# NOTES

## Initial Epigraphs

1. Chiang (2020), p. 57.
2. Thompson (1917), p. 160.

## Prologue

1. For the paper that changed my life, see Hazen et al. (2008).
2. I first presented the idea of the Never-Life Earth in an article for *Aeon*—see Judson (2022).

## PART ONE: THE NATURE OF LIFE

1. For "We have been thinking . . . ," see Osborn (1917), p. xv.

## A Surprising Fact

1. For "The difficulty of giving . . . ," see Lotka (1925), p. 7.
2. For an overview of previous efforts to define life see, for example, Luisi (1998).
3. For the human brain having particular structures for recognizing life that are distinct from those that recognize nonlife, see Perani et al. (1995) and Giese and Poggio (2003).
4. I found the book by Michael Welland at the wonderful Ivy Bookshop in Baltimore.
5. Bagnold was also a soldier. With the outbreak of the Second World War, his experiences in the desert in the 1920s and 1930s, which had been entirely

recreational, were put to military use. With the approval of the British high command in the region, Bagnold created, and was in charge of, the Long Range Desert Group, a small band of soldiers that, attacking from the desert, repeatedly ambushed the Italian forces in Libya. The Italians were taken utterly by surprise, as they had assumed that the desert was impregnable. For Bagnold's account of these exploits, as well as his earlier explorations of the desert, see Bagnold (1990).

## Revelations of the Sands

1. For "Here, where there existed no animals. . . ," see Bagnold (1990), p. 103.
2. For characteristics of dunes depending on the regimes of wind and sand, see Wasson and Hyde (1983).
3. For rates of barchan movement, see Finkel (1959) and Vermeesch and Leprince (2012).
4. For singing sands, see Welland (2009), p. 171 and Bagnold (1973), chapter 17.
5. For barchan dunes growing, moving, reproducing and repairing themselves, see Bagnold (1935), p. 315.
6. For particles of sand behaving differently from gravel or dust, see Welland (2009), p. 10.
7. For dunes of gypsum, see Welland (2009), p. 7. Although I do not know of dunes of sugar, Earth does have dunes of ice crystals—see Bagnold (1973), p. 221—and of basalt—Tirsch et al. (2012).
8. For the majority of Earth's sand grains being composed of quartz, see Welland (2009), p. 4.
9. For sand being self-accumulating, see Welland (2009), p. 158.
10. For humans being 99.7 percent SPONCH, see Sterner and Elser (2002), p. 3. (Note that these authors give the stoichiometric formula for a human, from which I calculated the percentage. I have rounded up to 99.7 from 99.656.)
11. For small sand grains being able to shift much larger grains, see Welland (2009), p. 156.
12. Flows of protons are also important for the energetic processes of life, but to keep things simple I won't talk about that here. For further information see, for example, Lane (2015).
13. Today, *reduction* refers to the process of *gaining* electrons, which is the opposite of what you might expect. Apologists for the terminology point out that a gain in electrons results in a decrease in the electrical charge, or the *oxidation state*, of the atom or molecule—but for the novice, that hardly helps. *Reduction* comes from the Latin word *reducere* and has its origins in the alchemical practices of early seventeenth-century Europe, a time when Latin was the language of scholarship. In Latin, *reducere* means "to lead back"; alchemists were performing experiments that would subject a metal, such as silver, to a variety of chemical onslaughts before reducing it—that is, leading it back—to its original state, often by heating. See Newman (2006), p. xiii. Under the right chemical circumstances, heating metals can in fact cause a reduction in the modern sense—that is, a gain of electrons. *Oxidation*, meanwhile, refers to the process of *losing* electrons—yet this process need not involve oxygen. (The term *oxidation* arose because the phenome-

non was initially identified through reactions involving oxygen and was thought to depend on it—but that is not the case.) Further confusing matters, in the course of one of these reactions, a reducing agent will become oxidized, and an oxidizing agent will become reduced. *Argh!*

14. For making and destroying a mass of ATP that is roughly equal to your body weight, see Buono and Kolkhorst (2001). These authors also show that during a marathon, an elite runner may create and destroy more than their body mass of ATP merely during the race's roughly two-hour duration.
15. Estimates of dune ages are from Bagnold (1973), p. 219.
16. For dunes dwindling if the sand is not replenished, see Bagnold (1973), p. 199.
17. There are several other ways to kill a dune. Big storms can wash away coastal dunes—see Flor-Blanco et al. (2021). Vegetation can hold sand in place and prevent it from moving (Bagnold, 1973, pp. 183–184). The same effect can be achieved more crudely by pouring tarmac on top of the sand (Welland, 2009, p. 167), or spraying petroleum mulch (Azoogh et al., 2018). Spreading pebbles on top of a dune will cause the sand to be scoured from beneath them; at the same time, the presence of the pebbles keeps incoming sand grains moving and prevents them from piling up (Welland, 2009, p. 167). Methods to baffle and redirect the wind have also proved effective at destroying dunes, thereby preventing them from advancing on houses and schools—see Meunier and Rognon (2000).
18. Rudolf Schoenheimer and his colleagues were among the first to show that molecules are perpetually built and unbuilt, a discovery that, at the time, was surprising—see Schoenheimer (1942).
19. Estimating the turnover of the skeleton of an adult human is tricky, because different types of bone are rebuilt at different rates. Although in a given year, roughly 10 percent of the skeleton may be replaced (Manolagas, 2000), this cannot simply be extrapolated to give an average replacement of the whole skeleton once every decade. Instead, during the course of a decade, one quarter of the skeleton (the "fast" bone type) may have been demolished and rebuilt several times, whereas the remaining three quarters (the "slow" bone type) will have been remodeled only in part. Even this is only a rough approximation, however, because different bones, and different parts within each bone, may be subject to different rates of turnover—see Parfitt (2002). But the essential point is that bones are amazingly dynamic structures, unbuilt and rebuilt throughout life. With death, obviously, the flow stops, and the bone becomes static.
20. When the flow stops, most lifeforms die. But some—certain bacteria, for example—can go into a state of suspended animation, like a sand dune where the wind has ceased to blow. For such lifeforms, how long this state can last remains unknown. Experiments in the laboratory have shown that, under particular conditions, the suspension can continue for decades, and that when the flow resumes, so do the lifeforms. The assumption is that if the flow were to cease for long enough, the constituent molecules would eventually begin to deteriorate, but when that would become problematic is unclear. Some bacteria have been revived after apparently having spent hundreds of thousands, or even millions, of years frozen in ice or permafrost, or even trapped in salt

crystals—but whether the flow was fully stopped throughout that time is not known. For further details, see Hallsworth (2022).

21. For "I think the desert dunes . . . ," see Bagnold (1935), p. 315.
22. For a fascinating discussion of why the language of machines is unsuitable for describing the structures of cells, see Nicholson (2019).
23. For Georges Cuvier comparing life to a vortex (*tourbillon*), see Cuvier (1817), p. 13.
24. For "in a stream of energy . . . ," see Sherrington (1940), p. 82. For an overview of the history of thought with respect to lifeforms as energetic structures, see Nicholson (2018).

### Servants of Energy

1. For "In all our doings . . . ," see Lotka (1925), p. 340.
2. For the coining of *entropy*, see Clausius (1865), p. 390.
3. The idea that entropy is a tendency to disorder is also very much disliked by some physicists. See, for example, the preface of Kondepudi and Prigogine (1998). These authors remark, "Since Ludwig Boltzmann (1844–1906) introduced a statistical definition of entropy in 1872, entropy is associated with *disorder*. The increase of entropy is then described as an increase of disorder . . . This has unfortunately led to the view that the consequences of the Second Law are self-evident or trivial. This is, however, not true." Many thanks also to Harvey Leff for a helpful conversation on this topic.
4. The term *dissipation* was introduced to physics by William Thomson in 1852—see Coopersmith (2015), p. 287. (The word itself is far older.)

### A Sketch of the Argument

1. I first presented the idea of energy expansions in a scientific paper published in *Nature Ecology and Evolution*—see Judson (2017).

## PART TWO: THE CO-CREATION

### Rock

1. For "I have sprung from . . . ," see Rolston (1971), p. 83.

### The Making of the Earth

1. For "If you wish to make . . . ," see Sagan (1980).
2. For dust drifting down from the heavens, see Gardner et al. (2014).
3. For meteorites containing grains of ancient stardust, see Nittler (2003).
4. For the age of the universe, and how this is known, see Page (2020).
5. For the time of the formation of the Solar System, see Amelin and Ireland (2013) and Connelly et al. (2017).
6. For the first stars not having planets, see Page (2020).
7. For an overview of the ways that atoms of different elements can form, see Sneden et al. (2008). Note that the situation is even more complex than I

have described. It's not just that each element has its own history. Atoms of a given element come in different forms known as isotopes, and each isotope has its own history. If someone had told me this when I was first studying chemistry, I would have been transfixed: I find the celestial beginnings of matter, and the unique histories of the different kinds of atoms, to be awe-inspiring.

8. For tiny diamonds, see Verchovsky et al. (2006). For fragments of ice, see Léger et al. (1979). For other kinds of mineral dust formed in the death throes of stars, see Nittler (2003).
9. For protoplanetary disks containing abundant water see, for example, Hogerheijde et al. (2011) and Ceccarelli and Du (2022). For the presence of carbon monoxide, see Zhang et al. (2019); for iron sulfide minerals, see Kama et al. (2019).
10. Estimates suggest that more than 400 million dead stars contributed materials to the Solar System—see Fiore et al. (2024).
11. For the early formation of Jupiter and Mars, see Kruijer et al. (2017) and Elkins-Tanton (2018), respectively.
12. For the possibility that the energy of the collision of two planets caused large fractions of both bodies to vaporize, see Lock and Stewart (2017) and Lock et al. (2018).
13. Exactly how Earth became endowed with water remains a matter of debate. However, recent evidence suggests that much of the planet's water was acquired during the process of its formation, up to and including the collision between two planets that created the Earth-Moon system, with relatively little water being delivered after this event—see, for example, Greenwood et al. (2018). Note, however, that although oceans of water are one of the most notable features of Earth, water represents less than one percent of the planet's mass, so Earth is arguably quite dry—see Marrocchi and Beck (2022). More striking, perhaps, than the oceans: The surface of the Earth permits the presence of all three phases of water—liquid, solid, and gas—and has done so for more than four billion years. Within the Solar System, this is unique.
14. For the extreme scarcity of rocks that date back more than 3.8 billion years see, for example, Bowring and Williams (1999).
15. Gem zircons can be clear, red, yellow, orange, blue, green, or brown. Which color they are depends on details of their composition (they sometimes contain traces of elements beyond their chief constituents of zirconium, silicon, and oxygen) and whether they have been heated.
16. For the geological history of the Jack Hills zircons, see Harrison (2009) and Nebel et al. (2014).
17. Methylene iodide and sodium tungstate are examples of "heavy" liquids. Many thanks to Simon Wilde for explaining the process of zircon hunting to me.
18. For ancient zircons hinting at the presence of land, oceans of water, and temperate climates, see Cavosie et al. (2005) and Harrison (2009).
19. For lifeforms floating in the surface waters of the oceans, see Nisbet and Fowler (2014); for hot springs, see Djokic et al. (2017); for rocks in deep waters, see Staudigel et al. (2015).
20. For the possibility that the teeny-tiny tubes in rocks from northern Québec

were made by bacteria, see Dodd et al. (2017). Not everyone agrees that these tubes are evidence of life: McMahon (2019), for example, argues they may equally have formed through nonlife processes.

21. For suggestions of life in ancient rocks from Greenland, see Rosing (1999) and Hassenkam et al. (2017).
22. For a 4.1-billion-year-old zircon that might house the remains of early lifeforms, see Bell et al. (2015).
23. For the changing luminosity of the Sun over time see, for example, Gough (1981); for higher levels of ultraviolet, see Zahnle and Walker (1982).
24. For the oceans being more voluminous four billion years ago, see Pope et al. (2012).
25. This assumes that the total number of seconds in the year has remained the same (31.56 million seconds), and only the duration of the day-night cycle has changed. Reconstructions of past day lengths suggest that 620 million years ago, it was around 21.9 hours (Williams, 2000) and 1.4 billion years ago, it was around 18.6 hours (Meyers and Malinverno, 2018). The reason that the day length has increased with time is that the gravitational tug of the Moon causes tides; over long spans of time, the tides act as a slow brake on the planet's rotation. (The Sun also contributes to tides, but the effect is far smaller.) Because the Earth and Moon are rotating around each other, the slowing of the Earth causes the Moon to move away. If it did not, then the angular momentum of the Earth-Moon system would not be conserved. The rate of recession has varied, but today the Moon is receding at about 3.8 centimeters (1.5 inches) per year—see Dickey et al. (1994). If the rotation of the Earth were to accelerate—perhaps owing to a massive avalanche deep within the planet—the Moon would be pulled closer, and the length of the day would again decrease. This may in fact have happened in the past—see Machetel and Thomassot (2002).
26. Many thanks to Kevin Zahnle for providing an estimate of the day length for the early Earth.
27. The debate over the timing and number of asteroid impacts has two dimensions. The first concerns whether there was a *late-heavy bombardment*—a postulated episode of intense asteroid impacts around 3.9 billion years ago. This idea, which was based in part on analyses of rocks collected from the Moon in the 1970s by American and Soviet missions (see Koeberl, 2006), has recently been challenged—see Boehnke and Harrison (2016) and Morbidelli et al. (2018). These authors have suggested that the late-heavy bombardment is an artifact of the data, and that while asteroid impacts were certainly an important phenomenon in Earth history, there was no concentrated pelting but rather a gradual tailing off. The second question is whether asteroid impacts would have sterilized the Earth, thus delaying the date when life could have taken form. Current views suggest that while impacts could have been problematic for lifeforms on the surface, lifeforms that were deeper within the planet would probably have been protected. See, for example, Abramov and Mojzsis (2009).
28. For evidence that the Earth had a magnetic field by 3.45 billion years ago, see Tarduno et al. (2010); for conflicting evidence regarding its earlier establishment, see Tarduno et al. (2015) and Borlina et al. (2020).

29. Many thanks to John Bohannon for creating a journey-length calculator for a time machine that travels at one thousand years per second.
30. For the human circadian rhythm being very close to twenty-four hours, see Czeisler et al. (1999) and Wright et al. (2001).
31. For difficulties adjusting to a day length that is less than twenty-four hours, and the resulting cognitive impairment, see Wyatt et al. (1999) and Dijk et al. (2001).
32. The impact that formed the Moon's Imbrium Basin is thought to have happened around 3.92 billion years ago—see Nemchin et al. (2021).
33. For the recent formation of the Pleiades see, for example, Gossage et al. (2018).
34. Mars is thought to have had bodies of liquid water in its remote past. But whether these were present as early as 4.2 billion years ago remains unknown. See Carr and Head (2010).
35. For the temperature and pressure at the surface of Venus, see Taylor et al. (2018).
36. For speculations about the nature of the young Venus and the possibility that it once had oceans, see Way and Del Genio (2020).

### Contemplating the Mystery

1. For the diversity of bacteria and archaea see, for example, Hug et al. (2016).
2. In case you're wondering, the ratio between a bacterium and a blue whale, and between a human and the Earth, is on the order of $10^{23}$, or 100,000,000, 000,000,000,000,000, or one hundred thousand billion billion. This observation comes from Schulz and Jørgensen (2001).
3. For examples of bacteria and archaea taking a variety of shapes, see Young (2006).
4. The claim that "most" bacteria and archaea live in biofilms comes from Flemming and Wuertz (2019).
5. For the composition of a biofilm matrix, see Flemming et al. (2016).
6. For a discussion of dental plaques as biofilms, as well as the numbers of species these films include, see Kuramitsu et al. (2007).
7. For the naming of the archaebacteria, see Woese and Fox (1977); for the abbreviation to archaea, see Woese et al. (1990).
8. In fact, the contrast between bacteria and archaea is far more profound than that between an elephant and a tulip. There is no comparison between familiar large lifeforms that can give a good sense of how different, biochemically speaking, bacteria and archaea are from each other.
9. For a survey of where archaea live, see Chaban et al. (2006).
10. The word *geovore* was suggested by my husband, Alexandre Courtiol—many thanks. The formal scientific term is *chemolithoautotroph*; however, as well as being Germanic in its agglomerated length, this word is not used in a consistent way in the scientific literature, so I'm going to avoid it. But in case you're interested, the word roughly translates as "self-feeding rock eaters." The *chemo* signifies that they do not require light (though in a broader sense of course all lifeforms are *chemo*, an objection that was raised by Baas-Becking and Parks, 1927). Technically, geovores should perhaps be called inorgivores, because they live from inorganic compounds. Although at the start of

the planet's history, the only source of inorganic compounds would have been the Earth, this has changed over time. In the modern world, inorganic compounds are sometimes produced by lifeforms. But *inorganic* and *organic* are themselves troublesome words. In regular speech, organic implies living, while inorganic implies nonliving; but in the context of chemistry, they both have less intuitive connotations, with organic meaning "reduced" (replete with electrons) and inorganic meaning "oxidized" (poor in electrons). It is, therefore, possible to speak of "bioinorganic chemistry." This is not an oxymoron.

11. Winogradsky describes his sites of collection in Winogradsky (1887) and Winogradsky (1890).
12. The quotation from Winogradsky is my translation of the French original, "Une vérité nouvelle, d'une importance physiologique générale, est dès maintenant établie par mes expériences: c'est *qu'une synthèse complète de la matière organique par l'action d'êtres vivants peut s'accomplir sur notre planète indépendamment des rayons solaires."* See Winogradsky (1890), p. 275, emphasis in the original.
13. Winogradsky's insights developed in two stages. First, he realized that some of the bacteria he was studying intercept energy as electrons flowed between inorganic compounds—see Winogradsky (1887). Second, he discovered that such bacteria could build biological molecules from carbon dioxide and other inorganic materials—see Winogradsky (1890), thus being able to live from a diet of water, rocks, and air. His own term for such lifeforms was *anorgoxidants*—see Winogradsky (1922)—but it evidently didn't catch on. The experiments were completed and published between 1886 and 1890. In the course of this work, he studied sulfur bacteria, iron bacteria, and nitrifying bacteria. For an excellent, brief overview of his contribution to this topic, see Brock and Schlegel (1989).

## The Fracturing Wet Rock

1. For "If it were given me . . . ," see Huxley (1870), p. 404.
2. For "give a degree of activity . . . ," see Dana (1863), p. 51.
3. The idea that a fracturing wet rock might be a place where lifeforms could have emerged was first put forward by Michael Russell. Other authors have elaborated on this idea, especially William Martin, who drew my attention to the importance of microbial physiology, and Nick Lane, whose work with Professor Martin first drew me to the field. My description of the idea that the ultimate ancestor of all lifeforms was a fracturing wet rock is mainly a distillation of the work of Russell, Martin, and Lane, and their coauthors, as I understand it. The literature on this topic is extensive. However, for an early statement of the hypothesis, see Russell and Hall (1997); for an account aimed at a general reader, see Lane (2015); for a recent overview and refined argument, see Schwander et al. (2023).
4. For serpentinization causing the fracturing and breaking of the original rock, see Evans (2004).
5. Hydrogen is not the only candidate for the primal electron donor. Elemental iron (present in certain minerals) could potentially have functioned in this

respect, too—see Sousa et al. (2018). Even today, certain lifeforms can grow as electrons flow from elemental iron to carbon dioxide—see Daniels et al. (1987).

6. In a hunk of metal, all the atoms effectively pool their outermost electrons, creating a kind of mobile electron sea. If this seems abstract, perhaps reflect on the fact that, in some circumstances, the behavior of these subatomic particles is visible to you. The shiny look that metals have is due to this mobile sea of electrons interacting with light—see Atkins (1995), pp. 41–42.
7. For serpentinization in New Caledonia, Iceland, and Lost City, see Pisapia et al. (2017), Price et al. (2017), and Kelley et al. (2001), respectively.
8. For serpentinization being more widespread four billion years ago than it is today, see McCollom and Seewald (2013).
9. The point here is the overall shape of the process—the details are less important. Carbon dioxide could be replaced by carbon monoxide; hydrogen, by native iron in the rocks. Differences in details like these would not invalidate the idea that lifeforms emerged as a byproduct of a cascade of electrons onto carbon atoms.
10. Acetate is the *acetic* part of acetic acid, one of the main components of vinegar.
11. For the range of sizes of sand grains and how they would cover your thumbnail, see Welland (2009), pp. 8–10.
12. For the sorting of sand during the formation of desert dunes see, for example, Bagnold (1937) and Bagnold (1973), p. 168. (In contrast, the sand that makes up coastal dunes has been pre-sorted in the course of its journey to the beach—see Bagnold, 1973, p. 168.)
13. The number of carbon atoms in a bacterium is from Milo et al. (2010), BNID 103010, estimated for *E. coli*.
14. For biochemistry enthusiasts, these include coenzyme A, which is an ancient molecule that was almost certainly present in the first lifeforms, as well as flavin adenine dinucleotide (FAD), nicotinamide adenine dinucleotide (NAD), and nicotinamide adenine dinucleotide phosphate (NADP).
15. The study of carbon chemistry is the branch of science known as organic chemistry. Contrary to what you might expect, this has little to do with the chemistry of lifeforms—that's biochemistry. Organic chemistry, instead, is about the development of techniques for the laboratory and industrial synthesis of carbon compounds. The term *organic* here is a hangover from a time when carbon compounds such as urea, a substance excreted in urine, were thought to be exclusively produced by the processes of life—an idea shown to be false when the German chemist Friedrich Wöhler synthesized urea in his laboratory in 1828. Today, to a chemist, the phrase *organic carbon* refers to reduced carbon—that is, to carbon atoms that are freighted with electrons. Biological molecules such as sugars, fats, and DNA are organic molecules in this sense; but so are nonbiological molecules like plastics. This is in contrast with the carbon in carbon dioxide, which has given its electrons to oxygen. The carbon in carbon dioxide is, therefore, considered inorganic.
16. For the variety of carbon compounds in the Murchison meteorite see, for example, Sephton (2002).
17. For the insight that in addition to accelerating reactions, catalysts can serve

as channels, making some reactions much more likely than others, see Copley et al. (2007).

18. For experiments showing that mixing metals with simple carbon compounds in warm water gives rise to short chains of reactions, and that these reactions produce many of the small molecules that are central to the processes of all lifeforms, see, for example, Muchowska et al. (2019) and Mrnjavac et al. (2026).
19. For babies expecting an object to fall if it lacks support, see Baillargeon (2002).
20. For very small entities experiencing water as viscous and sticky, see Purcell (1977).
21. Bütschli droplets are named for Otto Bütschli, one of a number of scientists who, toward the end of the nineteenth century, became interested in this phenomenon. Others included Johannes Gad, Georg Quincke, Ludwig Rhumbler, Julius Bernstein, Herbert Spencer Jennings, and Alfonso Luis Herrera—see Jennings (1904). The rancid oil plus alkaline water was Bütschli's recipe, see Bütschli (1890), but a number of other mixtures, including egg white mixed with cod-liver oil, were found to produce similar results—see Jennings (1904).
22. For the "social" behaviors of Bütschli droplets, see Armstrong and Hanczyc (2013).
23. For a sketch of many dunes developing together, see Bagnold (1973), p. 218.
24. In the biochemistry of life, flows of protons are also essential; I have not spoken about this here because it adds another layer of complexity to an already complicated discussion.

## Objections and Caveats

1. For "Long before having arrived . . . ," see Darwin (1859), p. 171.
2. For the dimensions of the Selima Sand Sheet, see Maxwell and Haynes (2001).
3. Bagnold's description of the Selima Sand Sheet comes from Bagnold (1990), p. 66 ("vast monotony" and the struggling to stay awake), and Bagnold (1935), p. 271 (lack of pebbles, and the sand "sweeping over the surface from the north"). The year of the trip is given in Bagnold (1935), p. 260.
4. For the formation of sand sheets, see Bagnold (1973), pp. 157–160, 180.
5. The idea of a "warm little pond" as the cradle of life was advanced by Charles Darwin in a letter to his friend Joseph Hooker in 1871. The idea of a primordial "soup" was proposed in 1929 by the British (later Indian) scientist J. B. S. Haldane (Haldane, 1929); the concept was developed independently, and in more detail, by the Russian (later Soviet) scientist Alexander Ivanovich Oparin (Oparin, 1953). (Oparin's book was published in Russian in 1924 but was not translated into English until 1938.) However, primordial soup is now out of vogue; for a discussion of why, see Lane et al. (2010) and Schönheit et al. (2016). The possibility of an RNA world was advanced by Walter Gilbert in 1986—see Gilbert (1986). There are also many other ideas; for a general overview see, for example, Hazen (2005).
6. In rare cases, smaller, creeping dunes can form from grains of coarse sand—see Lämmel et al. (2018).

7. For speculations about Earth rocks on the surface of the Moon, see Armstrong et al. (2002) and Armstrong (2010).
8. While analyzing a Moon rock collected in the 1970s by the crew of Apollo 14, Bellucci et al. (2019) identified a zircon crystal within it that they thought could have come from Earth. This finding has, however, been disputed—see Warren and Rubin (2020).
9. For barchan dunes on the surface of Mars, see Kok et al. (2012).
10. For a history of thought on panspermia, see Kamminga (1982). Not everyone likes the term; some authors have argued for *transpermia* instead, to suggest more clearly that lifeforms would be moving from one celestial body to another (see Nicholson, 2009), rather than raining down as cosmic dust as originally imagined. Please note that there is also a variant of this hypothesis, which you might call *organospermia*. Whereas panspermia refers to the transfer of lifeforms from one world to another, organospermia suggests that the first lifeforms were somehow constructed from molecules that arrived from space via meteorites or comets—see Delsemme (2001). In a trivial sense, this must be correct: As I have described in an earlier chapter, Earth was formed through the collisions of many different kinds of bodies, and its endowment of materials is due to those bodies. But there is no need to suppose that the first lifeforms were built out of amino acids and other carbon-rich molecules that arrived from space, or that those carbon-rich molecules were food for the first lifeforms. The vast bulk of carbon-rich molecules found in meteorites are not useful for lifeforms, and those that might be occur at very low frequency—for a longer discussion of this point, see Schönheit et al. (2016).
11. A large number of authors have considered the possibility that Mars was the "first world"; see, for example, Gladman (1997). For Venus as a possible first world, see Way et al. (2016). For Ceres, see Houtkooper (2011). Note that Ceres is also referred to as a dwarf planet.
12. For lifeforms surviving the conditions of outer space see, for example, Kawaguchi et al. (2020).
13. Simulations of the ejection of Martian rocks suggest that meteorites from the red planet could potentially arrive here in just a few years (Gladman, 1997). But analysis of actual Mars meteorites show that travel times have varied between around five hundred thousand years and more than eleven million years—see Gladman (1997).
14. For temperature fluctuations in outer space, see Rabbow et al. (2012).
15. For extreme radiation conditions in outer space, see Cockell et al. (2011).
16. For a general overview of the challenges that would-be "micronauts" are exposed to, including high-energy ionizing radiation and the problems of life in a vacuum, see Nicholson (2009).
17. Intriguingly, olivines and serpentines have been detected among ancient Martian rocks, suggesting that four billion years ago or so, rocks of the red planet, too, were undergoing serpentinization—see Ehlmann et al. (2010). However, it may be that Mars is too small to generate carbon dioxide and would therefore not have been able to produce life—see Russell and Ponce (2020). For the record, if life indeed emerged on one planet and then traveled to another, the source of lifeforms could also, in principle, have been

Earth. From a physical perspective, however, Mars makes for a more likely source as its gravity is weaker, so rocks chipped out of the planet's surface would be more likely to escape—see Gladman et al. (1996). Journey times from Earth to Mars are likely to be longer than the reverse; and for incoming rocks, Earth presents a larger target—Gladman (1997).

## Children of the Rock

1. For the biochemistry of carbon fixation in methanogens and acetogens and a comparison with that process in other lifeforms, see Fuchs (2011). In particular, methanogens and acetogens use the Wood–Ljungdahl pathway of carbon fixation, which, unlike the other known carbon fixation pathways, is linear. It is also the only carbon fixation pathway known to occur in both bacteria and archaea—see Berg et al. (2010).
2. For the energetic process predominating over the process of generating cell mass in acetogens and methanogens, see Martin (2016).
3. The possibility that methanogens might represent an ancient lineage was noted early on—see, for example, Decker et al. (1970), Woese and Fox (1977) and Woese et al. (1978). For genetic evidence showing that methanogens are ancient, and that the origin of methanogenesis coincides with the origin of the domain Archaea, see, for example, Mei et al. (2023). Efforts to map the evolutionary history of molecules involved in energy transduction date to the early days of molecular biology—see, for example, Granick (1965) and Eck and Dayhoff (1966). Decker et al. (1970) took this further than their predecessors and outlined an evolutionary scheme based on the molecules involved in energetics; from the progression they identified, they concluded that methanogens and acetogens were more ancient than any other known lifeforms. Note that this paper was published before archaea had been identified as a group separate from bacteria; for an updated version of this scheme, see Martin and Sousa (2016).
4. There is a third possible end product of the reduction of carbon dioxide with hydrogen—an alcohol called methanol. But I find it difficult to imagine lifeforms coalescing from this reduction, because the amount of energy it releases is extremely small. After all, if the wind is not strong enough to loft the sand, no dunes can form.

## The Powers of Life

1. For "What must be the effect . . . ," see Lotka (1925), pp. 356–357.
2. For the inheritance of acquired characteristics as a common assumption in Lamarck's day and subsequently, see Burkhardt (2013). Indeed, it was an idea that Darwin espoused. By the early twentieth century, however, it had become clear that, at least in animals, acquired characteristics cannot, in general, be passed on to offspring. You cannot make tailless mice by chopping off the tails of the parents: However much you chop, the offspring will still have tails. However, more recent research has shown that in special and limited circumstances, certain acquired animal traits can, in fact, be inherited—for examples, see Rechavi and Lev (2017). (Note that, because their biology is

so different, bacteria and archaea can readily pass on traits acquired during their lifetimes, but this fact was not discovered until the twentieth century and had no bearing on early thoughts about inheritance.)

3. For Lamarck decrying the notion that Earth is only six thousand years old, see Lamarck (1802), p. 88. For his ideas about evolution, see Packard (1901), Burkhardt (1995), and Burkhardt (2013). For his contributions to geology, see Geikie (1962).
4. Lamarck was the author of an enormous multivolume treatise called *Histoire naturelle des animaux sans vertèbres* (*Natural history of the invertebrates*); the coining of the term *invertebrate* is attributed to him. For a further assessment of his contribution to the study of invertebrates, especially the fossil forms, see Packard (1901).
5. For Lamarck and *le pouvoir de la vie* referring to the capacities of living beings to transform the surface of the Earth, see Lamarck (1802), p. 117. Note that he also used this phrase in other contexts and with other meanings—see, for example, Burkhardt (2013). His assessment of the impact of lifeforms on the surface of the Earth was not correct in its details, but in his intuition that lifeforms are a geological force, he was entirely right.
6. For enzymes tuning the electrical properties of metals, and some of the consequences, see Lippard and Berg (1994), especially pp. 26–28 and 349–375.
7. For examples of bacteria accelerating reactions by a factor of more than one million see, for example, Singer and Stumm (1970).
8. For enzymatic accelerations of seventeen orders of magnitude, see Miller and Wolfenden (2002). The enzyme in question is found in yeast, and its name is orotidine 5'-phosphate decarboxylase. The example is taken from the modern world; at the time of the first lifeforms, yeasts did not exist and would not for at least another three billion years.
9. The difference between *clay* and *clay minerals* is that each clay mineral has a particular composition and structure. Plain *clay* is a generic term for soft, malleable rock with very fine grains; it typically includes several clay minerals but can include other types of minerals as well. An important point about clay is that it often behaves differently when wet. This is because some clay minerals—smectites in particular—swell when you add water to them. It's thanks to the behavior of such minerals that mud can be so treacherous.
10. To estimate the kind of pressure you would experience if you were buried beneath the Eiger (3,967 meters) or Mount Shasta (4,322 meters), I am assuming that pressure increases at roughly 250 atmospheres (~25 megapascals) per 1,000 meters of rock, as stated in standard geoscience textbooks.
11. For details of the smectite-to-illite transformation, and how it can be accelerated by the activities of bacteria, see Kim et al. (2004).
12. For light carbon becoming concentrated in molecules produced by lifeforms, see Schidlowski (2001).
13. For methanogens fueled by carbon dioxide and hydrogen producing methane enriched in carbon-12, see Valentine et al. (2004).
14. Note that carbon has other isotopes, but in the context of Earth these are vanishingly rare. They are also transient: Over time they undergo radioactive decay, transforming into other elements. For both these reasons, I will

ignore them here. However, the most famous of these unstable isotopes of carbon, carbon-14, is an important tool in archaeology as its pattern of decay allows scientists to estimate the age of certain artifacts.

15. Methane molecules trapped in ancient rocks (older than 3.46 billion years) show a pronounced enrichment in carbon-12, consistent with their having been produced by methanogens—see Ueno et al. (2006).
16. The astonishing potential of bacteria to grow to enormous population sizes has been remarked on for more than 140 years—see, for example, Cohn (1881).
17. For bacteria estimated to have a global population of 2.4 × 10 to the power of 28, see Giovannoni (2017).
18. For the extremely short doubling time of *Vibrio natriegens*, see Eagon (1962); note that this bacterium was originally called *Pseudomonas natriegens*.
19. For "can make the immense work . . . ," see Cohn (1881), p. 12.
20. I'm using the mass of *E. coli* here. See Milo et al. (2010), BNID 103905, which is roughly the same as the mass of *V. natriegens*; see Fagerbakke et al. (1996) table 1. Note that the conditions under which bacteria are growing can affect their mass.
21. Assuming that each bacterium has the mass of a single individual of *E. coli* (0.95 picograms—see Milo et al., 2010, BNID 103905), and assuming that all cells divide and none die, then after 134 generations the mass of bacteria descended from a single founder would exceed the mass of the Earth. If the generation time is ten minutes, this would happen in less than twenty-three hours. (After 134 generations, the mass of bacteria in kilograms would be around 10 to the power of 25; the mass of the Earth in kilograms is on the order of 10 to the power of 24.)
22. A number of scientists attribute the initial insight that natural selection revolves around energy to the physicist Ludwig Boltzmann, who made a passing remark to that effect in a lecture in May 1886—see Boltzmann (1905). As far as I have been able to discover, however, Boltzmann made no attempt to develop this line of reasoning. (Also note: In his lecture, Boltzmann writes that lifeforms fight over access to "entropy"—see Boltzmann, 1905, p. 40—which could be read as a fight over the quality of energy. But a more conventional way of putting this would be to replace "entropy" with "free energy"—the energy available to perform work. See, for example, Nernst, 1904, p. 756, and Schuster, 2008.) In the first decades of the twentieth century, however, a number of researchers began to consider how energy shapes evolution. In 1917, for example, Henry Fairfield Osborn argued for the development of "an energy conception of evolution"—see Osborn (1917). And in 1922, Alfred J. Lotka published a brief, terse paper on energetics and evolution, in which he sketched how evolutionary processes could increase energy flow—see Lotka (1922). His language is somewhat outmoded, and I don't agree with all of his framing; nonetheless, reading this paper inspired some of my thinking on the topic. It is, however, worth noting that Osborn and Lotka were writing more than thirty years before the discovery of the structure of DNA. Once that spiraling, double helix form had been elucidated, genetics—the study of genes and DNA—would come to eclipse energetics as the central preoccupation of evolutionary biologists. Having said that, the eclipse of energetics by genetics started even before the structure

of DNA had been discovered. Neither J. B. S. Haldane nor Ronald Fisher, two founders of the modern synthesis—the fusion of Darwin's ideas with population genetics—appears to have considered energy as an aspect of evolution, making only the most glancing references to it. See Fisher (1930) and Haldane (1932). Nor has the eclipse been total: A number of scientists would subsequently incorporate energy into their evolutionary thinking—notably Blum (1951), Morowitz (1968), Van Valen (1976, 1980), Felsenstein (1978), and Vermeij (2019). But by and large, once the structure of DNA had been elucidated, energy became the province of ecology and biochemistry rather than being central to evolutionary thought.

23. A little more about mutations, a subject for which I have a slightly weird enthusiasm. In addition to how they are caused, you can classify mutations in terms of the physical changes to DNA—such as whether a segment of DNA gets added, deleted, or substituted. Sometimes changes are dramatic, with whole sets of genes being duplicated or lost. Note, however, that different kinds of mutations are not equally likely. Alternatively, you can take a different point of view and consider mutations in terms of their effects on the well-being of the lifeform. Mutations that involve big changes to DNA can nonetheless have negligible impacts on lifeforms, while mutations that just alter one of the bases in DNA can be lethal. Also, mutations can have different kinds of impacts: They can, for example, result in proteins with changed properties, or in changes to how those proteins are regulated. Mutations that result in the loss of DNA that a lifeform doesn't need can accelerate reproduction—after all, the more DNA you have, the longer it takes to copy it, and the slower your generation time. If you're a bacterium, a few minutes can make a difference. Mutations can even lead to more mutations: A mutation that interferes with the proofreading of DNA can lead to a lifeform that experiences a higher mutation rate. Finally, while some mutations are always bad—they disable an essential function and kill you early in life—the extent to which any mutation is beneficial will depend on a lifeform's surroundings, especially the capacities and traits of other lifeforms.
24. Darwin appears to have first used the term *natural selection* in a sketch of his ideas that he drafted in 1842. See Browne (2003), p. 437.
25. For faster growth of evolved bacteria under tightly controlled experimental conditions see, for example, Lenski (2004).
26. For "evolved" populations having a higher total biomass, see Vasi et al. (1994). Note, however, that this greater biomass resulted from individual cells becoming far larger, rather than becoming more numerous. Indeed, the population size declined.

### A World of Expanding Biospots

1. For lifeforms from: sediments 1.9 kilometers beneath the seafloor, see Ciobanu et al. (2014); wet rock fractures more than three kilometers below the surface of the land, see Moser et al. (2005); the interiors of rocks in the Antarctic Dry Valleys, see Friedmann (1982); boiling mud, see Lee et al. (2017).
2. Part of the difficulty is that bacteria and archaea have the habit of passing genes around sideways, which makes reconstructing the evolutionary his-

tory of these lifeforms much harder than it is for, say, animals or plants. Adding to the challenge: The full diversity of these lifeforms has not yet been discovered.

3. Sulfur is a versatile element and can form a variety of small inorganic compounds, including sulfates and sulfites, in addition to existing in pure, elemental form. When electrons flow to any of these, hydrogen sulfide is the chief waste product. Today, the most common metabolic pathway is known as sulfate reduction, where electrons flow to molecules of sulfate. But that may not have been the first sulfur-based energy metabolism—that might, instead, have been sulfite reduction, as argued by Neukirchen et al. (2023) on the basis of an analysis of 195,000 bacterial and archaeal genomes. The rock record suggests that by 3.47 billion years ago (see Shen et al., 2001; Ueno et al., 2008), some kind of microbial sulfur reduction was going on, but teasing apart the possibilities is not straightforward. Also note that today, many bacteria and archaea are versatile in their metabolic capabilities and can make use of more than one substance. Many sulfate reducers can also reduce sulfite, for example.
4. Evidence for least change comes from the fact that some sulfidogens employ the same pathways for carbon fixation as acetogens and methanogens do—see Rabus et al. (2015), section 5.7. A second line of evidence is provided by certain essential biomolecules. Mapping an evolutionary progression of these molecules suggests that those possessed by sulfidogens were derived from those possessed by methanogens and acetogens—see Decker et al. (1970).
5. For ancient black smokers, see Baumgartner et al. (2023).
6. For the formation of black smokers, see Van Dover (2000), p. 49.
7. For a fine dust of elemental sulfur falling from the sky, see Catling (2014). Many thanks to David Catling for clarifying that this dust would not be visible on your time travel suit.
8. For the microbial tendency to prefer the light isotope of sulfur see, for example, Havig et al. (2017), table 1.
9. For lightness of pyrites owing to microbial activity, see Rickard (2021), section 9.3.3.
10. For lifeforms coming to predominate in the formation of sulfides, see Rickard et al. (2017); lifeforms may cause pyrite to form one hundred thousand times as quickly as it would in the absence of life—see Canfield et al. (1998).
11. For fool's gold as the quintessential life rock of the modern world, see Rickard et al. (2017) and Rickard (2021).

### The Mass of the Dead

1. For "If the wandering . . . ," see Cohn (1881), p. 17.
2. For the argument that after the emergence of life, the exploitation of corpses would be among the first evolutionary developments, see Schönheit et al. (2016).
3. I am aware of only two exceptions to this statement, namely, *Uabimicrobium amorphum* and *U. helgolandensis*, which were discovered in 2019 and 2024, respectively—see Shiratori et al. (2019) and Wurzbacher et al. (2024). Even if

this group turns out to comprise more than two species, for bacteria and archaea such behavior is nonetheless highly anomalous.

4. For bacteria and archaea splitting open upon death, a process known as autolysis see, for example, Forsberg and Rogers (1971) and Rice and Bayles (2008).
5. For the consumption of amino acids as a possible "least" invention, see Schönheit et al. (2016).
6. A discussion of transformation can be found in any microbiology textbook.
7. For DNA in the environment being "good eating," see Finkel and Kolter (2001).
8. As an example, some species of methanogen can grow as either autotrophs or heterotrophs—see Buan (2018). This both-ways lifestyle is known as mixotrophy.
9. Many thanks to Lloyd Ackert for providing an English translation of the text of this lecture, which was originally given in Russian. For a more detailed analysis of the lecture, see Ackert (2013), especially pp. 100–103.
10. This quotation is also taken from Lloyd Ackert's translation of Winogradsky's lecture.
11. For "new life could not develop . . . ," see Cohn (1881), p. 17.
12. For an estimate of the quantity of carbon taken up by life over time and how it compares with the total carbon stock of the Earth, see Crockford et al. (2023).

### The Planetary Accountant

1. Different studies have estimated different numbers of bacterial and archaeal species, with guesses ranging from a few million to tens of trillions (eight orders of magnitude more). I go with the high estimate, as I am persuaded by the arguments of Locey and Lennon (2016) and Lennon and Locey (2020).
2. For estimates of the flow of carbon into the biosphere early in the history of life, see Crockford et al. (2023).

## INTERLUDE

### Nonservants: Viruses

1. I discussed some attributes of viruses in an article in the *Financial Times*—see Judson (2020b).
2. For the possibility that viruses originated in tandem with the first lifeforms see, for example, Koonin et al. (2006).
3. For the initial intuition that the cause of tobacco mosaic virus was fundamentally different in character from other known infectious agents, see Beijerinck (1898); for a discussion of the historical significance of Beijerinck's work see, for example, Lwoff (1957), Bos (1999), and Sankaran (2018).
4. For progress in understanding tobacco mosaic virus by the start of the 1930s, see Harrison and Wilson (1999); for the intense confusion surrounding the nature of viruses, see Rivers (1932).

5. For the claim that tobacco mosaic virus resembles a "cigarette-shaped" rod, see Fraenkel-Conrat (1981).
6. For the first images of viruses by means of the electron microscope, see Kausche et al. (1939).
7. For the wealth of viral shapes, see Ackermann and Prangishvili (2012) and Prangishvili et al. (2006).
8. For Lwoff on the attributes of viruses, see Lwoff (1957).
9. For multiple origins of viruses see, for example, Krupovic and Koonin (2017).
10. Lwoff (1957) gives a good historical perspective on the nature of viruses and concludes that they are not alive. For more recent discussions of the subject, Brüssow (2009) takes the line that viruses count as life, whereas Moreira and López-García (2009) argue that they don't. My own previous statement on viruses appeared in "A Gazillion Tiny Avatars," published in *The New York Times* online, December 15, 2009.
11. Arguably, viruses are merely the most famous of a number of sub-lifeform phenomena. Another example would be membrane-bound vesicles—small, spherical packages that contain a miscellany of biomolecules, including proteins and DNA, surrounded by a membrane, that are given off by different lifeforms. Like viruses, these vesicles are not alive. But once released, they can be captured by other lifeforms. For a discussion of this phenomenon see, for example, Biller et al. (2014).
12. For the abundance of viruses in the sea, see Breitbart et al. (2018).

## ROCK—LIGHT

1. For "Rays of light . . . ," see Vernadsky (1929), p. 71. This is my translation of the French original, "Le rayon, en tombant sur la Terre, rencontre partout l'organisme qui le guette."

## Into the Light

1. For Darwin enthusing about chlorophyll, see darwin-online.org.uk/content/frameset?itemID=F2093&viewtype=text&pageseq=1. He made this remark during a conversation with the Russian botanist Kliment Timiryazev.
2. For fossils of microbial mats in shallow waters 3.4 billion years ago, see Tice and Lowe (2006) and Sugitani et al. (2015).
3. For the possibility that a form of photosynthesis had evolved by 3.8 billion years ago, see Rosing (1999) and Pecoits et al. (2015).
4. For John Ruskin's grumbles about chlorophyll, see Ruskin (1869), pp. 72–73.
5. For the pathway for building chlorophyll as an elaboration of the one for building hemes see, for example, Bryant et al. (2020).
6. For the biochemical progression whereby sulfidogens have hemes but acetogens and methanogens do not, see Sousa et al. (2013) and Martin et al. (2018).
7. For an overview of tetrapyrroles, see Battersby (2000).
8. In a few exceptional cases, chlorophylls contain zinc instead of magnesium—see Bryant et al. (2020).
9. For a marvelous and elegant, if technical, account of the biochemistry of the

tetrapyrroles, see Bryant et al. (2020). Note that some tetrapyrroles, not mentioned here but still important in the energetic processes of various lifeforms, do not contain a metal ion—see Battersby (2000).

10. For the evolutionary relationships between the tetrapyrroles see, for example, Blankenship (2010) and Bryant et al. (2020).
11. For the initial suggestion that photosynthesis might have evolved in the depths of the ocean, see Nisbet et al. (1995); for the recent, much more detailed analysis that I sketch here, see Martin et al. (2018). This more recent paper maps out a series of biochemical developments that would have permitted the evolution of the first photosynthetic forms from the first geovores. It is a fascinating, albeit technical, piece of work; if you have an interest in the evolution of biochemistry, I encourage you to read it.
12. For the average depth of the oceans today, see Charette and Smith (2010).
13. For the early oceans having been more voluminous, see Pope et al. (2012).
14. For black smokers emitting light, see Van Dover et al. (1996).
15. For possible causes of "extra" light from black smokers, see Van Dover et al. (1996) and White et al. (2002).
16. For photosynthetic bacteria growing from very low levels of light more than eighty meters below the surface of the Black Sea, see Overmann et al. (1992) and Manske et al. (2005).
17. For the remarkable discovery of *Chlorobium bathyomarinum* in the fluid from a black smoker, and for the light available to it being comparable to the light available to green sulfur bacteria in the Black Sea, see Beatty et al. (2005). For the official name of the lifeform, see marinespecies.org/aphia.php?p=taxdetails&id=564146.
18. For the argument that hydrogen sulfide may have been the first electron donor for photosynthesis, see Martin et al. (2018).
19. For the penetration of ultraviolet light in water in the absence of a protective layer in the atmosphere see, for example, Sephus et al. (2022).

## A Planet of Pinks, Purples, and Greens

1. Again, for a fine dust of elemental sulfur falling from the sky, see Catling (2014).
2. For photosynthetic bacteria with different sensitivities to the Sun's spectrum, see Larkum et al. (2018).
3. For the initial discovery that, by means of sunlight, certain archaea can generate ATP via rhodopsins, see Danon and Stoeckenius (1974); for the discovery in bacteria, see Béjà et al. (2000).
4. For the remarkable abundance of rhodopsin-based photoheterotrophy among bacteria in the sea today, see Gómez-Consarnau et al. (2019).
5. For the probable antiquity of phototrophic lifeforms with rhodopsins, see Sephus et al. (2022).
6. For the coining of *stromatolite / stromatolith*, see Paul et al. (2011).
7. For the numbers of virus particles in a microbial mat, and for viruses potentially playing an important role in the lithification of stromatolites, see Pacton et al. (2014).
8. For stromatolites 3.4 billion years ago, see Allwood et al. (2007) and Sugitani et al. (2015). Modern stromatolites generally contain cyanobacteria, a

group that I will discuss in the next chapter; however, stromatolites can also form in their absence—see Bosak et al. (2007).

### Enter the Makers-in-Chief

1. For a discussion of how blue-green algae were recognized as actually being bacteria, see Stanier and van Niel (1962).
2. For the number of cyanobacterial species, see Nabout et al. (2013).
3. For cyanobacteria in the Atacama Desert, see Wierzchos et al. (2006). I can personally attest to cyanobacteria living in the hot soils of volcanoes—see Judson (2012).
4. For cyanobacteria living on glaciers, see Cook et al. (2016); inside rocks, see Kapitulčinová et al. (2015).
5. For estimates of the population size of *Prochlorococcus*, see Flombaum et al. (2013).
6. Several European travelers (warriors and friars) to Mexico around the time of the Spanish conquest in the sixteenth century reported that the Aztecs harvested a blue slime from the surface of a lake and turned it into a "bread" that tasted like cheese—for a fascinating compilation of such reports, see Farrar (1966). The identification of the blue slime as *Spirulina* came later—see Ciferri (1983). The species is thought to be *Arthrospira maxima*, formerly known as *Spirulina maxima*. Note that in the twentieth century a different but related species was reported to be harvested and eaten in Chad—see Ciferri (1983).
7. For cyanobacteria collecting manganese ions, and for this activity being stimulated by light, see Bartsevich and Pakrasi (1996).
8. For cyanobacteria storing large quantities of manganese, see Keren et al. (2002).
9. The process of water splitting also releases four protons; these are put to use by the lifeform as well.
10. The water-oxidizing complex takes approximately two milliseconds to split two molecules of water and release one molecule of $O_2$; however, the whole process of iteration is a little slower, taking around ten milliseconds—see Cox et al. (2020).
11. Many thanks to Avi Flamholz for calculating how long it would take a single cyanobacterium to produce enough oxygen for one human breath.
12. For the water-splitting properties of manganese being unique in nature, and for the fact that, in other biological roles, it can be replaced, see Pace et al. (2012).
13. For manganese being made in supernovas, see Barbuy et al. (2013).

### In the Offices of the Planetary Accountant

1. Estimates for the activity of the early biosphere, especially before the advent of cyanobacteria, vary tremendously. I am following Ward et al. (2019), figure 2.
2. For ancient lifeforms: living in sediments below the seafloor, see McLoughlin et al. (2012); basking in hot springs, see Sugitani et al. (2015); growing on

sediments in intertidal zones, see Homann et al. (2015); living on river bottoms, see Homann et al. (2018); in lakes, see Buick (1992); on the rocky surface of the land, see Lenton and Daines (2017).
3. For the idea that many bacteria and archaea require the presence of partner species and cannot live alone, see Schink (2002).
4. For microbial mats holding sediments in place see, for example, Grant and Gust (1987).

## INTERLUDE

### Mats of Gold

1. For bacteria causing the precipitation of very pure, tiny nuggets of gold see, for example, Fairbrother et al. (2013).
2. For the suggestion that these deposits are indeed due to the activities of cyanobacteria, see Frimmel and Hennigh (2015). For the argument that the mats were photosynthetic, see Frimmel (2018).
3. For an overview of bacteria and archaea that can precipitate gold, see Southam et al. (2009). For an example of a bacterium that accelerates the rate of gold precipitation, see Johnston et al. (2013).
4. For lifeforms being more efficient than nonlife at concentrating gold, see Fairbrother et al. (2013).
5. For the argument that the gold deposits of the Witwatersrand were due to the activities of lifeforms, see Heinrich (2015) and Frimmel (2018).
6. For the estimate that roughly 30 percent of all the gold ever mined has come from the Witwatersrand, see Frimmel and Hennigh (2015).
7. For the carbon seams that are associated with the gold of the Witwatersrand, and the assessment that these are residues of microbial mats, see Mossman et al. (2008).
8. For the argument that gold deposits mediated by life were necessary for later, different kinds of gold deposits, see Frimmel (2018) and Frimmel (2022).

## ROCK—LIGHT—OXYGEN

1. For “We must regard oxygen . . . ,” see Lotka (1925), p. 219.

### Let the Aerobics Begin!

1. Letter from Christian Friedrich Schönbein to Michael Faraday, May 7, 1852, in Kahlbaum and Darbishire (1899), p. 200.
2. For genetic evidence that aerobic respiration followed the evolution of cyanobacteria, see Soo et al. (2017) and Liao et al. (2026); for geochemical evidence, see Eigenbrode and Freeman (2006).
3. For the incorporation of oxygen being evolved from an earlier, simpler biochemistry, see George (1965), Broda (1970) and Degli Esposti (2020).
4. Some other materials outdo oxygen’s hunger for electrons—fluorine, for example, is a more avid electron acceptor than oxygen, making it a more en-

ergetic oxidizing agent. However, not only does fluorine attack biological molecules, electron-transfer reactions involving this element are so explosively violent that they are not compatible with life—see George (1965). Nitrate, meanwhile, is almost as good an electron acceptor as oxygen in principle, but the biological reality is that it is less effective. Lifeforms respiring nitrate generate less ATP than those respiring oxygen and grow less efficiently—see King (2005).

5. For alpha-proteobacteria evolving after the appearance of molecular oxygen, see Wang and Luo (2021).
6. For the naming of the proteobacteria, see Stackebrandt et al. (1988).
7. For communities of cyanobacteria creating high local levels of oxygen in otherwise anoxic environments, see Sumner et al. (2015).
8. For the range of oxygen concentrations enjoyed by different bacteria and archaea, see Taylor and Zhulin (1998) and Stolper et al. (2010).
9. For the initial discovery of magnetotactic bacteria, see Bellini (2009a) and Bellini (2009b).
10. For the initial discovery that magnetic bacteria contain magnetite, see Frankel et al. (1979).
11. For the purity of bacterial magnetite, see Amor et al. (2015). For the precise size and shape of magnetite crystals, see Müller et al. (2020).
12. For the making of the living compass needle, see Amor et al. (2015) and Müller et al. (2020).
13. For bacteria seeking out particular levels of oxygen, see Taylor and Zhulin (1998).
14. For oxygen concentrations going from supersaturated to none within the space of a millimeter, see Stolz (2000). For oxygen-respiring heterotrophs consuming oxygen within a mat see, for example, van Gemerden (1993).
15. For bacteria living by the knallgas reaction, see Schlegel (1966).
16. I have borrowed the phrase *chemical adversaries* from Catling (2014).
17. Winogradsky was writing in German; his original remark was "ein äusserst elegantes und belebtes Bild!"; see Winogradsky (1887), part two, column 515. For the translation, see Dworkin (2012), p. 368.
18. For aerobic bacteria and archaea having more genes than their anaerobic counterparts, see Nielsen et al. (2021).
19. For oxygen expanding the range of temperature, pH, and salinity that bacteria and archaea can tolerate, see Harrison et al. (2015).
20. For oxygen permitting new versions of preexisting molecules, see Raymond and Blankenship (2004).
21. For the greater expense of building proteins in the presence of oxygen, see McCollom and Amend (2005).
22. For oxygen inactivating metals in enzymes, and for the sensitivity of methanogens to $O_2$, see Lu and Imlay (2021); these authors also discuss other ways that $O_2$ can make trouble.
23. For the structural aspects of oxygen that prevent it from attacking normal biological molecules, see Lu and Imlay (2021).
24. Perhaps the most familiar of the reactive oxygen species is hydrogen peroxide—known to chemists as $H_2O_2$ and to everyone else as a disinfectant of wounds and a form of bleach. (Its capacity as a disinfectant should alert

you that it's dangerous.) But there's also the dreaded superoxide ion (a molecule of oxygen that has acquired an extra electron) and the even more destructive hydroxyl radical, formed when hydrogen peroxide comes apart. All these entities are reactive and unstable, and potentially destructive to lifeforms. The hydroxyl radical damages DNA, causing mutations. Hydrogen peroxide and the superoxide ion react with iron in the cell, and in doing so can bring many processes to a halt. For an overview of the damage that reactive oxygen species can do, see Khademian and Imlay (2021).

25. For energetic costs of protection rising with rising oxygen levels, see Fenchel and Finlay (2008).
26. For the bacterial production of light being an efficient and cheap way to mop up oxygen molecules, see Timmins et al. (2001).
27. For cold biolight, see Barnard (1902).
28. For Beijerinck's use of light-producing bacteria in studies of oxygen production in photosynthesis, see Beijerinck (1902); for his contemporaries see, for example, Gest (1991).
29. For a broad overview of luminous life, see Judson (2015). For a gorgeous survey of light in the oceans, see Haddock and Johnsen (2025). Many thanks to Steve Haddock for giving me the opportunity to see a number of unusual bioluminescent forms at close hand.
30. For the possible origins of bacterial bioluminescence as a means of controlling oxygen, see Rees et al. (1998) and Timmins et al. (2001).
31. For the growth of *Pyrobaculum islandicum*, see Kashefi and Lovley (2000).
32. For *Geobacter* and its electrical wires, see Lovley and Holmes (2020).
33. For the antiquity of nitrogen-fixing lifeforms, see Stüeken et al. (2015).
34. For lifeforms today tearing apart more nitrogen molecules than lightning does, see Fowler et al. (2013).
35. Some nitrogenases have vanadium instead of molybdenum; some contain just iron. See Boyd and Peters (2013).
36. For oxygen and the inactivation of nitrogenase, see Lu and Imlay (2021).
37. For cyanobacteria generating oxygen by day and fixing nitrogen at night, see Gallon (2001).
38. The new bacteria that grow in the presence of light and oxygen are called aerobic anoxygenic phototrophs. Unlike cyanobacteria, these are not photosynthetic, but require organic carbon. See, for example, Koblížek (2015).
39. For *Beggiatoa* accelerating the oxidation of hydrogen sulfide, see Nelson et al. (1986).
40. For an overview of magnetite made by bacteria accumulating in rocks, see Kopp and Kirschvink (2008) and Amor et al. (2020).
41. For more rapid degradation of biological molecules by aerobic lifeforms see, for example, Kristensen et al. (1995). For lifeforms deploying oxygen to break down molecules, see Hayaishi (2005).
42. For cooperative consortia working together in the absence of oxygen, and for lifeforms working alone in its presence see, for example, Schink (2002) and Morris et al. (2013).
43. For circadian fluctuations in oxygen within a microbial mat, and for *Beggiatoa* migrating through the mat to remain in the zone where oxygen and hydrogen sulfide are both available, see Garcia-Pichel et al. (1994).

### Change Is in the Rocks, the Water, the Air

1. For the timing of the initial accumulation of oxygen—the Great Oxygenation Event—see, for example, Warke et al. (2020). This is sometimes also referred to as the Great Oxidation Event—but that sounds less expansive, somehow.
2. For fossil stromatolites showing putative oxygen bubbles from 2.7 billion years ago, see Wilmeth et al. (2019).
3. For oxygen 2.5 billion years ago, as revealed by oxygen-sensitive elements, see Anbar et al. (2007) and Kendall et al. (2010).
4. For an early discussion of the participation of life in the creation of banded iron formations see, for example, Macgregor (1927).
5. For an overview of possible microbial involvement in the iron formations see, for example, Posth et al. (2011) and Konhauser et al. (2017).
6. For temperature fluctuation and the alternate depositions of iron and silica, see Posth et al. (2008).
7. For the timing of the deposition of the vast bulk of the banded iron formations, see Konhauser et al. (2017).
8. For estimates of the tonnage of various iron formations, see James (1983).
9. For an example of cyanobacteria producing oxygen within a mat while the overall environment remains anoxic, see Sumner et al. (2015).
10. For changes in volcanic gases contributing to the Great Oxygenation, see Kadoya et al. (2020) and O'Neill and Aulbach (2022). For the evolving composition of lavas playing a part, see Leong et al. (2021). For the contributions of a leak of hydrogen, see Zahnle et al. (2013).
11. For additional reasons that other planets might not be able to accumulate oxygen, see Catling et al. (2005).
12. For the ancient red beds near Lake Huron, see Chandler (1980) and Shawwa et al. (2024).
13. For copper deposits and iron-rich soils, see Farquhar et al. (2011).
14. For the bout of mineral creation in the wake of the Great Oxygenation, see Hazen et al. (2008) and Sverjensky and Lee (2010).
15. For the creation of new uranium minerals, see Hazen et al. (2009); many thanks to Ralf Thomas Schmitt, curator of minerals at the Museum für Naturkunde in Berlin, for showing me some of them.
16. For the problems of pyrite decay in museum collections, see Newman (1998) and Larkin (2011).
17. For the robustness of grains of pyrite in the absence of oxygen, see Johnson et al. (2014).
18. For an outline of Macgregor's professional life, see Anhaeusser (1997), p. 144.
19. For pyrites in ancient river rocks as evidence that the Earth's atmosphere initially lacked oxygen, and for the view that "great changes must have taken place," see Macgregor (1927).

### Events Began to Snowball

1. For oxygen levels in the atmosphere after the Great Oxygenation, see Lenton and Daines (2017), figure 1. These authors suggest that oxygen levels back then were perhaps one-tenth of what they are today.

2. For the snowball Earth following the Great Oxygenation Event, see Warke et al. (2020). For subsequent climate oscillations, see Poulton et al. (2021).
3. For the plunge in global temperature and the speed with which it may have happened, see Catling and Zahnle (2020).
4. I described the hot spots of Mount Erebus here: Judson (2012).
5. Nordenskiöld (1872a), p. 306.
6. For Nordenskiöld's coining of the term *cryoconite,* see Nordenskiöld (1872b), p. 356. Note that his original spelling was *kryokonite.*
7. For the initial suggestion that lifeforms cause cryoconite holes, see Nordenskiöld (1872b), p. 356. For modern research showing the involvement of lifeforms, especially cyanobacteria, in the formation of cryoconite holes, see Cook et al. (2016).
8. For the biology of modern cryoconite holes see, for example, Cook et al. (2016).
9. My account of the weird cryoconite holes in Antarctica is drawn from Tranter et al. (2004).
10. For brines in sea ice sustaining microbial life, see Boetius et al. (2015).
11. For microbial communities beneath glaciers and ice sheets, see Montross et al. (2013) and Lanoil et al. (2009), respectively.
12. For bacteria accelerating weathering beneath glaciers, see Montross et al. (2013).
13. For networks of rivers and lakes beneath the Antarctic ice, see Priscu et al. (2008). These authors also provide a review of the biology of Lake Vostok and propose that water beneath the Antarctic ice should be considered the world's largest wetland.
14. For bacteria that can grow at −15° C, see Mykytczuk et al. (2013). In general, archaea are not known to grow at quite such low temperatures, but cold-tolerant archaea certainly exist—see Cavicchioli (2006).
15. For the persistence of bacteria within ice for hundreds of thousands of years, see Christner et al. (2003) and Bidle et al. (2007).
16. The possibility that lifeforms might have accelerated the collapse of the snowball Earth is my inference from observations that today microbes accelerate melting in snowfields. See, for example, Kohshima et al. (1993) and Ganey et al. (2017).
17. For an experiment showing triple the melting rate in areas covered with cyanobacteria, see Kohshima et al. (1993).
18. For metabolic heat potentially contributing to the melting of ice, see Hollesen et al. (2015); note that this study is on microbial populations in permafrost.
19. Nordenskiöld (1872b), p. 356.

## A Planetary Parasol

1. For ozone damaging plants, see Ainsworth et al. (2012); for human health problems from ozone exposure, see Jerrett et al. (2009). Ozone also kills bacteria—see Varga and Szigeti (2016).
2. For the establishment of the ozone layer in tandem with the Great Oxygenation Event, see Catling (2014).

3. For the ozone layer and the end of the sulfur drizzle see, for example, Catling and Zahnle (2020).
4. For microbial communities on the surface of the land long before the ozone layer existed, see Lenton and Daines (2017) and Homann et al. (2018).
5. For bacteria coping well in high-radiation environments, see Slade and Radman (2011).
6. For sunscreens produced by bacteria see, for example, Gao and Garcia-Pichel (2011).
7. For thick hazes before the establishment of the ozone shield, see Arney et al. (2016).

### Painting the Sky

1. For the construction of de Saussure's cyanometer, and for the color of the sky at the summit of Mont Blanc, see de Saussure (1789). The original cyanometer had forty shades (de Saussure, 1789), but he later enlarged it to fifty-three—see Hoeppe (2007), color plate 15.
2. For Humboldt's climb of Chimborazo, see Wulf (2015). His reading from near the summit of Chimborazo is given on the *Naturgemälde der Anden*—a painting executed with his traveling companion, the botanist Aimé Bonpland, that shows how the distribution of plants changes with altitude. For the cyanometer reading of the color of the sky at noon at sea level, see Hoeppe (2007), p. 110.
3. For a general introduction to the causes of sky color, see Bohren and Fraser (1985) and Bohren (1987). Many thanks to Sönke Johnsen for fielding lots of questions on this topic.
4. Many thanks to David Catling for discussing the whys and wherefores of the Martian sky.
5. Many thanks to Fred Taylor (sadly, now deceased) for illuminating the color of the Venusian sky.
6. For the episodic formation of an organic haze, see Izon et al. (2015). For sky color under an organic haze, see Arney et al. (2016). For declining nutrient levels as a possible cause of a fall in methane production and a return to blue skies, see Izon et al. (2015).
7. For Lyell's brief remarks on raindrop size and past air density, see Lyell (1851), p. 247. For a more rigorous account of the relationship, see Som et al. (2012).
8. Many thanks to Roger Buick for showing me some imprints of fossil raindrops.
9. In order for bubbles in a lava flow to indicate past air pressure, the lava would ideally have been little altered by subsequent events and show signs that it flowed at sea level—for example, evidence that it flowed along an ancient beach. For a more detailed account, see Som et al. (2016).
10. For evidence that the air was thinner 2.7 billion years ago, see Som et al. (2012) (raindrops) and Som et al. (2016) (bubbles in ancient lava).
11. For the color of the twilight sky in the absence of ozone, see Hulbert (1953).
12. For an overview of bird vision, see Bennett and Théry (2007).

## Monstrous Union, Monstrous Power

1. Estimated day length for 1.6 billion years ago is given in Zahnle and Walker (1987).
2. For the term *matworld*, see Lenton and Daines (2017).
3. My description of the novel features of lifeforms around 1.6 billion years ago is based on work by Adam et al. (2017) and Javaux and Lepot (2018).
4. For sex as a phenomenon that originated with these new lifeforms, see Raval et al. (2022).
5. Lions, goats, and snakes are descended from a common ancestor that lived around 310 million years ago—see Dawkins (2004). At the time that eukaryotes began to evolve, bacteria and archaea had been separated for around two billion years.
6. For examples of eukaryotic fossils dating to 1.6 billion years ago, see Butterfield (2015) and Javaux and Lepot (2018).
7. Many thanks to Nicholas Butterfield for showing me fossils of early eukaryotes.
8. For the possibility that ancient, large, featureless blobs might be eukaryotes, see Javaux and Lepot (2018), especially figure 2c.
9. For the alpha-proteobacterial partner probably having been able to respire oxygen on a facultative basis see, for example, Mills et al. (2022) and Geiger et al. (2023).
10. For a general account of the discovery of Asgard archaea, as well as descriptions of where you can find them, see Zaremba-Niedzwiedzka et al. (2017). For the Asgard archaea that have been grown in the laboratory, see Imachi et al. (2020) and Rodrigues-Oliveira et al. (2023).
11. For examples of the strange mix of bacterial and archaeal traits, see López-García and Moreira (2015). For a description of how eukaryotes might have ended up with a membrane that resembles those of bacteria, see Gould et al. (2016).
12. Despite its ugliness, the term *eukaryote* appears to have been invented twice. It was coined in 1925 by a French scientist named Édouard Chatton; see Chatton (1925). Chatton was studying single-celled lifeforms and used the term in passing to distinguish between those that had a nucleus and those that did not. It is only later that other researchers extended the term to include multicellular lifeforms as well. Had it not been for the efforts of Chatton's student André Lwoff, however, the term might have lapsed into obscurity—see Stanier (1980) and Katscher (2004). Or perhaps it wouldn't have. The American biologist Ellsworth Dougherty appears to have coined the word independently in 1957, though he intended it to refer only to the nucleus and not to the lifeform; some researchers evidently began using the word as a consequence of Dougherty's work—see, for example, Ris (1961).
13. For bacteria and archaea, the size of the genome closely reflects the number of genes—see Westoby et al. (2021). This is not the case for eukaryotes, which, in addition to genes, often have accumulations of "intervening sequences," or introns, of DNA, the functions of which are various. (Introns may help regulate gene expression, but they are not genes because they don't contain the instructions for making proteins.) This decoupling of genome size and

gene number is a eukaryotic trait. Having said that, most single-celled eukaryotes not only have more DNA than most bacteria or archaea, they also generally have the capacity to make many more proteins—see Rebeaud et al. (2021).

14. For eukaryotes making larger proteins than bacteria and archaea, see Brocchieri and Karlin (2005).
15. The term *mitochondria* was coined in passing in 1898 by a German scientist named Carl Benda—see Benda (1898), p. 397. At the time, however, a number of other candidate terms were circulating, of which my favorite is *eclectosome*—see footnote 2 of p. 245 of Regaud (1919) for a discussion. This would actually have been appropriate, since mitochondria have diverse functions and are by no means restricted to the transformation of energy. But I see that I'm writing a footnote about a footnote, so I'll stop here.
16. Not all mitochondria respire oxygen—as eukaryotes have diversified, mitochondria have diversified with them. Today, mitochondria can be roughly classed into at least five general types—see Müller et al. (2012). One way or another, however, mitochondria are involved in the energetics of the cell.
17. For early remarks on the resemblance between mitochondria and bacteria, see Cowdry (1918).
18. The possibility that mitochondria were once bacteria was made famous by Lynn Sagan (later Margulis) in 1967, see Sagan (1967); however, the idea long predates her work. For a description of early ideas about the bacterial origins of mitochondria, and their later development, see Grun (1976). This author also has good descriptions of the structure, organization, and translation of mitochondrial DNA.
19. With one known exception, all eukaryotes alive today have mitochondria or structures derived from them. The exception, a single-celled lifeform called an oxymonad, clearly used to have mitochondria but has lost them—see Karnkowska et al. (2016).

## Singular Reflections

1. For a fascinating example of an intimate association between two different species of bacteria, see Liu et al. (2013).
2. For an account of the lifestyle of *Bdellovibrio*, as well as much that remains to be discovered about its biology, see Sockett (2009).
3. For a report of cyanobacteria possibly harboring internal bacteria, see Wujek (1979).
4. For recent work showing that putatively "internal" bacteria had actually arrived post-mortem, see Yamaguchi et al. (2020).
5. For nested bacteria living within an insect, see von Dohlen et al. (2001).
6. For the discovery of *Uabimicrobium*, see Shiratori et al. (2019) and Wurzbacher et al. (2024). Note that the group was initially called *Uab*, not *Uabimicrobium*.
7. There has been a long-running argument as to whether the archaeal partner in the fusion had in fact evolved the ability to engulf other cells. This remains a possibility, but it is not the only one. Alternatives that might result in the bacterium being taken into the archaeon include a bizarre process of

entanglement (as described by Imachi et al., 2020) or a process of growth around the bacterium while it is external to the cell, analogous to the process observed in spore-forming bacteria such as *Bacillus subtilis*—see Khanna et al. (2020).

8. The nature of the initial relationship between the bacterium and the archaeon is the subject of speculation and controversy; without a clearer sense of the nature of the lifeforms involved, it will remain so. I favor a mutually beneficial relationship of some kind, as that seems to me most likely to have a successful outcome, as well as being a common arrangement among archaea and bacteria. I am, however, agnostic as to the details. For some intriguing possibilities, see Martin and Müller (1998), Speijer (2017), and Spang et al. (2019).
9. For evidence that some bacteria—especially alpha-proteobacteria—are prone to releasing ATP, see Spari and Beldi (2020).
10. For a general need that lifeforms may have to spill excess energy, see Russell (2007). For the possibility that the export of ATP evolved as a way for the evolving mitochondrion to avoid problems of excess energy, see Blackstone (2013).
11. For a dramatic bout of genetic invention as eukaryotes formed, see Makarova et al. (2005).
12. This evidence comes from bacteria that, whether helpful or harmful, have evolved to live exclusively within the cells of eukaryotes; they often have dramatically reduced genomes. See Moran (2002) and McCutcheon and Moran (2012).
13. Today, mitochondria of different species vary in how many genes they have; however, even the largest known mitochondrial genomes have fewer than one hundred genes (Moreira et al., 2024), whereas a typical free-living alpha-proteobacterium may have upward of three thousand—Boussau et al. (2004).
14. For the extent of the changes to the alpha-proteobacterium, see Roger et al. (2017). The list of changes to the overall cell can be found in any biology textbook.
15. For the coming of eukaryotes bringing a major increase in lifeform size, see Payne et al. (2009).
16. For sex—meiosis and syngamy—evolving subsequent to the fusion of two lifeforms, see Raval et al. (2022).
17. For eukaryotes having large appetites for zinc, see Dupont et al. (2010).
18. For a general overview of bacterial and archaeal compartments, see Greening and Lithgow (2020). For an account of magnetosomes, see Lefevre and Bazylinski (2013). For the anammoxosomes, see Grant et al. (2018).
19. For the recent discovery of cytoskeletons in bacteria and archaea, and the greater complexity of those in eukaryotes, see Wickstead and Gull (2011).
20. For Asgard archaea that have been grown in the laboratory, see Imachi et al. (2020) and Rodrigues-Oliveira et al. (2023).
21. A number of authors—see, for example, Lane (2011) and Blackstone (2013)—have considered why eukaryotes appear to have evolved only once, and Lane (2011) gives a good account of what I call the evolutionary "zone."
22. In an extensive survey, Heim et al. (2017) found that the volumes of bacteria and archaea span around 10 orders of magnitude.

23. For the size of *Thiomargarita namibiensis,* see Schulz and Jørgensen (2001); for a coarse grain of sand, see Welland (2009).
24. For *Thiomargarita magnifica* being as long as an eyelash, see Volland et al. (2022).
25. For gigantic bacteria being mostly filled up with an inert sac of fluid, see Schulz and Jørgensen (2001) (*T. namibiensis*) and Volland et al. (2022) (*T. magnifica*).
26. At the time of writing, the smallest genome of a bacterium capable of independent replication belongs to *Mycoplasma genitalium*; this is two orders of magnitude smaller than the largest known bacterial genome, which belongs to *Sorangium cellulosum*. See the BioNumbers database, bionumbers.hms.harvard.edu.
27. As an example of a single-celled eukaryote with a large genome, see the dinoflagellate *Polarella glacialis*—Stephens et al. (2020).
28. The historical assumption was that these lifeforms are limited by diffusion—see Koch (1996). The idea is that, because these lifeforms lack an apparatus to shunt molecules around inside their cells, they are dependent on the rate at which those molecules diffuse through the cell on their own. The bigger you are, the more slowly this happens. Above a certain size, then, the molecules would take too long to get where they are supposed to go. But this is really just a description of the fact that these lifeforms lack an internal apparatus to move molecules; they lack this apparatus because they haven't got the genes and proteins to build it. And, in my view, this is a reflection of the fact that they are constrained by their architecture and the way that energy flows through them.
29. For fascinating discussions of the constraints that bacteria and archaea would face if they were to be scaled up, see Lane and Martin (2010) and Lane (2011).
30. Many thanks to Nicholas Butterfield for the phrase "a big fat nothing" to describe the events following the initial formation of eukaryotes.
31. Some geologists refer to this period of remarkable stability as "the boring billion." As far as I know, this language first appeared in print in 2006—see Holland (2006)—but the author appears to be referring to an established term, and the feeling that this episode was a snoozy time in Earth history was already in the Zeitgeist of the late 1990s and early 2000s, with Butterfield (2001) describing it as "achingly monotonous." These days, however, most authors are eager to attack the notion that this interval was dull, regarding it as "caricatured misleadingly" (Zhu et al., 2016) and "far from boring" (Zhang et al., 2018).
32. For a relative lull in mountain building, see Tang et al. (2021).
33. For the absence of glaciers, see Bradley (2011).
34. Estimates for the length of the day during Earth's long period of stability vary between 19.5 hours (Wu et al., 2023) and 21 hours (Zahnle and Walker, 1987; Bartlett and Stevenson, 2016).

### A Visit to the Planetary Accountant

1. For bacteria destroying magnetite, see Carlut et al. (2007).

2. The insight that minerals appeared in some kind of sequence and massively expanded with the Great Oxygenation is drawn from the work of Robert Hazen and his colleagues. See, in particular, Hazen et al. (2008) and Hazen and Ferry (2010).
3. For bacteria gathering iron in times of scarcity, see Andrews et al. (2003).

## INTERLUDE

### Cycles of Rock, Cycles of Life

1. For ". . . land and sea . . . ," see Witham (1833), p. 4.
2. The scholar Abraham Ortelius, writing in 1596, appears to have been among the first to propose that the congruence between Africa and South America suggests that the positions of the continents must have changed—see Romm (1994).
3. For the long-held supposition that the planet was inert, like a statue, see Wegener (1966), chapter 2, and Wilson (1968).
4. For an overview of the biological and geological resemblances between Africa and South America, see Wegener (1966).
5. For lost land bridges and vanished continents as early explanations for biogeographic patterns, see Wegener (1966), chapter 2.
6. For Wegener's first suggestion that the continents had moved, see Wegener (1912).
7. For Wegener's conclusion that the "continents must have shifted," see Wegener (1966), p. 17. Note that Wegener was anticipated in some of his ideas by an American named Frank Bursley Taylor, who in 1910 published a paper arguing that mountain ranges were created as continents crushed into one another (Taylor, 1910), however Taylor's evidence was less extensive.
8. For remarks on the historical reluctance to accept a mobile Earth, see Wilson (1968).
9. For accounts of how the idea of a mobile Earth came to be accepted in the 1960s, see Hurley (1968) and Hallam (1973).
10. For repeated changes in temperature causing physical weathering of rocks, see Collins and Stock (2016).
11. For chemical weathering leading to carbon dioxide becoming locked up in rocks see, for example, Kasting and Catling (2003).
12. For bacteria accelerating the chemical weathering of rocks see, for example, Barker et al. (1998).
13. For the possibility that without some form of planetary recycling, all the carbon dioxide would be incorporated into rocks, see Kasting and Catling (2003).
14. For a description of the processes that re-create carbon dioxide from rocks, see Kasting and Catling (2003).
15. For an overview of evidence showing clearly that plate tectonics has been in operation for the past one billion years, see Harrison (2024).
16. For the mystery of when plate tectonics began, see Korenaga (2013) and Harrison (2024).

17. For a description of how sagduction could work, and how it might transition into plate tectonics, see Rey et al. (2024).
18. For the possibility that lifeforms help with the manufacture of continents and the maintenance of plate tectonics see, for example, Höning et al. (2014) and Grosch and Hazen (2015).
19. For water being necessary for the formation of granites, see Campbell and Taylor (1983).
20. For microbes possibly facilitating the formation of early continents, see Grosch and Hazen (2015).
21. For the possibility that without life, plate tectonics might have ceased, see Höning et al. (2014).
22. For the frequency of diamondiferous eruptions, see Tappe et al. (2018).
23. For the most recent diamondiferous eruptions being more than fifteen million years ago, see Smit and Shirey (2019).
24. For inclusions bearing clues to the conditions of diamond formation, see Smith et al. (2017).
25. Nisbet et al. (1994) were among the first to suggest that diamonds could originate from dead bacteria. For evidence that diamonds contain hallmarks of life—in particular, an excess of the light isotope of carbon—and formed from organic carbon residues in subducted sediments see, for example, Ickert et al. (2013). For the suggestion that some of the largest, most famous diamonds formed from isotopically light carbon, see Smith et al. (2016) and Smith et al. (2017). Note that life processes are not the only path to compounds being made of isotopically light carbon—some geochemical synthesis can produce the same effect. But by virtue of their abundance, lifeforms are a good candidate for the source of some of the material that becomes diamond.

## ROCK—LIGHT—OXYGEN—FLESH

1. For the epigraph to this section, see Arthur Schopenhauer's *The World as Will and Idea*, translated by R. B. Haldane and J. Kemp, volume 3, 6th edition, p. 392, Kegan Paul, Trench, Trübner (1909), which appears to be a translation of the 3rd German edition, published in 1859.

### A Growing Hunger

1. For *Amoeba proteus* having distinct food preferences, see Gibbs and Dellinger (1908), p. 240.
2. For the "intensely interesting" sight of an amoeba capturing its prey and the urge to use anthropomorphic language, see Gibbs and Dellinger (1908), p. 240.
3. For the hunting behavior of *Myxococcus xanthus* see, for example, Zusman et al. (2007).
4. For predatory behavior in *Aureispira*, see Lien et al. (2024).
5. For examples of predatory bacteria, see Martin (2002).
6. I have not encountered any reports of predatory archaea, and searches of one of the main indexes of scientific articles, the Web of Science, with the terms *predatory* and *archaea* have turned up nothing.
7. More phagocytic bacteria may await discovery; even so, among bacteria this

way of life is clearly unusual. Also, while the genetic underpinnings of *Uabimicrobium amorphum*'s ability to engulf other lifeforms remains unknown, its capacity to do this appears to have evolved independently from the forms of phagocytosis conducted by eukaryotes—see Shiratori et al. (2019) and Wurzbacher et al. (2024).

8. For *Amoeba proteus* resting after eating, see Gibbs and Dellinger (1908).
9. As an example of bacteria where individuals have more metabolic possibilities than all eukaryotes together, consider *Rhodopseudomonas palustris*—see Larimer et al. (2004).
10. The timing of the evolution of the eukaryotic capacity for phagocytosis remains controversial. I am outlining a scenario suggested by Yutin et al. (2009) and Mills (2020), among others.
11. For evidence that phagocytosis evolved more than once, see Mills (2020).
12. I learned of the appetites of *Uabimicrobium amorphum* in a fascinating conversation with Ken-ichiro Ishida in January 2022; many thanks. For the appetites of *Paramecium caudatum,* see Fabbro et al. (2001); this paper reports that these parameciums eat 1,300 bacteria per hour. I have extrapolated to the number of bacteria per division by assuming that the parameciums divide after eight hours. Note that the rate of division depends on circumstances, including temperature and the availability of food.
13. For *Amoeba proteus* capturing one hundred parameciums in a single attack, see Wichterman (1986), p. 385.

### Powers of Intimacy

1. For protists generally having other lifeforms living inside them see, for example, Zhang et al. (2024).
2. For the capacity for phagocytosis in the protist that initially captured a cyanobacterium, see Maruyama and Kim (2013).
3. For proteins that transport materials to both mitochondria and chloroplasts, see Carrie et al. (2009).
4. For an overview of algae being gobbled up by other protists, which go on to become photosynthetic, see Keeling (2013).
5. For the acquisition of bacteria that fix nitrogen, see Nowack and Melkonian (2010).
6. For methanogenic archaea as symbionts of hydrogen-producing protists, see Hackstein (2018).
7. For protists having intimate relations with sulfidogens, see Jerlström-Hultqvist et al. (2024).
8. For magnetic bacteria guiding protists, see Edgcomb (2019).
9. For the shenanigans of *Histiobalantium natans,* see Esteban et al. (2009).
10. For amoebas being killed by bacteria they have eaten, see Jeon (1995). For parameciums, see Wichterman (1986), especially p. 391.
11. For amoebas with enormous numbers of internal residents that take up a lot of space, see Jeon (1995).
12. For *Kentrophoros* conveying its symbionts to where they grow best, see Finlay and Fenchel (1989).
13. For bacteria chasing algae, see Barbara and Mitchell (2003).

14. For the Earth and the Moon being pelted with huge meteorites around eight hundred million years ago, see Terada et al. (2020).
15. For vivid descriptions of the snowball Earths that started around 717 million years ago, see Hoffman et al. (2017).
16. For the possibility that the climate disturbances of the Cryogenian broke the resonance between the Earth and the Moon, allowing the day to lengthen, see Bartlett and Stevenson (2016).
17. For the possibility that the activities of algae increased the formation of clouds and triggered a snowball Earth, see Feulner et al. (2015).

### And When the Hearts Began to Beat

1. Many thanks to Steve Haddock for helping me to identify the strange lifeforms of Pemba.
2. No one knows how many species of protist there are, but for a recent estimate, see Larsen et al. (2017). These authors estimate around one million free-living protists, with millions more living as parasites of animals.
3. For *Monosiga brevicollis* being single celled, see King et al. (2008). For an account of choanoflagellate feeding, see Pettitt et al. (2002).
4. For an array of choanoflagellate colonies of different forms, see Hartog (1910). Although in modern texts choanoflagellates are often described as being single celled, this author clearly shows that multicellular forms have been known for a long time, and that some of them are relatively common. For examples of colonial protists that are not choanoflagellates see, for example, Hartog (1911).
5. For *Choanoeca flexa*, the choanoflagellate that behaves like a popper toy, see Brunet et al. (2019).
6. For the costs of digestion see, for example, Secor (2009).
7. For early observations that choanoflagellates closely resemble sponges, see James-Clark (1866). Note that the term *choanoflagellate* would be coined later.
8. That some choanoflagellates can switch between swimming and crawling was noted in the nineteenth century—see Saville Kent (1880), p. 172—and recently corroborated by Brunet et al. (2021). For amoeboid cells in sponges distributing food to the rest of the lifeform, see Hartenstein and Martinez (2019).
9. The extent to which phagocytosis remains important within the gut depends on the animal—many insects have retained a phagocytic capacity within the gut, whereas mammals have not—see Hartenstein and Martinez (2019).
10. Macrophages also represent a potential weak spot in the immune system. For example, some bacteria escape being broken down and actively replicate inside macrophages. Some of these are often associated with free-living amoebas, such as the bacterium that causes Legionnaires' disease. See Price and Vance (2014).
11. For a fascinating overview of the roles of macrophages, see Ovchinnikov (2008).
12. For a detailed account of the history of animals between six hundred million years ago and five hundred million years ago, see Mitchell and Pates (2025).

13. For the start of the Phanerozoic being the greatest break in the geological record, see Chadwick (1930).
14. Among animals, oxygen requirements vary considerably. Animals that drift passively, like jellyfish, require much less oxygen than those that swim. Similarly, small animals generally require less oxygen than large ones. The question is not whether a rise in oxygen somehow "caused" the evolution of animals as such but whether a sharp rise in oxygen levels permitted the evolution of large, active animals from smaller, less oxygen-hungry ancestors. For a relationship between oxygen and the diversification of large animals, see Chen et al. (2015) and Sperling et al. (2015); for the possibility that the activities of animals increased the availability of oxygen, see, for example, Butterfield (2018).

## Predators Are Metaservants

1. For predatory protists and their effects on cyanobacteria see, for example, Caron et al. (1991).
2. For protists accelerating the bacterial processes of decomposition, see Fenchel (1987), p. 132.
3. For blue whales sustaining the ecosystem through their excrement, and for populations of krill falling after the populations of whales declined, see Savoca et al. (2021).
4. For excretions of protists feeding bacteria, see Legner (1973).
5. Note that the expansion of predatory lifeforms did not simply add new biomass. It also added new viromass: As predatory lifeforms evolved and expanded in number and kind, the number and kinds of viruses evolved and expanded too.
6. For the biomass of predators, see figure 1B of Hatton et al. (2021). These authors have grouped lifeforms in the ocean by size, with each group containing lifeforms ten times as large as those in the previous group. The surprising result is that each size group contains roughly the same mass, which is roughly one billion metric tons. Their data spans twenty-three orders of magnitude—that is, they have twenty-three size groups, of which fourteen include only predators. A further six contain roughly half predators and half photosynthetic lifeforms such as algae and cyanobacteria, adding at least another three billion metric tons, giving a rough total of seventeen billion metric tons.

## Deadly Terrors

1. For parameciums and their explosive particles, see Hamel et al. (2011).
2. For *Amoeba proteus* selecting one kind of lifeform over another, see Mast and Hahnert (1935).
3. For *Amoeba proteus* being poisoned by a small rose-colored protist, see Terazima and Harumoto (2004).
4. For holes in shells from 730 million years ago, see Porter (2016).
5. For predators attacking shelled animals before the start of the Phanerozoic, see Hua et al. (2003).

6. For evidence of thicker shells due to predatory attacks 517 million years ago, see Bicknell et al. (2025).
7. For ancient guts full of shell fragments, see Peel (2017).
8. For coprolites packed with shells, see Bicknell et al. (2022).
9. For shells showing repairs and thus successful resistance to attack, see Peel (2015) and Bicknell et al. (2022).
10. For the diversification of animals increasing the diversity of protists, see Tang et al. (2024); for the increasing diversity of armor, see Knoll and Kotrc (2015).
11. For the early agglutinated shells of amoebas, see Porter and Riedman (2019).
12. For surprising selectivity in protists building agglutinated tests, see Makled and Langer (2010), which describes lifeforms that make shells that are rich in grains of the titanium-bearing mineral ilmenite, even though these grains are not particularly common in the sediment.
13. For the antiquity of radiolarians, see Braun et al. (2007).
14. For the lower density of calcite compared to aragonite, see Vermeij (1993), p. 51.
15. For nacre being thousands of times as stronger as inorganic versions of aragonite, see Nudelman and Sommerdijk (2012); for the comparative expense of building nacre, see Vermeij (1993), p. 52.
16. For the various onslaughts that shells can be subjected to, see Vermeij (1993), pp. 100–108.
17. For the size of the shells of *Fragum erugatum*, see Morton (2000).
18. For translucence in the shells of *Fragum erugatum*, see Berry and Playford (1997).
19. For the super-salty waters at L'Haridon Bight, see Hickman (2003).
20. For the age of the bay and storms sweeping shells onto the shore, see Morton (2000).
21. For coquina from 550 million years ago, see Hofmann and Mountjoy (2001).
22. Radiolarite knives can be seen at the Naturhistorisches Museum in Vienna.
23. For the sizes of nummulites, see Purton and Brasier (1999).

### Charles Darwin, Biogeologist

1. A version of this chapter was published in *Aeon*. See Judson (2022).
2. For "We feel surprise . . . ," see Darwin (1996), p. 403.
3. For Darwin's account of the development of his ideas, see Barlow (1958), p. 98.
4. For Darwin exploring the reef with at low tide with a "leaping-pole," see Darwin (1842), p. 6. For corals breaking "the violence" of the sea, see Darwin (1996), p. 393.
5. For "there are enormous areas . . . ," see Darwin (1996), p. 405.
6. For Darwin disparaging the reigning reef hypothesis, see the letter from Charles Darwin to his sister Caroline, April 29, 1836, Darwin Correspondence Project, "Letter no. 301," accessed November 23, 2025, https://darwinproject.ac.uk/letter/?docId=letters/DCP-LETT-301.xml ("monstrous"); and Darwin (1842), p. 50 ("preposterous")—he continues his criticisms on pp. 146–147.

7. For "The ocean throwing its waters . . . ," see Darwin (1996), p. 398.
8. For "a monument over an island now lost," see Darwin (1996), p. 418.
9. For "*Starbuck* Isld . . . ," see Darwin (1842), p. 156.
10. Charles Darwin wished for the doubly rich millionaire, and expressed the desire to be "knocked on the head and annihilated" if his ideas were wrong, in a letter to Alexander Agassiz, May 5, 1881. Darwin Correspondence Project, "Letter no. 13145," accessed September 21, 2021, darwinproject.ac.uk/letter/DCP-LETT-13145.xml.
11. The earthworm book was published on October 10, 1881, and by November 5, the publisher was gloating over having sold 3,500 copies, which was a lot for the time. See Robert Francis Cooke to Charles Darwin, November 5, 1881, Darwin Correspondence Project, "Letter no. 13460," accessed August 31, 2022, darwinproject.ac.uk/letter/?docId=letters/DCP-LETT-13460.xml.
12. For Darwin's short paper on worms, see Darwin (1840).
13. Letter from William Buckland to the Geological Society of London, March 9, 1838, Darwin Correspondence Project, "Letter no. 404," accessed August 12, 2021, darwinproject.ac.uk/letter/DCP-LETT-404.xml.
14. For Darwin and his wife moving from London and buying a house with some land, see Browne (2003), pp. 441–442.
15. For Darwin's plan for a long-term experiment, see Darwin (1881), p. 139.
16. For worms producing "intestine-shaped heaps," see Darwin (1840).
17. For "During several years . . . ," see Darwin (1881), p. 145.
18. In his earthworm book, Darwin refers only to "a lady, on whose accuracy I can implicitly rely." But the Darwin correspondence project shows clearly that this lady was Lucy Caroline Wedgwood, Darwin's niece. See Lucy Caroline Wedgwood to Charles Darwin, February 8, 1872, Darwin Correspondence Project, "Letter no. 8203," accessed August 30, 2022, darwinproject.ac.uk/letter/?docId=letters/DCP-LETT-8203.xml.
19. For Darwin's estimate of how much soil earthworms move over the course of one million years, see Darwin (1881), p. 258.
20. For "Archaeologists are probably not aware . . . ," see Darwin (1881), p. 176.
21. For "When we behold . . . ," see Darwin (1881), p. 313.
22. For an account of the expedition to Funafuti, see the report of the Royal Society (1904), especially pp. 40–60 and 186–361.
23. For the expedition to Kitadaitōjima, see Hanzawa (1938).
24. For basalt beneath Enewetak Atoll, see Ladd and Schlanger (1960).
25. For the age of the oldest limestones at the base of Enewetak Atoll, see Ladd et al. (1953).
26. For the estimate of the volume of life-built rock at Enewetak Atoll, see Ladd (1973).
27. For "It may be doubted . . . ," see Darwin (1881), p. 313.
28. For ants in Brazil moving more soil per hectare than earthworms in England, see Branner (1910).
29. In general, the burrowing activities of animals are well known, but for badgers creating hillocks that last for centuries, see Coombes and Viles (2015), and for the contribution of bandicoots, see Fleming et al. (2014).
30. For burrowing in the southern sand octopus, see Montana et al. (2015).
31. For giant fossil burrows in South America, see Lopes et al. (2017).

32. For the corkscrew-shaped burrows of giant beavers in North America, see Martin and Bennett (1977).
33. For burrowing dinosaurs, see Martin (2009).
34. For very early burrows, see Pecoits et al. (2012).
35. For the proposed relationship between burrowing, sulfates, and gypsum deposits, see Canfield and Farquhar (2009).
36. For animals mixing the oceans, see Butterfield (2018) and Houghton et al. (2018).

### Inner Lives and After Lives

1. For "The more life . . . ," see Herbert (1965), p. 267.
2. For the bacterial and archaeal inhabitants of your mouth, see Kuramitsu et al. (2007).
3. For the mass of your microbes, see Fraune and Bosch (2010). Note that quantifying the contribution of the microbiome to human body mass has two components. The first is the mass of all the individual lifeforms. The second is the impact that these lifeforms have on the human tendency to gain weight. Studies from mice show that changing the microbiome can lead to lean mice becoming obese, and obese mice becoming lean—see Fraune and Bosch (2010).
4. The animal nature of corals was established in the eighteenth century, while the presence of some sort of photosynthetic lifeform within the animal tissues was noted about a century later. However, the nature of the relationship between the two forms was much more difficult to establish, with some authors arguing that it was essentially predatory (the coral was eating the dinoflagellates) or parasitic rather than symbiotic and of mutual benefit—for a historical overview, see Yonge (1968). It wasn't until the late 1960s that experiments confirmed the symbiotic nature of the relationship—see Muscatine (1967). For the symbiotic origin of the photosynthetic capacity of certain dinoflagellates, see Keeling (2013). Note that these are secondary symbioses—they acquired chloroplasts from a lifeform that already had them.
5. For dinoflagellates passing glycerol to coral animals, see Hackett et al. (2004). For the corals providing nitrogen and phosphorus, see Yonge (1968).
6. For the advantages of translucent shells for symbiont-harboring clams, see Yonge (1968) and Hickman (2003).
7. For an account of the biology of *Riftia*, see Van Dover (2000), starting on p. 174. For its size, see McClain et al. (2015).
8. For huge numbers of bacteria living inside *Riftia*, see Van Dover (2000), p. 176.
9. For *Riftia* digesting its bacterial residents, see Hinzke et al. (2019).
10. For the site of discovery of *Chrysomallon squamiferum*, see Warén et al. (2003).
11. For the amazing armor of *Chrysomallon squamiferum*, see Warén et al. (2003) and Yao et al. (2010).
12. For the geovorous symbionts of *Chrysomallon squamiferum*, see Goffredi et al. (2004).
13. For a fascinating overview of relationships between marine animals and geovores, see Dubilier et al. (2008).

14. For the initial account of the discovery of biological communities living on deep-sea vents, see Corliss et al. (1979).
15. De Bary took *symbiosis* to mean all relationships between dissimilar lifeforms, be they parasitic or beneficial, or something in between—see Oulhen et al. (2016). Since then, the term's definition has been refined (though it is still somewhat slippery); I use it in the sense of lifeforms that live together with mutual benefit.
16. For early work on relationships between animals and photosynthesizers, see Geddes (1882) and Krueger (2017). Note that de Bary was not working on animals but on lichens. These result from a symbiosis between a fungus and an alga or cyanobacterium.
17. For the "extra" area provided by the shell of a giant clam, see Vicentuan-Cabaitan et al. (2014).
18. For lifeforms that live on the shells of giant clams, see Vicentuan-Cabaitan et al. (2014).
19. For the astonishing microbiome of the sponge, see Hentschel et al. (2012).
20. For marine snails spending 60 percent of their energy making mucus, see Davies and Hawkins (1998), p. 40.
21. For snails saving themselves the costs of making mucus, see Davies and Blackwell (2007).
22. For mucus trails sustaining bacteria, see Davies and Hawkins (1998), p. 46.
23. For pyritized mucus trails in ancient rocks, see Schieber (2002) and Savrda et al. (2016).
24. Many thanks to Mark Laidre for clarifying how long a single shell may remain in use after the death of the maker.
25. For hermit crabs wearing fossil shells, see Barnes (2001).
26. For an impressive array of hermit crab associates, see Williams and McDermott (2004) and (for the snails) Vermeij (1993), p. 145.
27. For relationships between hermit crabs and anemones, see Gusmão et al. (2020).
28. For fish nesting in empty shells, see Sato (1994).
29. For a protist building its agglutinated house exclusively from shells of a different species of protist, see Pearson and IODP Expedition (2018).
30. For an ancient hermit crab installed in an ammonite, see Fraaije (2003).
31. For trilobites making use of nautiloid shells, see Davis et al. (2001).
32. For ancient sandstones showing tracks that might be due to an early hermit lifestyle, see Hagadorn and Seilacher (2009).

## The Tragedy of Animals

1. For the parameciums eating 1,300 bacteria per hour, see Fabbro et al. (2001).
2. For the quantities of food consumed by whales, see Savoca et al. (2021).
3. For the estimate that, collectively, three thousand pairs of swifts nesting on Gibraltar feed their chicks eighteen million insects each day, see Cramp (1994), p. 661.
4. For Darwin's attempt to reconcile himself to the cruelty of predation, see Darwin (1859), p. 79.

5. For an experiment that shows algae eaters enhancing the diversity of algae, see Leibold et al. (2017).
6. For Darwin on the rippling effects of predators, see Darwin (1859), p. 74. Note that he speaks of "humble-bees"; today, however, these are known as bumblebees.

### The Planetary Accountant Gets a Headache

1. For changes in reef area over time, see Kiessling (2006).
2. The shatterproof properties of coquina were discovered in 1702, when the British attacked the Castillo de San Marcos, a fort in Florida that was then under Spanish control. The fort had been built out of coquina from a local quarry and turned out to be impervious to cannon fire. This was a surprise even to those defending the fort—see Williams (2019), chapter 5. For an analysis of the properties of coquina, see Subhash et al. (2015).
3. Many thanks to Paolo Conti for explaining the relationships between limestones, marbles, and the folds of mountains to me. Also see Carmignani et al. (2017).
4. For the mass of protists being twice that of animals, see Bar-On et al. (2018). Note that this estimate is quite uncertain and that it is for the Earth today, not for any point in the past. However, I see no reason to think that the overall pattern in the past would have been different.

## SEGUE

### A Terrestrial Enlightenment

1. For evidence of early terrestrial ecosystems—that is, ecosystems on the surface of the land—see table 1 of Lenton and Daines (2017); for the dark colors of such ecosystems, see Garcia-Pichel (2023).
2. For the first traces of plant fossils around 470 million years ago, see Edwards et al. (2022).
3. For the configuration of the continents at 470 million years ago, see Scotese (2021).
4. For an estimate of oxygen levels around 470 million years ago, see Brand et al. (2021).
5. For carbon dioxide levels around 470 million years ago, see Nardin et al. (2011); they estimate the quantity of the gas at that time to have been between 2,800 and 4,760 parts per million. For comparison, in 2023, the global average carbon dioxide was measured to be 419.3 parts per million (research.noaa.gov/no-sign-of-greenhouse-gases-increases-slowing-in-2023); in the late 1700s, the annual average was 280 parts per million. As carbon dioxide is a greenhouse gas, such high levels of it would have warmed the climate of back then, but not as dramatically as such levels would today, owing in part to the Sun of those days being fainter than it is now.
6. For moderately elevated levels of carbon dioxide causing cognitive problems, see Jacobson et al. (2019). Note that exposure to higher levels of carbon

dioxide—the dreaded "black damp" of coal miners—can be lethal. See Haldane (1940a) and Permentier et al. (2017).

7. For fragments of early plants resembling mosses, see Edwards et al. (2022). Many thanks to Paul Kenrick for clarifying a number of points and providing me with a mental image of the earliest known fossil plants, the eophytes.
8. For freshwater green algae as the ancestors of plants, see Delwiche and Cooper (2015).
9. As eukaryotes also evolved only once, plants could be argued to be triply singular, but for simplicity, I am counting singularities that arose after the origin of eukaryotes.
10. I estimated the number of chloroplasts in a spinach leaf by extrapolating from the table given in Possingham and Saurer (1969).
11. For the number of plant species known to science, see Christenhusz and Byng (2016).
12. For the numbers of fungi known to science, see Cheek et al. (2020); for an estimate of those remaining to be discovered, see Hawksworth and Lücking (2017).
13. For fungi not being objects of "general interest" see Berkeley (1860), p. 77. Note that certain species of ants and termites cultivate fungi with great success; indeed, the largest known mushroom is produced by fungi that are cultivated by termites. The cap of this mushroom can be as much as one meter across—see Pegler and Piearce (1980).
14. For the high value of matsutake mushrooms and where to find them, see Tsing (2015). For difficulties in cultivating mushrooms, especially matsutake and white truffles, see Wang and Chen (2014).
15. For parasitic plants, see Twyford (2018).
16. For fungi being more closely related to animals than they are to plants, see Wainwright et al. (1993) and Baldauf and Palmer (1993).
17. For the singular origin of fungi, see Berbee et al. (2020).
18. For the antiquity of fungi, see Bonneville et al. (2020); for their protistan ancestors see, for example, Berbee et al. (2020).
19. For the effects that fungi may have upon rocks, see Gadd (2007).
20. For the weirdness of fungi, see Fricker et al. (2017) and Roper et al. (2015).
21. For the antiquity of the association between plants and fungi see, for example, Field and Pressel (2018).
22. It is, of course, possible to imagine a world without fungi, in which plants of some kind evolve anyway. However, that would require plants to have more and different cell types, including some rather unlike those they actually have, and the path length, and thus the waiting time, would be correspondingly longer.
23. For the activities of plants contributing new minerals (and also greatly increasing the rate of formation of clay minerals) see, for example, Hazen and Ferry (2010).

### Fire Planet

1. For the frequency of lightning strikes today, see Christian et al. (2003); for lightning causing fires, see Wierzchowski et al. (2002), Larjavaara et al. (2005), and Zanon et al. (2008).

2. Just to clarify, a volcano is not itself a fire. Instead, it is a source of hot gases and molten rock—otherwise known as lava. If lava flows down a hillside, it can incinerate trees and other structures in its path. Burning ash can then be blown by wind to start a fire somewhere else.
3. Jupiter's moon Io is among the celestial bodies in the Solar System that presently have active volcanoes. Mars and Venus have had them in the past, though whether they might erupt again is unclear; the same goes for Earth's Moon.
4. For the naming of *Feuerluft*, see West (2014).
5. For how much oxygen is required for ignition, see Lenton (2013).
6. Many thanks to Andrew Scott for clarifying the characteristics of charcoal and how it can resist compression.
7. The earliest clear fossils of animals that lived on land date to around 415 million years ago—see, for example, Jeram et al. (1990) and Glasspool et al. (2004). Older fossils and traces of terrestrial animals remain controversial—see, for example, Wellman et al. (2023)—with a number of authors arguing that earlier animal traces are marine, not terrestrial. However, it seems very likely that the appearance of terrestrial animals predates the oldest undisputed fossils.
8. In general, nontracheophyte plants are low and flat, rising just a few centimeters from their substrate, but some mosses are exceptions, growing to heights of seventy-five centimeters. These "tall" mosses have independently evolved a vascular system but are limited in other ways—see Brodribb et al. (2020).
9. For the dimensions of *Prototaxites*, see Nelsen and Boyce (2022).
10. For a summary of the controversies surrounding *Prototaxites*, see Nelsen and Boyce (2022). For the argument that these lifeforms were neither plant nor fungus but instead belonged to an entirely different, and now extinct, group of multicellular eukaryotes, see Loron et al. (2026).
11. For the possibility that *Prototaxites* would be struck by lightning and consequently initiate fires, see Glasspool and Gastaldo (2022).

### The Nature of Fire

1. For Egyptian views of fire as described by Herodotus, see book 3, chapter 16, of his *Histories*. My rendition is a slight adaptation of the translation provided by Tylor (1865), p. 232.
2. For fires traveling uphill, see Stott (2000).
3. For Haldane's comparison between flames and animals, see Haldane (1940b), p. 57.
4. For vivid accounts of fire whirls, see Pirsko et al. (1965) and Haines and Updike (1971).
5. For smoke from wildfires altering patterns of cloud formation and rainfall, see Andreae et al. (2004).
6. For fires causing temporary drought, see Bevan et al. (2009); for violent thunder- and hailstorms, see Andreae et al. (2004).
7. For wildfires in Mexico creating storms in Canada, see Lyons et al. (1998).
8. Fires started by lightning strikes caused by storms that were caused by fires have been reported in both Canada and Australia. See, for example, Latham and Williams (2001) and Dowdy et al. (2017).

9. Today, some ecologists agree with the ancient Egyptians and argue that fire should be considered an herbivore—see Bond and Keeley (2005).
10. For the tardy appearance of herbivory, see Labandeira (2013).
11. For plant responses to fire see, for example, Keeley et al. (2011).
12. For examples of fire-loving fungi, see Hughes et al. (2020).
13. For the relationship between lightning, fires, and the dry season, see Stott (2000).
14. For higher oxygen meaning hotter fires that are easier to ignite, easier to sustain, and more likely to burn when wet, see Glasspool et al. (2015).

## Two Worlds of High Fire

1. For the composition of Gondwana, see Scotese (2021).
2. For temperatures at 314 million years ago, see Scotese (2021), table 3. For the temperatures in 2025, see Copernicus (2026), p. 5.
3. For the stature of the giant club mosses, see Thomas and Cleal (2018).
4. For the unusual densities of giant club mosses, and for light filtering to the forest floor, see Kenrick and Davis (2004), pp. 85–86.
5. For giant millipedes weighing fifty kilograms, see Davies et al. (2022). Note that the giant dragonflies of 314 million years ago are more correctly (but, to the uninitiated, less informatively) called griffinflies. Also note that there is considerable disagreement about why all these animals were so large then, but not since. Some have pointed toward the prevailing high oxygen levels, others to higher air pressure, and still others to the absence of flying predators like birds. Or perhaps there is no single explanation, and it was a conspiracy of the three.
6. The diet of the extinct giant millipedes is generally assumed to have been plant remains, but no mouthparts of these animals have so far been found, and some authors speculate that they might have been predators—see Schneider et al. (2010).
7. For a fossil forest dating to 390 million years ago, see Davies et al. (2024); for trees evolving repeatedly see, for example, Kenrick and Davis (2004), pp. 68–71.
8. The island of Socotra in the Indian Ocean provides a similar example: It is home to *Dendrosicyos socotranus*, also known as the cucumber tree, which is the only species in its family to have evolved into a tree.
9. For different ways to be a tree, and for the presence of different tree habits in the Carboniferous, see Kenrick and Davis (2004), pp. 68–71.
10. For the shiftiness of meanders in the absence of vegetation, see Ielpi and Lapôtre (2020).
11. For log jams more than three hundred million years ago, see Gastaldo and Degges (2007) and Gibling et al. (2010).
12. For animals sheltering in burned-out tree stumps, see Scott (2001).
13. For coal deposits from plants that lived more than four hundred million years ago, see Kennedy et al. (2013).
14. Many thanks to Michel Raymond for a wonderful trip to Graissessac.
15. For the strike in Graissessac, see Johnson (1985).
16. For the average global temperature around ninety million years ago, see Scotese (2021), table 3.

17. For sea level differences ninety million years ago, see Scotese (2021).
18. For the estimated number of species of flowering plants (the angiosperms), see Christenhusz and Byng (2016).
19. For the number of species of the other major extant group of seed plants, the gymnosperms, see Christenhusz and Byng (2016).
20. The question of when angiosperms first appeared has vexed scientists for more than a century. For one current view, see Silvestro et al. (2021).
21. For early angiosperms as small, weedy plants, see Royer et al. (2010) and Friis et al. (2015).
22. For the suggestion that trampling by dinosaurs might have opened up spaces for angiosperms, see Bond and Midgley (2012).
23. For the evolution of the greater photosynthetic efficiency of angiosperms compared to other plants, see Feild et al. (2011).
24. For flowering plants burning hotter than ferns, see Belcher and Hudspith (2017).
25. As an example of the vicious cycle of fire leading to shifts in vegetation leading to fire, see Laurance (2003).
26. For angiosperms causing shifts in fire and the distribution of vegetation, see Belcher and Hudspith (2017). For angiosperms causing the extinction of other plants, see Condamine et al. (2020).
27. For examples of flowers preserved as charcoal and some of the insights they can lead to, see Friis et al. (2006).
28. For flowers preserved in amber, see Shi et al. (2022).
29. For resins being produced in abundance during this time in Earth history, see Delclòs et al. (2023).
30. For resin production in response to wildfire, see Seyfullah et al. (2018), especially figure 9. Note that fire is not the only phenomenon that stimulates plants to produce resin—other stimuli include insect attacks and storm damage.
31. For hotter fires changing the soil structure and increasing erosion, see Brown et al. (2012).
32. Note that the reasons that coccolithophores manufacture coccoliths remain under discussion. Armor is the most popular explanation, but there are others, including protection from viruses, or a greater capacity to sequester carbon dioxide and therefore grow faster. See, for example, Monteiro et al. (2016) and Stanley et al. (2005).
33. Until recently, *Gephyrocapsa huxleyi* was named *Emiliania huxleyi*, or Ehux to its friends. For the renaming, and the reasons for it, see Bendif et al. (2019).
34. For the size of the 1998 coccolithophore bloom, and for the blooms forming pale patches that are readily visible from the air, see Raitsos et al. (2006). For less spectacular, but still enormous, blooms see Brown and Yoder (1994) and Tyrrell and Merico (2004).
35. For numbers of coccoliths in different species see, for example, Monteiro et al. (2016).
36. For one-third of the energy generated from photosynthesis being devoted to the production of coccoliths, and for the rate of production of coccoliths, see Monteiro et al. (2016).

37. For flint nodules in old animal burrows see, for example, Bromley and Ekdale (1984).
38. For hypotheses to account for flint formation in old animal burrows, see Mortimore (2020).
39. For the suggestion that carbon burial in the oceans led to more forest fires during the Cretaceous, see Boudinot and Sepúlveda (2020).
40. For extensive deposits of petroleum dating to the Cretaceous see, for example, Bishop (2023).

## One Day in Spring

1. For the size of the object that smashed into the planet sixty-six million years ago, and where it landed, see Morgan et al. (2022).
2. For the time of year that the Cretaceous-ending asteroid struck, see During et al. (2022).
3. For the quantities of dust and gas generated by the impact at the end of the Cretaceous, see Morgan et al. (2022). For the collapse in average global temperature, see Scotese (2021), table 3. For tsunamis and wildfires, see Gulick et al. (2019).
4. For bees, beetles, and butterflies evolving in tandem with angiosperms, see Peris and Condamine (2024).
5. For early mammals around 225 million years ago, see Cabreira et al. (2022).
6. For mammals evolving to be out and about during the day after the demise of the dinosaurs, see Maor et al. (2017).
7. For the evolution of primate diet in the context of angiosperms see, for example, Lim et al. (2021).
8. For fewer fires in the time from the Cretaceous, and for an increase in fires starting around seven million years ago, see Bond (2015). For the expansion of grasslands around seven million years ago, see Cerling et al. (1997).
9. For grasses benefiting from fires removing young trees, see Bond et al. (2003).
10. For sediments showing fires and savannas spreading together see, for example, Hoetzel et al. (2013).
11. For grazing animals evolving in concert with grasses, see Cerling et al. (1997).
12. Today the closest cousins of humans are the chimpanzees—the common chimpanzee and the bonobo. The divergence between the ancestors of humans and those of the chimpanzees seems to have begun between 9.3 and 6.5 million years ago—see Almécija et al. (2021). That is, the histories of humans and the chimpanzees began to diverge at roughly the time that grasses, grazers, and fires were all becoming more abundant.

## The Planetary Accountant Is in a Frenzy

1. For fungi attacking plants more than four hundred million years ago, see Strullu-Derrien et al. (2023).
2. For viruses of coccolithophores, see Wilson et al. (2002); of fungi, see Hough et al. (2023); of plants, see Lefeuvre et al. (2019).
3. For diversity on land overtaking the diversity in the oceans, see Vermeij and Grosberg (2010).

4. For coccolithophores contributing to albedo, see Tyrrell et al. (1999).
5. For the possibility that giant plant-eating dinosaurs might have contributed to global warming in the Cretaceous, see Wilkinson et al. (2012).

## ROCK—LIGHT—OXYGEN—FLESH—FIRE

1. For "Of all human inventions . . . ," see Frazer (1930), p. 1.

### Fire Creature

1. Frazer (1930), p. 50.
2. For evidence of hearths from almost 790,000 years ago, see Goren-Inbar et al. (2004).
3. For fires in the Wonderwerk Cave, see Berna et al. (2012).
4. For evidence of fires and hominins in East Africa 1.5 million years ago, see Hlubik et al. (2019). Many thanks to Sarah Hlubik for describing to me the environment in which these fire creatures would have lived.
5. The early fire creatures might have lit fires for reasons other than cooking. Fires, obviously, provide light and warmth (perhaps particularly important for a hairless ape—see Wrangham, 2017). In addition, they may provide protection from biting insects and the diseases they bring (although some such insects appear to be drawn to fires—see Duke, 1955), and perhaps also from dangerous predatory animals. Although the latter is widely assumed (and often stated as fact), the evidence is actually equivocal and may depend on the species. Some observers report that hyenas are drawn to fire; others, that black rhinos sometimes charge campfires and stamp them out—many thanks to Simon Mduma for describing his experiences to me. At the same time, lions are more likely to attack humans on dark, moonless nights—see Packer et al. (2011). Perhaps the real advantage of campfires is less deterrence than the fact that flames illuminate the shadows of the night, making any approaching predators easier to spot and thus reducing the element of surprise. Fires also have uses beyond the campsite. They can be used to drive game or smoke animals out of holes or nests (think bees). They can also be used to burn off long grasses and brush, clearing out undergrowth where dangerous animals could hide and also regenerating landscapes—a process called firestick farming. For these and other examples, see Scherjon et al. (2015). However, since—as I describe in this section—our ancestors likely discovered cooked food by following landscape fires, since cooking appears to have had such dramatic effects on the evolution of the human form, and since these other uses leave no distinct traces, I focus on fire and cooking here.
6. For birds being drawn to wildfire, see Thiollay (1971) and Bonta et al. (2017).
7. For chimpanzees looking through ash for roasted nuts, see Brewer (1978), p. 232.
8. For rhesus monkeys eating coconuts retrieved from the ashes of a fire, see Armelagos (2010).
9. For baboons eating cooked grasshoppers, see Parker et al. (2016).
10. For chimpanzees preferring cooked food, see Wobber et al. (2008).
11. For mice preferring cooked food, see Carmody et al. (2011).

12. For captive chimpanzees keeping raw food until they can cook it, see Warneken and Rosati (2015).
13. For the strong effect of cooking on roots and tubers, see Hardy et al. (2015).
14. For cooking increasing the digestibility of potatoes, see Cummings and Englyst (1995).
15. For the argument that in killing pathogens, cooking reduces expenses incurred by the immune system, see Carmody et al. (2016).
16. For humans spending a remarkably short time on meals each day, see Organ et al. (2011). These authors predict that without cooking and other forms of food processing, humans would be required to eat for almost twelve hours each day.
17. For how much time chimpanzees and gorillas spend eating, see table S1 in Fonseca-Azevedo and Herculano-Houzel (2012).
18. For amenorrhea and weight loss in raw foodists, see Koebnick et al. (1999) and Kwanbunjan et al. (2000).
19. For modern raw foodism being permitted by the advantages of appliances as well as high quality, easily digestible food, see Wrangham (2017).
20. The hypothesis that cooking was an essential step in human evolution has been developed by Richard Wrangham and his colleagues. See, for example, Wrangham et al. (1999), Carmody and Wrangham (2009), Wrangham (2009), and Wrangham (2017).
21. For modern humans having smaller guts, teeth, mouths, and weaker jaws than their ancestors, see Wrangham (2017).
22. For the human brain consuming 20 percent of your energy when you are resting, see Fonseca-Azevedo and Herculano-Houzel (2012).
23. For the energy costs of the brains of nonhuman primates, see Fonseca-Azevedo and Herculano-Houzel (2012).
24. For human brains containing three times as many neurons as gorilla brains, see Fonseca-Azevedo and Herculano-Houzel (2012).
25. For gorillas being at their limit with respect to the hours spent eating, see Fonseca-Azevedo and Herculano-Houzel (2012).
26. For chimpanzees reigniting fires by rearranging the embers, see Brewer (1978), p. 176.
27. For observations of captive chimpanzees handling cigarettes, see Brink (1957).
28. For reports of firehawks spreading fires, see Bonta et al. (2017).
29. For Darwin's account of fire-making in Tahiti, see Darwin (1996), p. 354.
30. For a fascinating account of tinder in different cultures, see Hough (1926), pp. 120–123.
31. For fire legends involving mountain lions or bison, see Reclus (1910), p. 400. Note that the source gives *panther* and *buffalo*; but these terms are now antiquated, and I have replaced them with modern equivalents.
32. For myths featuring toads, vultures, and hawks, and for fire being hidden in a tree, see Frazer (1930).
33. For a survey of the mythology of fire, including tales of humans stealing fire from animals who were cooking food, see Frazer (1930).
34. Flint struck against flint generates a kind of luminescence but no spark—see Hough (1926), p. 111.

35. For the possibility that owing to their inherent instability, pyrites for fire making may have vanished from archaeological sites, see Hough (1926), p. 111.

### The Furnace of Invention

1. For Pliny on the wonders of fire, see book 36, chapter 68, of Bostock and Riley (1857).
2. For the heating of flints improving the ease of knapping them, see Agam et al. (2021).
3. For animals butchered at Qesem Cave, see Stiner et al. (2009).
4. For a simple method of making pitch from birch bark, see Schmidt et al. (2019).
5. For possible recipes for mixed glues and the need to heat them, see Wadley et al. (2009).
6. For ancient charcoal drawings and torch marks at the Chauvet-Pont d'Arc Cave see, for example, Quiles et al. (2016) and Théry-Parisot et al. (2018).
7. The possibility that flickering firelight was intended to create an animated effect in cave art has been proposed by, for example, Azéma and Rivère (2012).
8. For clay pots in Asia around eighteen thousand years ago, see Cohen et al. (2017).
9. For limestone being transformed into plaster 10,500 years ago, see Kingery et al. (1988).
10. For early wine making, see McGovern et al. (2017).
11. For an account of the obsidian trade, see Kuzmin et al. (2020).
12. For the domestication of donkeys and their use as pack animals, see Rossel et al. (2008).
13. For copper initially being preferred to gold, see Roberts et al. (2009).
14. For descriptions of how ancient peoples worked with native copper, see Craddock (1995), pp. 97–101. Many thanks also to Paul Craddock for explaining techniques of ancient metalworking to me.
15. For trinkets of native copper from around ten thousand years ago, see Maddin et al. (1999).
16. For suggestions of magic at the origins of metallurgy, see Budd and Taylor (1995).
17. For the age and hillside settings of ancient furnaces, see Craddock (2000).
18. For bellows being more efficient than humans blowing through pipes, see Rehder (1994). Note that over time, the technology of bellows has also evolved—see Craddock (1995), pp. 180–185.
19. A few terrestrial deposits of native iron also exist, the most significant of which—and the only one known to have been exploited by humans prior to the last two hundred years—has been found on Disko Island, off the coast of Greenland. See Craddock (1995), pp. 101–103.
20. Many thanks to Ansgar Greshake of the Museum für Naturkunde in Berlin for showing me some iron meteorites.
21. The timing of the Hoba meteorite's fall is necessarily uncertain; eighty thousand years ago is thought to be the earliest it could have landed—see McCorkell et al. (1968).

22. For an account of the discovery of the Hoba meteorite, see Spargo (2008). According to this source, the discoverer, a Mr. Jacobus Hermanus Brits, described the event thus: "While I was sitting on the rock [the meteorite] it struck me that this rock was black whereas everything around it was limestone. I took my knife, scraped it, and discovered that it was shiny . . ."
23. For the mass of the Hoba meteorite, see Beech (2013).
24. I published an account of my visit to the Hoba meteorite in *Air Mail*—see Judson (2020a).
25. For the gentle landing of the Hoba meteorite, see Beech (2013).
26. For the mining of iron meteorites, see Craddock (1995), pp. 103–109.
27. For ancient beads of meteoric iron and the circumstances in which they were found, see Rehren et al. (2013) and Johnson et al. (2013).
28. For a discussion of the spread of iron's adoption and an analysis of various hypotheses, see Erb-Satullo (2019).
29. For an estimate of the mass of limestone in the Great Pyramid, see Romer (2007), p. 118.
30. This translation of Ovid's *Metamorphoses*, book 1, lines 137–143, is from Agricola (1950), p. 7.
31. For a brief primer on firesetting and an account of its history, see Craddock (1992).
32. For a single fire causing the collapse of hundreds of kilograms of rock, see Craddock (1992).
33. For picks of antler and hammers of stone, see Craddock (1992).
34. In places, firesetting remained in use into the twentieth century—see Weisgerber and Willies (2000).
35. For pictures of ancient mines that were excavated by firesetting, see Craddock (1992).
36. Methane is a common cause of problems in coal mines. In metal mines, it is less common, but not unknown. Many thanks to Paul Craddock for clarifying this point.
37. For fumes from firesetting resulting in arsenic poisoning, see Agricola (1950), p. 215.
38. Firesetting is referred to in some ancient texts, including the Book of Jeremiah in the Old Testament of the Bible (for further discussion of ancient references to the technique, see Craddock, 1992; Weisgerber and Willies, 2000). But as far as I've been able to discover, the first images of it didn't appear until 1556—see Agricola (1950), p. 120.
39. Plato's remarks on deforestation are cited in Wertime (1983).
40. For the inefficiency of converting wood to charcoal, see Craddock (1995), pp. 193–194.
41. For the area of the copper mines at Wadi Faynan and the quantities of slag there, see Hunt et al. (2007). To estimate the mass of charcoal and wood, I have followed Craddock (1995), pp. 193–194, and assumed a fuel-to-slag ratio of 2 to 1, and that from burning a given mass of wood, only 20 percent becomes charcoal (though depending on the type of wood burned, this may be a significant overestimate).
42. For trees disappearing in the vicinity of Wadi Faynan, see Hunt et al. (2007).
43. For ancient religions holding trees to be sacred, see Hughes (1983).

44. For slag heaps all around the Mediterranean, the quantity of slag that they are thought to contain, and the number of trees required to fuel all that industry, see Wertime (1983).
45. For lime kilns requiring one thousand donkey loads of wood, see Forbes and Koster (1976).
46. For copper pollution of rivers seven thousand years ago, see Grattan et al. (2016).
47. For patterns of lead emissions, see Shotyk et al. (1998).
48. For Pliny describing the transport of marbles, see book 36, chapter 1, of Bostock and Riley (1857).
49. For Pliny deploring the absence of laws against importing marble, and for humans elevating themselves above the gods, see book 36, chapter 2, of Bostock and Riley (1857).

## A Fiery Transcendence

1. There is scant evidence for the regular use of coal as fuel before 3,700 years ago—see Qiu et al. (2023); however, the stuff was perhaps used sporadically as fuel somewhat earlier—see, for example, Théry et al. (1996).
2. For jet beads more than twenty thousand years ago, see Corchón et al. (2008).
3. For Marco Polo's remarks about coal and warm baths in China, see Wright (1907), pp. 229–230.
4. In the late seventeenth century, the number of oak trees required for one ship of the line seems to have varied between 760 and 2,900, depending on the class of vessel—see Flinn (1959).
5. For an account of wood shortages in Britain in the sixteenth and seventeenth centuries, see Rhodes (2018), chapter 1, and Galloway (1898), p. 79; in France, see Wulf (2015), p. 58; in Portugal, see Kumar (2018); in Venice, see Appuhn (2009).
6. I came across this quotation about the Newcomen engine in Rhodes (2018), p. 41, but have been unable to discover who said it.
7. For a comparison of the costs and benefits of the Newcomen engine versus horses, see Galloway (1882), p. 82.
8. For the most difficult industrial problem of the seventeenth century, see Galloway (1882), p. 39.
9. For the use of coke in China and in Europe, see Craddock (1995), p. 198.
10. For iron production doubling every eight to ten years, see Galloway (1898), p. 304.
11. For railways and locomotives being called into existence by mining, see Galloway (1882), p. vi.
12. For roughly one-third of electricity coming from coal-fired power stations, see IEA (2025), p. 7.
13. For quantities of coal mined in Britain and the United States in 1905, see Howarth and Ross (1910), p. 579, table iv.
14. For coal production in China in 2024, see Energy Institute (2025), p. 47. In that year, Chinese mining accounted for just over half of all coal production.

15. The nomenclature for these materials is confusing, with many terms used interchangeably and inconsistently, even in the scientific literature.
16. For Pliny's remarks about the Dead Sea, see book 5, chapter 15, parts 15 and 16, of Bostock and Riley (1855).
17. For great lumps of asphalt coming to the surface of the Dead Sea, see Nissenbaum (1978).
18. For hypotheses as to origins of the Dead Sea asphalt, see Nissenbaum (1978).
19. For bitumen being used for hafting by Neanderthals 40,000 years ago, see Boëda et al. (1998) and Connan (1999).
20. For boats waterproofed with asphalt in what is now California, see Arnold and Bernard (2005).
21. For asphalt as a mortar in the Ishtar Gate of Babylon, see Connan (1999).
22. For the Babylonians using asphalt to make a road surface, see Connan (1999).
23. For asphalts from the Dead Sea being used for mummification, see Clark et al. (2016).
24. For an ancient naval battle fought over the asphalts of the Dead Sea, see Nissenbaum (1978).
25. For bamboo pipes carrying natural gas in China more than 2,200 years ago, see Temple (1991), pp. 78–81.
26. For Pliny's account of the oil spring near Agrigentum (modern-day Agrigento), see Bostock and Riley (1857), book 35, chapter 51.
27. For beeswax as an early source of lighting, see Longmuir (1998).
28. For oil wells in China 2,000 years ago, see Feng et al. (2013), p. 3.
29. For an account of digging for oil in Myanmar, see Longmuir (1998).
30. In the West, kerosene appears to have been discovered at least twice, at more or less the same time, by people working independently. In North America, it was discovered by Abraham Gesner; in Europe, by Jan Zeh and a number of his associates in Lemberg. Gesner received a patent in 1854; Zeh received his in 1853. Kerosene was, however, refined in China perhaps two hundred years earlier—see Feng et al. (2013), p. 2.
31. For kerosene lamps in the general hospital in Lemberg, see Frank (2005), p. 58.
32. For oil production in Pennsylvania between 1859 and 1879, see McLaurin (1896), p. 53.
33. The first oil tankers were designed by Ludvig Nobel—brother of Alfred, the inventor of dynamite who is remembered today for the prizes he endowed. Ludvig came to Baku to help his elder brother Robert, who had started an oil refinery there. With financing provided in part by Alfred, the Nobel brothers built an oil empire and contributed to the transformation of the industry—see Tolf (1976).
34. For the transatlantic crossings of oil tankers becoming routine, see Tolf (1976), pp. 59–60.
35. For advantages of oil on board ship, see Dahl (2000).
36. For the tsar's fleet in the Caspian converting to oil, see Tolf (1976), p. 70. For the Royal Navy, see Dahl (2000).
37. For the production of 7,800 million metric tons of plastic by 2015, see Geyer et al. (2017).
38. For forty kilograms of plastic per person per year, see Zalasiewicz et al. (2016).

39. For the quantity of oil used to make plastics, see Thompson et al. (2009).
40. It may strike you as curious that nitrogenase is restricted in its distribution. After all, bacteria and archaea often pass genes around. Yet in many environments, the ability to fix nitrogen may not be useful. This is particularly likely to be the case where the supply of phosphorus (the *P* of SPONCH) is limited and having access to extra nitrogen may not alleviate the constraint. Certainly, some cyanobacteria appear to have lost the genes for nitrogenase, which suggests that in at least some cases, the costs of having the genes outweighs any advantages.
41. For the collection of bird droppings from special pigeon towers, see Tepper et al. (2018).
42. For the sizes of deposits on the guano islands, see Hutchinson (1950), p. 68.
43. For Peruvian exports of bird droppings, see Cushman (2014), p. 45.
44. For the US government encouraging citizens to seize uninhabited guano islands, see Cushman (2014), p. 82.
45. For Bolivia losing its coastline during the War of the Pacific, see Cushman (2014), p. 73.
46. For a history of the early efforts to synthesize ammonia, see Travis (2015).
47. For "The pursuit of a single . . . ," see Travis (2015), p. 146.
48. For the estimate that roughly half of the human population is dependent on nitrogen fertilizer produced by the Haber–Bosch process, see Erisman et al. (2008).
49. For the change in labor required to produce one kilogram of American wheat, see Smil (2022), p. 51.

## The Greatest Servants

1. For chimpanzees using tools, see Visalberghi et al. (2015).
2. For monkeys using tools, see Proffitt et al. (2016).
3. For crows using tools see, for example, Weir et al. (2002).
4. For parrots using tools, see Auersperg et al. (2012).
5. For insects using tools, see Pierce (1986).
6. For early hominin-made stone tools, see Harmand et al. (2015).
7. For vervet monkeys making different sounds for different predators, see Seyfarth et al. (1980).
8. For the vocabularies of sperm whales, see Sharma et al. (2024); of elephants, Poole (2011).
9. For the dance language of bees, see von Frisch (1974).
10. For the scale of human energy flow as compared to the biosphere, see Kleidon (2023).
11. For underground rivers, see nationalgeographic.com/environment/article/underground-rivers (n.d.).
12. For Jakarta sinking, see Tzampoglou et al. (2023).
13. For subsidence in the San Joaquin Valley and its consequences, see Lees and Knight (2024).
14. For the pumping of water from aquifers contributing to the Earth shifting on its axis, see Seo et al. (2023).

15. For early reports of tremors and their clear association with gold mining in South Africa, see Gane et al. (1946).
16. For rockbursts and their part in mining fatalities, see Heunis (1980).
17. For mining activities triggering sizable earthquakes that result in deaths, injuries, and collapsing buildings, see Durrheim (2010).
18. For the "grand geomechanical experiment," see Hennings (2024).
19. For the reawakening of ancient faults by fracking, see Magnani et al. (2017).
20. For earthquakes due to fracking, see Villa and Singh (2020).
21. For the earthquake in Pohang, see Lee et al. (2019).
22. For bombs and the cratering of landscapes in Verdun and Vietnam, see Hupy and Schaetzl (2006).
23. For the effects of the "Bravo" blast over Bikini Atoll, see Maragos (2011). Note that Nam is sometimes referred to as Namu.
24. For the detonation of bombs underground causing ridges to lose height, see Hupy and Schaetzl (2006); for lurching mountains, see Wang et al. (2018); for weakened mountains, see Adushkin and Leith (2001).
25. For the size of the shell mound at Saida, see de Saulcy (1864).
26. For humans moving ten times as much rock and sediment as all other natural processes together, see Wilkinson (2005).
27. For human-mediated minerals, including calclacite, see Hazen et al. (2017).
28. I have personally observed birds, from crows to coots, lining their nests with plastic wrappings.
29. For hermit crabs living in plastic bottle tops, see Jagiello et al. (2024).
30. For biofilms on microplastics see, for example, Gaylarde et al. (2023).
31. For amoebas building shells from polystyrene and other synthetic materials, see Bian et al. (2019).
32. For plastics in the Arctic, see Bergmann et al. (2022).
33. For plastiglomerates in Hawaii, see Corcoran et al. (2014).
34. For plastic fibers being buried in sediments of the deepest seas, see Zalasiewicz et al. (2016).
35. For the possibility that some plastic objects might leave imprints in rocks, see Zalasiewicz et al. (2016).
36. For the mass of human-made objects outweighing the mass of all lifeforms, see Elhacham et al. (2020).
37. For unusually large fires burning in the years since 2020, see MacCarthy et al. (2025) and Fisher (2024). For the link with climate change, see Richardson et al. (2022).
38. For extreme water shortages in Chennai, see BBC (2019). For Cape Town, see Pascale et al. (2020).
39. For heat and humidity records above what humans can tolerate, see Raymond et al. (2020).
40. For the pace of change being far faster than even the gloomiest alarmists had thought, see Lenton et al. (2019).
41. In March 2024, an international panel of geologists rejected the idea that the Anthropocene marks a new geological epoch in the history of the Earth—see Witze (2024) and IUGS (2024). This decision does not, however, invalidate the concept of the Anthropocene as the age of irreversible human impacts

upon the Earth. A geological Anthropocene must meet a number of formal requirements and is separate from what you might term a *practical Anthropocene*. The impacts of humans upon the planet are unquestionably accumulating, accelerating, and often interacting in ways that were not anticipated—see, for example, Zalasiewicz et al. (2024). That, collectively, humans have become an extraordinarily powerful geological force is beyond doubt.

42. Forecasting how human activities will reach into the planet's future is obviously fraught with difficulties. However, some estimates suggest that current human impacts on the climate may endure for at least one hundred thousand years (see Steffen et al., 2018, supplementary information) while impacts upon the biosphere may last longer still. Meanwhile, if humans were to vanish, a subsequent lineage of intelligent lifeforms might struggle to develop a technological civilization because humans have already depleted the most easily accessible deposits of metals and fossil fuels. (Stores of fossil fuels can potentially be renewed by the life-planet system, but the process would take many millions of years.)

## The Power of the Stars

1. For dreams of star power, see Windsor (2019).
2. For optimism that fusion may start to supply electricity grids in the early 2030s, see Conroy (2024).
3. Although the storage of wastes from nuclear fission is not trivial, it's worth noting that fission power is in other respects very clean. In contrast, pollution from burning fossil fuels is estimated to have been responsible for 8.7 million premature deaths in 2018 alone—or almost one in six deaths worldwide—see Vohra et al. (2021). Nuclear accidents such as the one at Chernobyl in Ukraine in 1986 are terrible and not to be downplayed, but the total number of people affected was small compared to the number of people killed each year by fossil fuels, and most fission power facilities have operated safely for decades.
4. For natural fission reactors two billion years ago, see Bentridi et al. (2011).
5. For the rate of the fission reactions two billion years ago, see Meshik (2005).
6. For wind turbines removing energy from the air, see Miller and Kleidon (2016).
7. For the gloomy forecasts of Kliment Timiryazev, see Timiryazev (1958).
8. For old solar panels overwhelming landfill sites, see Atasu et al. (2021).
9. For drought and hydropower in California in 2021, see Turner et al. (2022).
10. For fleeting fusion reactions, see Zylstra et al. (2022) and Abu-Shawareb et al. (2024).
11. For the rare pure quartz sands required for making computer chips (and for the intricate, energy-demanding processes involved), see Beiser (2018), chapter 5.
12. For the use of air-conditioning raising the temperature of cities like Phoenix, Arizona, and further increasing the demand for air-conditioning, see Salamanca et al. (2014).
13. For the possibility that dissipative heating will lead to problematic planetary warming, see Mullan and Haqq-Misra (2019).

## PART THREE: DREAMS OF OTHER WORLDS

1. For Epicurus on infinite worlds, see his letter to Herodotus, p. 25, in Bailey, C. (Trans.) (1926). *Epicurus: The Extant Remains*, Oxford University Press.

### The Search for Inhabited Planets

1. For the discovery of the first planets beyond the Solar System, see Wolszczan and Frail (1992); for their distance from Earth, see Yan et al. (2013).
2. For a continuously updating list of exoplanets, see exoplanet.eu/polar_plot.
3. For an example of a dense planet, see Osborn et al. (2023); for one that is unusually puffy, see Yoshida et al. (2023).
4. For planets whizzing around their stars see, for example, Winn et al. (2018).
5. For planets orbiting two stars, see exoplanet.eu/planets_binary_circum.
6. For planetary nomads, see Limbach et al. (2021).
7. For a consideration of photosynthetic pigments that might evolve in response to light from different kinds of stars, see Kiang (2008).
8. Some scientists have argued that the biosphere of a water world would be so limited that it would be unable to generate an oxygenated atmosphere—see, for example, Höning and Spohn (2023).
9. For a consideration of alternative chemistries for life see, for example, Henderson (1913), Haldane (1954), and Bains (2004).
10. Enceladus was named by the astronomer Sir John Herschel in a work published in 1847—see Herschel (1847), p. 415. He wrote, "As Saturn devoured his children, his family could not be assembled round him, so that the choice lay among his brothers and sisters, the Titans and Titanesses (*vide* Lempriere)." John Lemprière was the author of the *Bibliotheca Classica; or, A Classical Dictionary Containing a Full Account of All the Proper Names Mentioned in Antient [*sic*] Authors*. The 1792 edition of this work reports that Enceladus was "a son of Titan and Terra, the most powerful of all the giants who conspired against Jupiter."
11. For Enceladus having a salty ocean and a rocky, iron-rich core, see Choblet et al. (2017).
12. Many thanks to Francis Nimmo for explaining the frictional heating of Enceladus to me.
13. For Enceladan plumes feeding Saturn's rings, see Nölle et al. (2024).
14. For Enceladus having a source of molecular hydrogen, see Waite et al. (2017); for phosphates, see Postberg et al. (2023); for carbon chemistry, see Postberg et al. (2018).
15. For temperatures at the surface of Enceladus, see Filacchione et al. (2016).
16. For the coldest temperatures recorded at the surface of the Earth, see Scambos et al. (2018).
17. For the average thickness of Enceladan ice, see Park et al. (2024).
18. For the length of the Mars day, see Barger et al. (2012).
19. For lethal Martian soils, see Wadsworth and Cockell (2017). Note, however, that some bacteria may be able to tolerate Martian conditions better than others, and few have been tested outright.

20. For salty Martian water beneath the ice, see Lauro et al. (2021).
21. For the suggestion that detection of Martian methane is due to measurement error, see Viscardy et al. (2025).
22. For Martian formations that resemble fossils of microbial mats, see Noffke (2015).
23. For a resemblance between structures in Martian rocks and those that, in Earth rocks, are caused by lifeforms, see Ruff and Farmer (2016).
24. For Martian mudstones containing organic molecules together with reduced minerals, see Hurowitz et al. (2025).
25. For the loss of the Mars magnetic field and subsequent loss of its atmosphere, see Dehant et al. (2007).
26. For the sequestration of Martian water, see Scheller et al. (2021).

### A Grand Experiment

1. For the start date of the long-term evolution experiment on *E. coli*, see Lenski (2004), p. 232. For details of the protocol, see Lenski et al. (1991) and Lenski (2004). Note that the experiment has recently changed hands and is now overseen by Jeffrey Barrick of the University of Texas at Austin.
2. For bacteria rapidly evolving to gobble up glucose, see Lenski (2004), p. 242.
3. For the number of *E. coli* generations that elapsed before individuals appeared that were able to grow from citrate, see Blount et al. (2008).
4. I arrived at 620,000 by assuming 31,000 generations of humans with an average generation time of 20 years. However, compared to *E. coli*, 31,000 human generations would have less potential for evolutionary change. *E. coli* populations are enormous, whereas human populations generally are not—and population size is a key determinant of evolutionary potential.
5. For replaying the citrate experiment, see Blount et al. (2008).

### The Silence of the Cosmos

1. The quotation from Enrico Fermi is reported by Finney and Jones (1985), p. 299.
2. For Tsiolkovsky anticipating the Fermi Paradox, see Lytkin et al. (1995).
3. For Tsiolkovsky suggesting that Earth has been specially set aside by the rest of the Galactic community, see Lytkin et al. (1995).
4. For the hypothesis that intelligent aliens are patiently waiting for us to answer their signals see, for example, Cocconi and Morrison (1959).
5. For the notion that humans are presently uninteresting to aliens see, for example, Dyson et al. (1973), pp. 210–215.
6. Claims that governments are covering up alien contact are persistent and numerous. As a recent example, consider *The Age of Disclosure*, a 2025 documentary film directed by Dan Farah.
7. For stars in the Milky Way being far older than the Sun, see Haywood et al. (2016).
8. For a pulse of star formation in the Milky Way two to three billion years ago, see Mor et al. (2019).
9. For the gloomy possibility that technological civilizations may rapidly de-

stroy themselves, see Frank et al. (2018), Mullan and Haqq-Misra (2019), and Wong and Bartlett (2022).

10. For suggestions that extraterrestrials might turn away from a high-energy lifestyle, see Mullan and Haqq-Misra (2019) and Wong and Bartlett (2022).

### The Universe Is Not a Menu

1. For optimism that problems of interstellar travel will soon be solved, and for the goal of finding new habitable planets, see Dole and Asimov (1964), p. 7.
2. For the notion that most habitable planets will be like the Earth, see Dole and Asimov (1964), p. 12.

### Appendix 2: The Fate of the Earth

1. By "nothing unexpected," I mean without deliberate intervention of one kind or another. For instance, some have suggested that the energy of passing asteroids could be used to nudge Earth farther out into the Solar System, expanding its orbit and keeping it from warming—see Korycansky et al. (2001). However, as these authors acknowledge, such a strategy would be replete with risks.
2. For a general sketch of Earth's future, see Ward and Brownlee (2007). Note that the timing of the Sun's expansion is relatively clear, but the timing of total biospheric collapse is less certain—see Mello and Friaça (2020).
3. For Earth on the cusp of doom, see Ward and Brownlee (2007), p. 162.

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