

Chapter 14

The Future and Fate of Living Systems



The future of life on Earth and elsewhere in the Universe is the least studied of the three fundamental questions posed by NASA's Astrobiology Roadmap (Des Marais and Walter 1999; Des Marais et al. 2003, 2008). A lack of focus on this question raises two concerns. First, in a sense, the future of life is the question that has the greatest practical significance, since an ability to anticipate the consequences of human actions for the biosphere on Earth and wherever humans may come in contact with alien life in the future, should be a critical consideration in formulating policies for human activities on Earth at present and exploratory strategies for the future. The only one of the Roadmap's seven Goals and Objectives (#6) that relates to the future of life focuses narrowly on the fate of ecosystems and the evolution of microbes on Earth and in alien environments. The biosphere is now being changed so rapidly by anthropogenic forces, though, that the bigger and more immediate question is the general fate of groups of organisms, including especially those with the greatest environmental impact (Tong 2000; Woodruff 2001). This might also include an alteration of the genetic code (Xue and Wong 2017), intended or unintended. Secondly, on planetary systems older than the Solar System, there is little reason to doubt that life has emerged in some cases, and therefore had longer to evolve than on Earth. The question may then be asked whether the history of life on Earth provides insights into the fate of living systems that have had longer to unfold.

14.1 Evolutionary Alternatives

We propose that the history of life on Earth reveals consistent patterns that can be grouped as a working formalism into one of three scenarios: taxonomic groups either (1) reach a stable *plateau* from which they do not deviate for a long to indefinite period of time; (2) they *collapse* into near or total extinction; or (3) they undergo *transition* to a form of life with dramatically new features—after which a new round of evolution radiates into new forms, each of which again follows one of the three

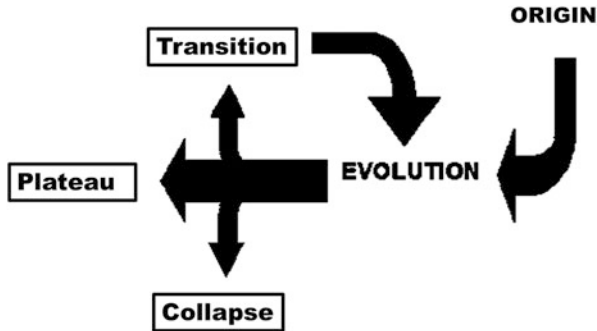


Fig. 14.1 Generic scheme for the cycle of evolution. The point at which life begins is a matter of definition. Once underway, life diversifies through evolution, with different taxa progressing ultimately to either collapse and extinction, a plateau phase leading to prolonged stability, or a radical transition to a new precursor that itself then radiates into a variety of forms, each with the same set of potential fates

scenarios. These interrelated possibilities are shown in Fig. 14.1. Each of these scenarios is considered below, with examples from the history of life as we know it.

14.1.1 Plateau

Organisms that occupy stable environments are subjected to stabilizing selection, which minimizes variation and optimizes adaptation over time (Campbell 1996). So long as the environment remains constant, form and function persist relatively unchanged. Hence, over geological time spans characterized by relatively constant environmental conditions, organisms tend to show little modification from the ancestral forms that emerged when they first arose. If that origin occurred as the consequence of punctuated equilibrium (Eldredge and Gould 1972), emphasis over the vast majority of the taxon's life span will be on equilibrium. Even in changing environments, highly successful and robust biological features may be retained. Evolutionary plateaus are the result.

The most obvious examples of the plateau scenario are life's most ancient surviving organisms, the bacteria and Archaea (Altermann and Kazmierczak 2003). Many microbes are likely unchanged from very early in their history. Cyanobacteria, though doubtlessly possessing a more elaborate photosynthetic machinery than the earliest versions, have remained virtually unchanged ecologically and morphologically for over two billion years (Altermann and Schopf 1995). A particularly good example is sulfur-cycling fossil bacteria from Western Australia, which are markedly similar in microbial morphology, habitat, and organization to their modern counterparts (Schopf et al. 2014). Among the plants, once they invaded the land, bryophytes quickly developed a morphology and physiology that has

remained constant for at least 360 million years (Hueber 1961; Karssilov and Schuster 1984).

Among the invertebrates notable for their evolutionary longevity are crustaceans such as the horseshoe crab (Xia 2000), insects such as ants (Grimaldi and Agosti 2000), and mollusks such as the nautilus (Landman 1987). Among the vertebrates, the sharks emerged during the early Devonian and developed some unusual physiological features that have remained relatively stable for 400 million years (Lisney and Collin 2006; Miller et al. 2003; Speers-Roesch et al. 2006). Likewise, the turtles emerged in the late Triassic with a highly successful defensive morphology that has preserved them relatively unchanged for 200 million years (Krenz et al. 2005; Pritchard 1979).

The history of life on Earth leaves several unanswered questions about the Plateau scenario. First among them is whether evolutionary plateaus remain stable indefinitely as long as the environment does not change. Can genetic drift give rise to change even in unchanging environments? What are the critical factors that promote survival of some forms through global catastrophes, such as the persistence of bryophytes and sharks through the Paleozoic-Mesozoic (P-M) boundary, and the survival of turtles through the Cretaceous-Tertiary (K-T) transition?

14.1.2 Collapse

Biologists have long recognized that most taxa have finite life spans; hence the majority of species that have ever lived have become extinct (Eldredge 1985; Woodruff 2001). Collapse, therefore, is the ultimate fate of most forms of life. This presumably reflects the fact that even optimal adaptations are essentially irreversible, and sooner or later circumstances will change to the point that the basis for past evolutionary success becomes maladaptive. Alternatively, previously well-adapted forms may simply be displaced by more highly adapted competitors. Or, precipitous events may lead to a relatively sudden collapse, as in the global catastrophes that mark several prominent paleobiological boundaries.

The stromatolites dominated the biosphere for three billion years, but disappeared at the end of the Proterozoic (Cowen 1995) except in a few scattered niche environments such as Shark Bay, Australia. The Ediacaran fauna provided numerous experiments in animal morphology over a 40 million year period just prior to the Cambrian, but few representatives survived into the Paleozoic (Cowen 1995). With the advent of the jawed fishes, the placoderms came to dominate the early Devonian seas, but were displaced entirely by unarmored but more resilient competitors by the end of the Devonian. Dinosaurs rose to prominence during the Mesozoic but were exterminated precipitously by the K-T catastrophe. It has been estimated that extinction is now occurring on an unprecedented scale, accelerated by the impact of human activity on the biosphere (Tong 2000; Woodruff 2001; Braje and Erlandson 2013). The relatively sudden disappearance of the mammalian megafauna in North America has been attributed to the arrival of humans, though the precise

role played by human-megafaunal interactions remains controversial (Barnosky et al. 2004; Brook and Bowman 2002; Diniz-Filho 2004; Johnson 2002; Remmert 1982). And the human species itself is the lone survivor of a number of hominids that appear to have been unable to compete with *Homo sapiens* during the late Pleistocene and early Holocene (Kaifu et al. 2005; McBrearty and Brooks 2000).

The question of causation is the one most relevant to the Collapse scenario. What is the relative importance of maladaptation and competition in precipitating extinction? Does collapse ever occur due to genetic drift, absent precipitating competition or abiotic changes? How common is Collapse, even in relatively stable environments?

14.1.3 Transition

According to the punctuated equilibrium model of the origin of species (Eldredge and Gould 1972), most new taxa come into existence through relatively rapid transitions from ancestral forms. The power of directional selection to drive adaptive change when either the biological or abiotic environment is altered compels often drastic and rapid evolutionary changes (Eldredge 1985; Elena and Lenski 2003; Reznick and Ghalambor 2001). Transition thus represents a third scenario among the fates that befall life.

Major transitions in the history of life that emphasize information transfer and hierarchical organization have been outlined by Szathmáry and Smith (1995). Highlights that affect the nature and biodiversity of life on Earth include the emergence of a metabolic machinery for photosynthesis, the endosymbiotic creation of eukaryotic cells, the origin of calcified exoskeletons, and reproductive innovations that drove protistan diversification in the late Proterozoic (Cowen 1995; Margulis and Sagan 1995). The Cambrian explosion generated several major transitions, the most successful of which appear to have been the origin of the arthropods and mollusks. The vertebrates represent a somewhat later but equally successful transition. Among the vertebrates, transitional innovations include the development of jaws, leading to the formulation of more complex food webs with larger and more active animals; the evolution of lungs, leading ultimately to the colonization of terrestrial niches by organisms with higher metabolic rates supported by the richer supply of oxygen; development of the amniotic egg that freed reproduction from restriction to aquatic habitats; and endothermy, which enlarged the range of climates and niches which animals could occupy.

The Transition scenario raises questions as well. Is transition inevitable, given enough time under hospitable conditions? Is transition even possible for most forms of life, especially for macrobiota, if the environment changes radically over a short time span, as appears to be occurring now in the global biosphere? A study of the survivors of past mass extinction events may lead to instructive insights in that regard (Ward 2001).

In rare cases, the transitions have been great enough to transcend biology. The evolution of photosynthesis altered the global atmosphere, while redirecting the course of evolution itself. Multicellularity transformed life from an exclusively microscopic domain, to macroscopic and megascopic dimensions (Beck and Irwin 2016; Schulze-Makuch and Bains 2017). The evolution of nervous systems gave rise to “neural individuals” (Jablonka and Lamb 2006), which evolved intelligence to varying degrees. The combination of intelligence and sophisticated communication with manual dexterity enabled humans to develop technology, which has so amplified biological capabilities that the Earth in its entirety is being transformed.

14.2 Evolution of Intelligence

Intelligence has evolved independently several times during the evolution of life on Earth (Irwin and Schulze-Makuch 2008, 2011). Four specific examples of the independent evolution of a transforming degree of intelligence are provided by the social insects, cephalopods, cetaceans, and primates.

Insects evolved on land during the Silurian, though the eusocial ants, wasps, and bees apparently did not diversify until the Mesozoic, ~150 million years ago (Moreau et al. 2006; Schultz 2000; Wilson 1980). Biologists do not rate the social insects as intelligent in the conventional sense, and as individual organisms they certainly do not meet the usual criteria for intelligence. But in the aggregate, they display some of the features that would suggest intelligence, were they a single organism. They build elaborate housing, divide labor, communicate symbolically (in the case of bees), radically modify their microenvironment, grow food (in the case of fungal cultivating ants), domesticate other species, wage war, and cooperate for the good of the whole (Brady 2003; Mueller et al. 1998; Wilson 1980). As such, they represent a case of social intelligence, which obviously has been subject to strong group selection.

Cephalopods have achieved the pinnacle of intelligence among all the invertebrates (Young 1964). They diverged from other mollusks in the late Cambrian, became numerous in the Ordovician, and suffered a cataclysmic decline during the Permian crisis, with only the octopi, squids, cuttlefish and a few nautiloids surviving to the present day (Cowen 1995; Landman 1987). Those forms, however, are active benthic foragers and predators, with highly developed tactile and visual sensory abilities, and elaborate motor systems for the control of jet-like propulsion, complex mouth part movements, and fine manipulation of each of their eight appendages.

The Cetaceans probably diverged from their terrestrial ancestors near the start of the Cenozoic 65 million years ago, since the oldest fossil whale has been dated from the early Eocene, ~55 million years ago (Bajpai and Gingerich 1998). Whales have the largest brains that have ever evolved, the brain of the blue whale measuring nine times the size of the human brain. By the Miocene (~20 Ma), cetacean brains had achieved essentially their modern size (Jerison 1973). Most of the enlargement of the brain in cetaceans reflects a huge elaboration of the neocortex beyond the

sensorimotor primary projection areas (Hof et al. 2005; Lilly 1978). While cetaceans have essentially lost their olfactory sense, the pyriform cortex has not been reduced, perhaps reflecting compensatory enhancement of their gustatory sense. Anatomical changes have enabled the sound production that forms the basis of a sophisticated echolocating capability and a communication system whose full complexity is not yet known (Herman 1986).

Primates diverged from ancestral insectivores early in the great mammalian radiation at the start of the Cenozoic, about 65 million years ago (Cowen 1995). The evolution of hominids shows a relentless increase in brain size, characterized mainly by expansion of the neocortex, and in humans by increase in the prefrontal lobes in particular (Byrne 1995). The evolutionary acceleration in brain size occurred in the anthropoids much more recently than in the cetaceans—the qualitative expansion of the human brain over that of the chimpanzee occurred within the last 6 million years, while neocortical expansion in the Cetacea exceeded that of humans probably 20 Ma earlier (Jerison 1973). The acceleration of neural complexity in these two very distantly related mammals has thus been a completely independent event. By 4 million years ago, humans had split from chimpanzees, and begun to diversify into a number of species (Cowen 1995). *Homo sapiens* is the sole survivor of several competing human lineages, achieving modern morphology and brain size ~200,000 years ago (Jerison 1973; McBrearty and Brooks 2000).

From an astrobiological perspective, the relative infrequency with which intelligence has arisen is noteworthy. Even among those species that have developed the capacity for insight such as chimpanzees, that ability appears to be underutilized in their natural habitat (Byrne 1995). It may be that high intelligence has sufficient negative attributes that its evolution is not commonplace. Thus, if and when complex living entities are found on other worlds, it should not be taken for granted that intelligent forms will be among them.

14.3 The Rise of Technological Competence and Its Fate

An equally compelling though lesser mystery is why technology has developed so rarely among species that have the intellectual capacity for it. Technology (the use of energy, tools, material, and information to amplify the impact of a species on its environment) has emerged fully in only the human species. Crude prototypes can be seen in other species, particularly among the primates and some birds. The social insects show limited forms of technology, in the construction of elaborate housing and limited domestication of other species. But only humans have fully exploited technology to the point of significantly changing their environment beyond their purely biological impact. A particularly pertinent issue raised by the human example is whether any technologically capable form of life will inevitably metamorphose into something else—perhaps (a) custom-designed, genetically engineered organic beings, (b) totally mechanized forms with artificial intelligence, or even (c) virtual (non-material) entities.

Technology for the first alternative is advancing rapidly. The pace at which humans create genetically modified species (Xue and Wong 2017), perhaps to the point of giving rise to new species, and/or enabling their own custom-designed genetic transformation, at this time appears to be constrained more by social, political, and moral attitudes than by technological capabilities. Inasmuch as social, political, and ethical views change over time, the trend to engineer new organic beings—non-human, human, or both—is likely to continue if not accelerate.

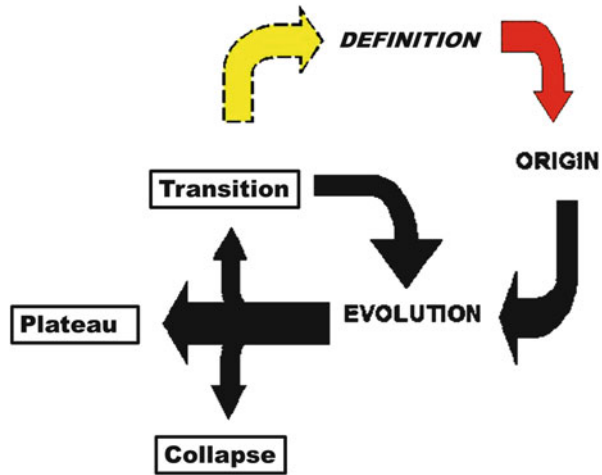
The second alternative leads to the question of the relationship between evolving machines and their human innovators. A symbiotic fusion is one possibility, and is already in the early stages of occurring (Clark 2003). Artificial limbs, sensory aids, and implanted mechanical devices such as pacemakers reflect this trend. An alternative relationship would be an ongoing co-evolution of humans and machines, with increasingly comparable capabilities of organic and mechanical forms but without significant fusion between the two. The advancement of robotic technology illustrates this trend. In this case, the ultimate possibility of replacement of organic by mechanical beings clearly looms. How rapidly (and how peacefully) the mechanical entities will replace their organic predecessors, is clearly a compelling question. The ability of machines to compete with humans depends ultimately on the capacity of the former for feature extraction, abstract processing, and anticipation—in short, to be intelligent. While it is commonplace to argue that computer intelligence is merely decades away, fundamental arguments that digital computers can never be intelligent have been advanced (Chyba and McDonald 1995; Hawkins and Blakeslee 2005; Searle 1984).

The third possibility is reflected in the growing sophistication of human-engineered virtual reality. As human biology becomes increasingly dominated by and subservient to cognitive experience, the motivation to manipulate that experience by artificial means is likely to grow. Once the ability to create enriching and satisfying virtual realities becomes feasible, and the logistical problems of sustaining sufficient other (social, economic, and political) requirements of the material world to support the virtual world are solved, organic humans would become progressively superfluous. The argument has been pushed even further by Bostrom (2003), who suggested that humans may have reached a “posthuman” stage capable of running a significant number of simulations of their own evolutionary history (or variations thereof), and that we might already be living in one such simulation.

In the event that technologically-capable species spawn mechanical adjuncts to their own biology, the nature of life and the forces that influence its evolution may be radically altered. In such cases, depending on the nature of the descendent forms, an adjustment in those definitions of life that emphasize organic complexity and evolution by natural selection may be required (Grinspoon 2003; Lwoff 1962, see also Chap. 2), as indicated in Fig. 14.2.

The benefits of considering the fate of life in a formal way may thus be not only to determine whether the scenarios observed over the course of life on Earth represent exhaustive examples of the fate that can befall living organisms anywhere, but to reexamine clearly the definition of life itself.

Fig. 14.2 The cycle of evolution with a redefinition of life. In the case where life evolves technological capabilities, the prospect of non-organic organisms and artificial intelligence requires a reconsideration of the definition of life



14.4 Application to the Possibility of Life on Other Worlds

We and others have argued previously that if life exists elsewhere in our Solar System—and we rate the probability that it does so moderately high (Irwin and Schulze-Makuch 2001; Irwin et al. 2014)—it almost surely exists in a microbial to small and relatively ancestral form. This is because conditions on the surfaces of all the other planets and satellites, with the possible exception of Titan (Campbell 1996; McKay and Davis 1999; Schulze-Makuch and Grinspoon 2005), are not favorable for complex liquid-based biochemistry. Whatever life may have arisen on (or been transported to) them, it would be expected to have become sequestered in stable, environments once life on the surface became untenable. Since subsurface habitats favor small organisms (Sect. 8.2), life on such bodies would likely be microbial to small, and probably near its ancestral state, or whatever state it was in when subsurface existence became mandatory.

Lack of knowledge about the nature of planetary bodies in other Solar Systems that could harbor life severely constrains informed speculation about the nature of living systems beyond our own Solar System. Of the over 3800 extrasolar system planets confirmed to exist as of this writing, most are giant planets orbiting near their central stars (Méndez 2015), presenting formidable challenges to the existence of life. Because there are also solar systems with planets more distant from their central stars (and more will be discovered in the future), many of them perhaps containing water or other liquids at temperatures where complex biochemical reactions can proceed, the chances are greater on bodies such as those that complex ecosystems could develop, leading to multiple trophic levels, hence complex macrobiota. To the extent that many planetary bodies resemble the cold arid surface of Mars, or the icy satellites of the outer planets, life on them would likely be subterranean, rendering the plateau scenario most likely.

If the conditions that enabled the evolution of complex life on Earth are indeed as rare throughout the Universe as they are in our own Solar System, so too might be the prevalence of complex life. However, we do not yet know that complex life *cannot* arise under conditions exotic by Earth standards (Schulze-Makuch and Irwin 2006), so a generalization about the rarity of complex life throughout the Universe (Ward and Brownlee 2000) is not yet justified.

We have previously defined life in a way that avoids limitation to the carbon-based, water-borne form of living organisms that currently inhabit Earth (Schulze-Makuch 2002). At the same time, our analysis of physicochemical constraints suggests that carbon-based, water-born life is by far the most likely form for life to take (Chaps. 6 and 7). In as much as numerous planetary bodies in our Solar System have, or have had, conditions for the origin and evolution of life as we know it (Irwin and Schulze-Makuch 2001), we suggest that planning continue for ~~space~~ space exploratory missions ~~continue~~ to aquatic subsurface habitats on Mars, Ceres, Europa, and the other satellites of the outer planets, where ecosystems may be found to persist largely in a plateau stage of evolution. At the same time, the atmosphere of Venus (Grinspoon 1997; Schulze-Makuch et al. 2004) and the surface or subsurface of Titan (McKay and Smith 2005; Schulze-Makuch et al. 2005a, b) may offer habitats for forms of life quite unknown to us.

Where extreme geophysical transformations have occurred over the history of a planetary body, as on Venus and Titan, forms of life quite different from those known on Earth could be the outcome. Thus, the definition of life that guides our search for it needs to be generic enough to consider all the possibilities, including those difficult to envision by analogy with life on Earth.

14.5 Chapter Summary

With robotic missions to Mars and the outer planets increasing our knowledge of other potential habitats for life, and with astrobiology becoming an institutionalized interdisciplinary field of study, the time has come to formalize models for the life history of biospheres in their entirety. We propose a generic framework for considering the history and fate of life wherever it occurs in the Universe. Using analogs from the history of life on Earth, we extrapolate to a variety of circumstances likely to be encountered by life on other planetary bodies. The most common fate of life is evolution to a “plateau” state in which life stabilizes into forms optimally suited for persistently unchanging environments. Assuming that life on other worlds is most often microbial and ancestral, this is likely the most widespread scenario. “Collapse” occurs when evolutionary changes produce forms incapable of adapting to altered biotic or abiotic conditions. Total extinction is a special case of collapse, but near extinction leading to survival of only a few, significantly altered descendent forms is another, perhaps more common outcome of the collapse scenario. “Transition” occurs when evolution leads to biotic or environmental changes sufficient to generate radical transformations. The climactic evolution of neural complexity and

manual dexterity, leading to symbolic language and technology in humans raises the question of whether any technologically capable form of life will inevitably be transformed through codependency with machines and external data processing and storage, into entities that require a redefinition of life. If the fate of living systems as we propose here holds generally for other worlds, it is most reasonable to expect that life will be found to be simple and near its ancestral state on worlds that solidified into a constant, constraining physical condition early in their history, such as the icy satellites in our Solar System. The transition to complex life, with the possible evolution of intelligence and rise of technology, is likely to be found only on worlds which have experienced a history of multiple physical transformations and persist in a heterogeneous state.