chemical fuel by using the energy from sunlight or reactions with inorganic chemicals found in the environment. Heterotrophs derive their chemical fuel and carbon by consuming autotrophs, other heterotrophs, or their organic products. The energy thus harvested is used not only to maintain the highly ordered state of the system, but to power any autonomous activity (work performed) by the system. Collectively, the repertoire of chemical reactions and interactions that carry out these processes constitute metabolism, so the capacity to carry out energy-consuming metabolism in order to maintain order and perform work is either explicitly or implicitly part of most definitions of the living state.

Now that any macromolecule whose precise chemical structure is known can in principle be synthesized in the laboratory, any metabolic reaction should be inducible by placing together the right constituents in appropriate concentrations under conducive conditions in a test tube. Would a minimal set of such metabolic processes carried out exclusively *in vitro* constitute a living system? Most would say not, unless that system could be shown to perpetuate itself indefinitely in a stable, autoregulated state with input only of simple constituents and energy. In the poetic words of Loren Eiseley (1946),

> . . . every bubble of the chemist's broth has left the secret of life as inscrutably remote as ever. The ingredients are known; they are to be had on any drug-store shelf. You can take them yourself and pour them and wait hopefully for the resulting slime to crawl. It will not. The beautiful pulse of streaming protoplasm, that unknown organization of an unstable chemistry which makes up the life process, will not begin. Carbon, nitrogen, hydrogen, and oxygen you have mixed, and the same dead chemicals they remain.

Thus chemistry alone, in the absence of organizing components, does not constitute the living state. But the day in which the biochemist and molecular biologist may indeed be able to brew a mixture with some elementary life-like functionality may not be far away. Theoretical models of self-sustaining metabolic systems have been in the design phase for some time (Cloney 2016; Luisi et al. 2006; Maturana and Varela 1981), and host cells infused with synthetic macromolecules are moving toward genomically engineered hybrids between natural and synthetic forms of life (Juhas 2016). These advances are described in greater detail in Chap. 3. Suffice it to say that definitions of life must include at a minimum the requirement of self-sustaining autoregulation, or autopoiesis (Luisi 2003a), powered by the controlled consumption of free energy.

2.5 Reproducibility Criteria

Metabolism in biological organisms is carried out in a directed, not a random, way because proteins (enzymes) catalyze specific reactions. The specificity of catalysis is due to the three dimensional structural uniqueness of the protein (Luisi 1979), and that in turn is a consequence of the one-dimensional (primary) structure conferred by the particular sequence of amino acids that make up the protein. The amino acid sequence of a given protein, with minor exceptions, is the same for that protein in every organism of the species, and to varying degrees in other species in which the protein catalyzes the same reaction. The ability to synthesize proteins of the same structure within organisms, and pass the instructions for synthesizing proteins of the same structure to succeeding generations, is based on a linear code of nucleic acid bases which can replicate themselves with high fidelity. This nucleic acid code determines not only the structure of protein catalysts, but controls many other structural and regulatory functions of the cell.

From the earliest observations of ancient people that organisms reproduce offspring as near-identical versions of their parents, the concept that information must be passed from parent to offspring has been self-evident. Thus the potential for reproduction is a vital part of any definition of life. Yet the failure of an individual organism to reproduce does not preclude it from being alive. Even if an individual organism does not duplicate itself in its entirety, it must continually replicate the macromolecular components that keep its metabolic disequilibrium operating. And for multicellular organisms, continual cellular turnover, requiring replication of all of a cell's constituents and capabilities, is the norm.

Two additional features of reproduction in biological organisms need to be specified to distinguish the living state from superficially similar processes in the inanimate world. The first is that living cells and multicellular organisms reproduce near-exact replicas of themselves, with regard to size and morphology. While mineral crystals grow by replicating precise molecular configurations, the resulting overall crystal is indefinite in size. While clouds multiply, they generate offspring of variable shapes and sizes. Indeed, it is this constancy of form through successive generations that enables the assignment of a living organism to a taxonomic category that extends through time and constitutes a unique and traceable biological history. The second unique feature of biological reproduction is that it constructs its descendants from raw materials, adding the informational specificity as well as the material composition to the offspring through the mere agency of its own intrinsic metabolism.

While biological organisms as they have evolved on Earth do reproduce near-exact replicas of themselves, it is less clear that mechanical entities would need to do so. To be considered alive, they certainly must be capable of autonomous fabrication from raw materials, but it is conceivable that a greater variety of structural and functional variations could be coded into the program that mechanical forms of life propagate through succeeding generations.

2.6 Evolutionary Criteria

Living entities reproduce themselves through an indefinite number of cycles, ensuring survival of the information content and metabolism for which it codes, despite the demise of predecessor carriers of the information. As a result, the living state at any point in time, in any single organism, has a history. Every species has a species history, marked by changes over time that have been introduced into its genetic code, resulting in alterations of form and function. Most (but not all) of these changes are assumed to be driven by natural selection— the mechanism for biological evolution first enunciated by Alfred Russell Wallace and, in greater depth, by Charles Darwin—resulting in the designation of this type of biological change over time as 'Darwinian evolution.' Some would argue that the ability to undergo Darwinian evolution is also a defining characteristic of living systems. It clearly is not, however, a property of an individual organism; so this criterion is not useful when evaluating whether a specific entity is alive at a given point in time (Fleischaker 1990). A nuanced version of this criterion is that the living state consists of materials that have been ordered as they are, through a sequence of historical contingencies (Luisi 2003b).

2.7 Life as a Global Entity

The notion that the Earth is alive as a whole is prevalent in ancestral cultures, and was famously promulgated in the late sixteenth century by Bruno, but generally fell out of favor as the Renaissance progressed and inanimate chemistry and physics matured as sciences. In the twentieth century, the concept was reborn in two different versions. Vernadsky (1997) argued that geology and biology are fundamentally indistinguishable - that biology is simply a particularly dynamic construction of the same material that constitutes the matter of all the Earth. Lovelock (1979, 1995) has argued that the Earth in its entirety operates as a living, self-regulating, homeostatic system whose properties derive from and define the nature of life itself (The Gaia Hypothesis). Both points of view have merit, and the Gaia Hypothesis, in particular, has some predictive value for the nature of biospheres on other worlds where living systems might be abundant (Lovelock 1965). They are not helpful, however, in assessing whether a specific entity is alive at a given point in time. Furthermore, if life exists in isolated local pockets of some other worlds, it seems unlikely that global indicators would reflect it. This is the fundamental flaw in Lovelock's (1965) *a priori* dismissal of the existence of life on Mars based solely on its atmospheric characteristics. At some semantic level it might always be argued that any world that harbors life at all is itself "alive," but acceptance of the argument does not have practical utility in finding and identifying local pockets of living systems.

2.8 Artificial Life

The rise of technological capability by the human species on Earth has raised the prospect that new forms of life could be created by *Homo sapiens.* Since such forms of life will have been brought into existence by means other than the natural process of evolution, they are referred to as **artificial life.** No such life has yet been created that matches all the criteria fulfilled by naturally evolved, organic life, but progress is being made in three areas, colloquially categorized as (1) “wetware,” (2) “software,” and (3) “hardware.”

2.8.1 Synthetic Life (“Wetware”)

Synthetic biology is a field of research in which the main objective is to create fully operational biological systems from the smallest constituent parts possible, including DNA, proteins, and other organic molecules (Rugnetta 2016). For our purposes, its greatest significance lies in the insights it can provide into the origin of life under natural circumstances. Accordingly, it is treated in more detail in the next chapter.

2.8.2 Virtual Life (“Software”)

The computer revolution has brought forth the ability to create dynamic computer programs which have several functional similarities to biological forms of life, including the ability to execute dynamic actions, and to reproduce themselves and spread beyond their points of origin. But they are neither autonomous (absent a triggering event) nor do they exist in a material form that can carry out any actions outside a machine host. While artificial intelligence is dependent on such programmed information, and will play an increasingly critical role in developing intelligent, autonomous machines, the software itself does not have sufficient attributes to make it useful in the search for life elsewhere in the Universe. Therefore, it will not be considered further, apart from the role it plays in robotics.

2.8.3 Mechanical Life (“Hardware”)

Once machines are fabricated which have significant intelligence and autonomy, to what extent will they qualify as being alive? A machine is a finite structure, clearly distinct from its surroundings. It is structurally complex, at an entropic level well below that of its ambient environment. It can, and ultimately will, fall apart if not maintained by an input of energy. It performs work by consuming free energy. Even the processing, evaluation, and storage of information (as in a computing machine) consumes some energy. So the thermodynamic criteria for being a living system can be met by any operable mechanical device.

On the other hand, machines at our current state of technology do not autonomously fabricate new machines from raw materials. They can, of course, be fabricated in unlimited numbers by other agents, including other machines. But they do not do this of their own accord, based on instructions derived from a predecessor, at their own initiative and under their sole control. Thus, they fail to meet the criterion of autonomous reproduction.

If and when a machine is built that can assemble from raw materials another machine (either like or different from itself) and pass along the instructions for the fabrication process so that the newly built machine can repeat the fabrication process through a succession of descendant machines with the same capability, then the reproducibility criterion will have been met. Any generic definition of a living system must take into account this eventuality.

It should be noted that even if fabricated entities do not meet all the requirements of being alive in themselves, they imply a "fabricator" that must be or have been alive. In that sense, they are bioindicators of living entities, even if the living entities are not themselves present where the fabricated entities are found.

2.9 A Utilitarian and Generic View

We see, therefore, that defining life is semantically ambiguous and operationally difficult. But a generic and objective definition is needed, to make the recognition of the living state as unambiguous as possible whenever and wherever it may be encountered in the Universe.

We propose to sidestep the semantic difficulties of defining "life," by focusing instead on defining a "living entity" – a finite collection of matter and energy for which search parameters can be devised and criteria for recognition can be specified. Our intent is to propose a definition that is both utilitarian but generic.

We propose, therefore, to define a "living entity" as a material system that (1) is a self-sustaining bounded local environment in disequilibrium with its surroundings, (2) consumes energy to maintain its high level of internal organization, carry out intrinsic activity, and adjust to its environment, and (3) is autonomously generated from or fabricated by antecedent (parental) entities that transmit information to the descendant (offspring) entities sufficient for the autonomous generation or fabrication of an indefinite succession of offspring.

The reader is referred to Chap. 9 for practical consequences of our definition of life and to Chap. 10 on how to use it to detect extraterrestrial life. In this section we expound on the theoretical basis for our definition.

2.9.1 Self-Sustaining and Bounded Environments in Thermodynamic Disequilibrium

A living entity is self-sustaining in that the processes necessary for its function and perpetuation arise from the particular collection of materials (molecules, for biological systems; fabricated components, for mechanical systems) that constitute the entity. A flow of energy through the system activates ordered processes, some of which produce distinctive structures. Components of a living system are constrained within space distinct from their surroundings because they constitute a more highly ordered state of matter than the environment, and physical constraint prevents rapid entropic decay. This requires a boundary which is finite and discontinuous between the non-living surroundings and living contents within the bounded space. The boundary is not absolute, since materials and energy have to be exchangeable between the entity and its surroundings, but it is sufficiently impervious to maintain a clear-cut distinction between the interior and exterior of the entity. Living entities are thus thermodynamically open but far from equilibrium.

A closed natural inorganic system, isolated from its surroundings, adheres to the 2nd Law of Thermodynamics and moves spontaneously toward a state of maximum entropy. It also moves toward a minimum amount of free energy with the Gibbs free energy between reactants and products being zero at equilibrium. Life, on the other hand, maintains a high free energy state. This enables it, first, to do work on its environment. Secondly, the entropy of living systems is low because they are highly organized compared to their environments (even though the 2nd Law of Thermodynamics remains valid, as it applies to the macrocosm as a whole). Minerals fall ambiguously between these two extremes. They are highly organized and therefore have low entropy (Fig. 2.2). But in a natural system they generally move spontaneously toward a lower state of free energy. However, as previously discussed, some luminescent minerals can absorb energy that temporarily elevates them to a higher free energy state than their external environment. Lacking a permanent storage mechanism, however, the energy gain is generally soon dissipated.

A major distinction between biological organisms and non-living systems is the presence of biomembranes. These establish boundaries that serve to (1) preserve the high free energy state of the system from dissipation, (2) encapsulate and confine a high concentration of interacting solutes and macromolecules, and (3) carry out complex functions such as selective solute permeation, light transduction and the development of chemiosmotic potentials that generate energy gradients and provide the basis for reversible states of excitation (Deamer and Pashley 1989).

Disequilibrium on a cellular scale is made possible by the cell membrane, which enables the establishment of different solute concentrations within and outside the cell. On a supracellular scale disequilibrium conditions are created most visibly by colony-forming organisms such as stromatolites and corals, which are multicellular aggregates on a local scale (see microenvironments below). On a planetary scale,

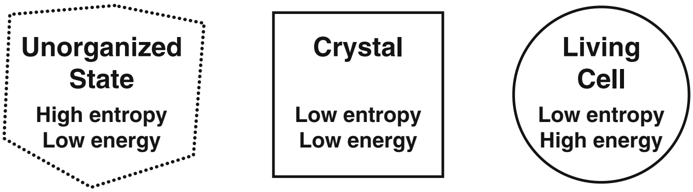

Fig. 2.2 Thermodynamic view of unorganized, crystalline and living state

disequilibrium conditions can be established by biological processes such as photosynthesis.

As we criticized the traditional definition before by comparing it to analogs in the mineral world, it is only fair to evaluate how our definition stands up to these kinds of comparisons. Minerals do not have a membrane composed of fatty acids or similar compounds that living systems use. However, macromolecules within clay minerals can be protected. Clay particles can be linked in face to edge contact that results in an open internal framework with very high porosity (Bennett and Hulbert 1986). In such a clay fabric compartment, macromolecules (or clay minerals themselves) can be protected from disturbances in the environment. This type of framework structure can even lead to selectivity of specific ions. Some surface-active solids such as double-layer metal hydroxide minerals are capable of transporting matter against concentration gradients.

Stable disequilibrium conditions are also possible in the inorganic world but only to a limited extent (by sudden volcanic activity or for the time a hydrothermal vent is active). In a completely inorganic world plutonic rocks with their volatile components would be expected eventually to reach equilibrium with sediments, the atmosphere and ocean water. Disequilibrium conditions or concentration gradients can be maintained within clay minerals for a period of time due to geometrical constraints and large energy barriers against ion exchange. Concentration gradients are most likely to form in the geometrically tight tetrahedral sites and to a lesser extent in the more spacious octahedral sites. However, lacking a distinctive boundary comparable to a biomembrane, clay minerals cannot maintain stable disequilibrium conditions at their reactive outer edges or in their reactive interlayer sites. Thus, like any inorganic system, this system would eventually reach equilibrium with its natural surroundings. Thus, while at any given instant, disequilibrium can be achieved by inorganic processes, this condition cannot be maintained indefinitely. By contrast, living systems are able to establish order within a chaotic world and perpetuate that order as long as energy is available for resisting the inexorable tendency toward increased entropy.

2.9.2 Transformation of Energy to Maintain a Low Entropy State, Adjust to Change, and Perform Work

Maintenance of the low entropy state of living systems requires the persistent infusion of energy (Morowitz 1968), first, to enable the system to maintain its complex organization and resist dissipation toward randomness. The second requirement for an input of energy derives from the fact that living processes adjust to their environments and perform work by growing and retracting, moving through the environment, emitting energy, counteracting concentration gradients, transforming materials, erecting and breaking down structures, and other endogenous activities.

While energy transformations are characteristic of all dynamic physical and chemical systems, energy flow in non-living systems tends to result in greater disorder among all elements of the system. Energy released through different stages of the rock and water cycles, for instance, generally erodes land and distributes water to increase the entropy of the total collection of water and land toward equilibrium (lower mountains, more dispersed water and soil). The energy transformations of living systems, on the other hand, serve primarily to harvest and store the levels of free energy necessary for maintaining the highly ordered structure of the organism and performing the work that living entities carry out. The net effect for living systems, in contrast to that for non-living systems, is to maintain and often increase order at local levels and on microscopic scales.

There are two consequences to the way in which life transforms energy. One is that much of the energy is used to create and sustain a level of complexity that supports emergent functions that in their totality exceed the sum of the parts of the system. A mountain may be structurally complex but its role in the rock cycle is not dependent on the detailed organization of its individual rocks and sediments. The mountain is in essence a simple conglomerate of its component parts. The function of a living organism, on the other hand, depends critically on precisely how it is put together. Its component parts function in a coordinated manner, to generate a complex array of emergent properties, both structurally and functionally. The generation and maintenance of this complexity is one of the primary uses of the energy that living systems transform.

A second consequence of biological energy transformations is to create one or more additional microenvironments within the natural environment. The Eh (redox-potential), pH, solute composition, and structural complexity of the living cell is maintained at levels different from the extracellular environment because of the autonomous functions carried out by the cell, but not in the abiotic environment surrounding the cell. New environments can also be created on a larger scale by colony forming organisms such as stromatolites and corals, which can alter the topography of large amounts of habitat. Life-induced changes can occur even on a planetary scale, such as the change in atmospheric oxygen composition brought about by oxygen producing microbes on Earth, beginning with the emergence of photosynthesis as a uniquely biological form of energy transformation (Knoll 1999; Schopf 1994). This innovation enabled life to become autotrophic (manufacturer of its own food from the simple and abundant molecule, CO_2) on a global scale. Thus, not only is the transformation of energy a characteristic of life, but so is the ability of life to alter conditions in the natural environment.

Note the dual requirement of living systems: to resist an increase in entropy, and to perform work. Both requirements are essential for the definition of a living entity. Any fabrication or machine is, for the time being, at a lower state of entropy than, and in disequilibrium with, its environment. Indeed, such objects are known to exist on other worlds: the lifeless Huygens lander rests on Titan, and the surfaces of Mars and the Moon are littered with man-made objects. They are not alive, however, in part because they perform no work and make no adjustments to changes in their environments. The rovers and orbiters on Mars that still are consuming energy and performing work are not alive because they fail the criterion in the next section.

2.9.3 Information Encoding and Transmission

Order is maintained within living systems despite the turnover of its individual components because information is contained within the system that directs replacement of the lost components, regulates their relative abundance, and controls their interactions. Furthermore, when the entity reproduces itself, all the information needed for reconstitution and function is passed intact to each successive entity. That information serves to constrain the structure and function of each reiterative, succeeding entity.

For biological organisms at the cellular level, this means that multiple descendent cells acquire the genetic information previously held by a single parental cell. At the level of the multicellular organism, it means that all the information for the organism's development and function is replicated, then passed through reproductive cells to the offspring (next generation). When a cell or organism can no longer maintain steady disequilibrium conditions it approaches equilibrium with its environment and therefore dies. Despite the death of the parent organism, the informational blueprint for the organism's structure and function, which for life as we know it on Earth is based on a chemical code, survives to the descendent organism, and will be transmitted from generation to generation. Despite the demise of the individual organism that harbors the code in its cells during any single generation, the transmission of the code to a subsequent generation ensures that the instructions for life specific to that particular kind of organism will persist.

Genetic codes are meaningful because of the characteristics that they impart to the systems in which they reside. However, a code of information by itself is useless if there is no meaning or consequence associated with it. The distribution of atoms in mineral lattice may be understood as a code, in that the information content of the distribution pattern is greater than zero, but there is no apparent meaning associated with it since there is no functional consequence to the pattern. Another main difference that distinguishes living systems from the mineral world is a sharp difference between substance and information. Genetic information is chemically codified in separate units (nucleic acids) of the cell that are distinct from their physical manifestation, hence the functional consequences of the code. A segment of DNA codes for a protein that carries out a particular function. If the protein is broken down, the function ceases, but the DNA that coded for the protein persists through replication and the reproduction of successive generations indefinitely. A mineral, on the other hand, may be capable of rearranging atoms and molecules in response to environmental influences such as weathering; but even if it is supposed that this rearrangement has changed the nature of information encoded in the mineral, the altered information has no effect apart from the specific rock in which it is embedded. Therefore, the information persists only so long as the mineral itself remains intact. There is no obvious consequence to the information, and no expression of it distinct from itself.

A distinctive feature of a living entity, whether biological or mechanical, is that its construction requires only raw unorganized material from the environment, instructions provided by the informational code derived from a preceding entity, and energy. It differs from the manufacture of exact copies of inanimate objects in that the entity manufactures a copy of itself, the copy repeats the reproductive process, and this reiterative cycle of reproduction can continue indefinitely.

2.10 Implications for the Remote Detection of Life

If life conforms to the way we have defined it, our efforts will be maximized by focusing on the consequences of and requirements for the three components of our definition.

If living entities consist of bounded local environments in disequilibrium with their surroundings, we will be seeking to detect evidence of entities that stand out as collections of matter with discontinuous boundaries between themselves and their environment. Thus, any evidence of local chemical concentrations or physical properties distinct from their surroundings would be presumptive evidence for the possibility of life. In many cases, the living units may be small to microscopic, for reasons discussed in the next chapter, and therefore require high spatial resolution in the instruments sent to detect them. However, aggregates of those entities, analogous to stromatolite mats and coral reefs on Earth, may be large enough collectively for remote detection. The necessity for enclosure in a barrier, most likely and often in a liquid medium, leads us to look for particular types of molecules in particular environments—especially amphiphilic molecules.

Physical objects that are clearly distinguished from their surroundings as fabricated, technologically sophisticated objects, even if not living entities themselves, would indicate the involvement of living entities in their creation. While the host of robots and material residues from Earth that already litter the Moon, Mars, and Titan are not themselves alive, they indicate (and surely would be interpreted by alien intelligence as) products of technologically capable forms of life that put them there.

The nature of energy transformations—a nearly universal component of all definitions of life—depends on the nature of the energy gradients available. Since the easiest and most obvious way to detect biologically driven energy transformations is probably through either localized or global effects of the transformation, our instruments need to be attuned to the forms of energy available on the planetary object of our search. Energy sources other than light or chemical energy may be used by life elsewhere, as discussed in Chap. 5. And because of the simplicity of chemical conversions as a source of energy, disequilibrium chemistry in the atmosphere or global habitat is probably relevant anywhere. Finally, because energy is transformed in order to do work by living organisms, evidence of work, such as reactivity, growth, motion, repair, or maintenance of chemical, thermal, or other types of gradients is further presumptive evidence for the living state.

The third component of our definition—capacity for information encoding and transmission independent of the life span of the individual organism—will be difficult to confirm until actual samples of the candidate life forms are in hand.

The constraints applied by this part of the definition for remote detection strategies are thus limited. However, this part of the definition becomes critical once candidate samples are available, for only this third component will enable confirmation that the candidate structure in question is or was alive. The validity of this point is illustrated by the fact that all the lines of evidence in support of fossil organisms in the Martian meteorite ALH84001, including the pictures which could possibly be interpreted as nanomicrobial-like organisms (Chap. 10.2; McKay et al. 1996), are inconclusive, absent confirmation that the presumed fossil actually derived from an organism that did in fact replicate itself from a pre-existing organism. The same applies to the very early fossil record on Earth (Brasier et al. 2002; Schopf and Packer 1987; Schopf 1993; Dodd et al. 2017).

Our definition is geared toward the search for life on other planets and moons. The technical approaches needed for detecting life as we have defined it on other worlds is discussed in Chap. 10. However, the possibility of the existence, and hence detectability, of "alien" life on our home planet, has attracted some attention. Davies and Lineweaver (2005) computed probability scenarios of the origin of life and found that there is a significant likelihood that at least one more type of life has emerged on Earth and could have coexisted with known life. Cleland and Copley (2005) go even further to argue the possibility that the contemporary Earth contains a yet unrecognized alternative form of microbial life. Two counterarguments have been advanced. The first is that any "alien" life on Earth based on a different molecular architecture and biochemistry would be outcompeted very quickly. The second is that no tangible evidence of such organisms has been found in over a century and a half of microbiological study. Cleland and Copley (2005) responded by pointing to the complexity and diversity of microbial communities, and by emphasizing that microbial exploration relies heavily on detecting DNA and RNA, which may not be part of the "alien" forms of life.

2.11 Chapter Summary

Identifying the fundamental features of living entities is essential for identifying them on other worlds, particularly where they may exist in an unfamiliar form with novel features. There are several obstacles, however, to achieving a useful definition of life: (1) Living systems use compounds that are abundant in the surrounding environment and processes that are not intrinsically different from reactions that occur inorganically. (2) There does not appear to exist a single characteristic property that is both intrinsic and unique to life. (3) There was probably no sharp line but rather a gradual transition between a non-living and a living state of matter at the origin of life. (4) Finally, the condition of "being alive" has to be distinguished from the abstract concept of "life." We have chosen to sidestep the abstract concept in favor of defining "living entities" in a way that provides a practical guide for detecting instances of life in alien environments. We propose that living entities (1) are self-sustaining bounded local environments in disequilibrium with their surroundings, (2) consume energy to maintain their high level of internal organization, carry out intrinsic activity, and adjust to environmental changes, and (3) are autonomously generated from or fabricated by antecedent (parental) entities that transmit information to the descendant (offspring) entities sufficient for the autonomous generation or fabrication of an indefinite succession of offspring.

Our definition contains no components that are original with us, though our emphasis on physical boundaries, implying finite structures, has seldom been accorded the priority that we give it. We are consistent with most modern efforts to define life by emphasizing the three key features of low entropy, energy transformation, and replication. This definition anticipates that detection of life on other worlds must include three determinations. The putative life form must be shown to consist of a more highly organized state than its surroundings. It must be shown to transform free energy in a form available to it, to maintain its highly ordered state, adjust to its environment, and perform work at some level. And ultimately it must be shown to reproduce itself in a manner which preserves all the information necessary to perpetuate the living state through successive, individual replications of the entities from which they were replicated. Our definition excludes notions of evolution through time or globally distributed systems, not because these concepts are irrelevant, but because they are not useful in identifying living entities at a fixed point in time in a local habitat.