Astrophysics meets permaculture in a book about the design and construction of gaiomes: artificial worlds in space that would sustain themselves through natural ecology. Discover how living beyond Earth challenges not just technology, but our very identity as a species.

Gaiome: Notes on Ecology, Space Travel and Becoming Cosmic Species

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ISBN 978-1-60145-242-9

Printed in the United States of America.

Computations, typesetting and interior illustrations by the author using Ruby, LaTeX and Star Office.

Gaiome.com
Bloomington, Indiana
2007

Contents

Introduction

On a crisp fall evening in 1985, the Princeton University chapter of Students for the Exploration and Development of Space (SEDS) held an open meeting. About two dozen undergraduates attended, spreading out in groups of two or three among the raised, hardwood pews of a small lecture hall.

The club's President, Jeff Bezos, talked a little about SEDS and a lot about his dreams for a glorious future in space. At one point he was describing a scheme to build gigantic space habitats that theoretically could house millions of people. The construction technique involved using huge solar mirrors to heat a metal asteroid until it was completely molten. Then workers would plunge a long tungsten tube into its center and inject large quantities of water. This would flash into steam, inflating the asteroid like a balloon to make a spherical hull—

A loud slam cut him off. A student in the middle of the room jumped up and, choking back sobs of rage, yelled, "How dare you rape the universe!" After she had stormed out, Jeff, more bemused than ruffled, leaned toward me and another SEDS officer and said: "Did I hear her right? Did she really just defend the inalienable rights of *barren rocks?*"

Jeff, like the rest of us, had no trouble brushing aside criticism before it could sink in. Having grown up in the belt-tightening Carter administration, under the Cold War threat of Mutually Assured Destruction, Earth seemed small to us: fragile and crowded. Beyond lay boundless space, with limitless energy, resources and opportunity. Out There, population and consumption, and hence science and the arts, could grow forever. Our template was Gerard K. O'Neill's *The High Frontier* (1976), a plan to build miles-long habitats along the inside walls of huge, spinning cylinders in orbit.[1] Green and spacious, O'Neill colonies would house tens of thousands or even millions of people. The colonists would earn their way by building giant orbiting solar power stations that would beam energy down to microwave receivers on Earth. Everything would be built using lunar and asteroidal ores, eventually moving all polluting industry off-Earth. According to O'Neill, the colonies could earn and grow fast enough to off-load Earth's entire population in a mere 35 years.[2] The Moon and asteroids had enough mineral resources to build thousands of Earths-worth of new, enclosed land. In the era of energy crises, *Limits to Growth* and Skylab, O'Neill's proposal made the front pages of *Physics Today*, *Science* and the *New York Times*, attracting a grass-roots following of techno- and eco-humanists that has not been rivaled since.

Still, a long and notable list of critics were as furious at the concept as Jeff's accuser. Historian Lewis Mumford regarded space colonies as "technological disguises for infantile fantasies." Nobel prize-winning biologist George Wald wrote "Let me say at once that I view them with horror." Educational reformer John Holt remarked that O'Neill and his followers had "lost the feel of real things."[3] To the critics, the whole mythology of finding escape in the heavens from the wreckage we seemed certain to make of Earth seemed both apocalyptic and futile. Given our struggles to sustain ourselves on Earth, where evolution and long experience have adapted us to its abundance, how could a single generation hope to do better in an unexplored, radioactive vacuum?

Privately, I had a few doubts of my own. Not about space colonies; the problem was the Space Shuttle. Still in the design stages when O'Neill first proposed his colonies, it was finally flying—at fifty times the ticket price that the National Aeronautics and Space Administration (NASA) had promised. Of course that killed O'Neill's colonies, which depended on low transportation costs. But NASA was the only game in town. Where else could spacers such as myself go to realize our dreams?

That fall, I sought out celebrity physicist-author Freeman Dyson for some career counseling. On the theory that the Henry Fords of rocketry would emerge from garages rather than NASA centers, he gently suggested that I get out of the space business entirely and earn my living in the much more lucrative field of computers. With some luck, perhaps I could earn enough money to experiment with new launch schemes as a hobbyist. I believed him, but I couldn't turn away—not even a few months later, when the Space Shuttle Challenger crashed. Instead, I went into astronomy, managed an archive of images from NASA's planetary missions, designed satellite orbits and parts, published astronomy software and trained to operate the Microphone experiment aboard the doomed Mars Polar Lander.

Meanwhile, cleverer souls followed Dyson's plan. In college, Jeff Bezos switched from aerospace to computer science. Later he founded Amazon.com, made billions, and launched a very secretive space company that, according to its web site (www.blueorigin.com), is "creating an enduring human presence in space." Bezos is hardly alone. In recent years, at least six self-made billionaires have begun to experiment with passenger space transport. Unlike Christopher Columbus or Nazi rocketeer Wernher von Braun, they don't need to convince skeptical rulers or dip into the national treasury; they already have the money. They can explore space any way they want. They know technology. They know business. They know what to do.

Or do they? Giving the old space dreams a new, corporate face would hardly comfort the critics. Will Bezos, Musk, Branson and the rest have any better "feel for real things" than NASA? Will they beat NASA's prices by factors of tens to hundreds? Will they make space launch safe enough to attract millions of travelers? And if they succeed, can humanity expand into space without also expanding its fatal wars on itself and nature, as the critics had warned?

With these questions in mind, I began building spreadsheet models of a rocket business. To inject some economic reality into the analysis, I started with a hefty operating profit margin and worked back through the technical details to obtain a better estimate of ticket price (which rocketeers all too often and quite erroneously equate to their operating costs). The results were mixed. I found that a private company probably could send a passenger safely and profitably into orbit for $140,000 rather than today's going rate of $20 million. But the development costs, lifted straight from published figures in aviation, came to several times as much as the space entrepreneurs appear to be spending. Worse, many of them appear to be building the wrong kind of rocket and trying to sell it to the wrong customer.

Next I turned to O'Neill's cylindrical colony design—and recoiled as technical flaws leapt out of nearly every system. With an inherently unstable rotation, mirrors too large to hold their shape and a chemically volatile atmosphere, the design was a giant Rube Goldberg contraption just waiting to burn up or fly apart. O'Neill and colleagues had known about some of these issues, but angrily waved them away as engineering details. With a cadre of True Believers at NASA and elsewhere, the design and its economic basis in beamed solar power have remained largely unchallenged. Until now.

I began by simplifying the habitat design, making its hollow shape short and squat for stability and turning it on its side to avoid pointing problems. I got rid of the co-rotating mirrors, external shielding, agriculture pods, dish antennae and other protrusions. This made it easier and cheaper to build and maintain. As with an O'Neill colony, it would spin to simulate gravity, allowing people to live on its inside walls. I chose a thick hull so it could hold an Earth-like atmosphere at sea-level pressure. This also helped it resist radiation. To simplify the problem of recycling, I surveyed the biospherics literature for clues about relying less on untried mechanical systems and more on familiar plants and soils. This drew me deeper into ecology—and led to a paradox.

In the mid-1970s, Australian ecologists Bill Mollison and David Holmgren had developed *permaculture*, a practice of designing homes, towns and cities that sustained themselves through complex, forest-like ecologies. This may seem a step backward until you consider the enormous efficiency of forest systems. For example, acorns from an oak woodland can match a wheat field in terms of calories produced per acre. Yet unlike our monocrop agriculture, a natural forest includes many other plant species, all of which are edible—either by humans or hundreds of other animals.[4] Healthy forests can also have hundreds to thousands of times less soil erosion and dozens of times better nutrient recycling than monocrop agriculture.

As a designer, I could not ignore these efficiencies. How might permaculture work in space? I imagined, as Russian space pioneer Konstantin Tsiolkovsky had over a century ago, a "greenhouse conservatory" that could run on sunlight as autonomously as Earth itself.[5]

How odd, then, that O'Neill and his libertarian followers, who knew of Tsiolkovsky, would design their tiny world as a *colony*: an economic possession of a distant nation or corporation. Like colonial powers throughout history, these owners would have every incentive to secure and control their formidable assets by any means available, including debt bondage and coercive monopolies. About the last thing they would ever want to do is make the colonies autonomous. Thus the colonists themselves would have even less freedom than today's ground-controlled astronauts.

My notion of an autonomous, permacultural mini-world did not fit the colonial model. Lacking significant exports or need for imports, it would offer prospective investors little by way of recurring income. For residents, though, it would provide plenty of value as permanent real estate—the very thing that launched O'Neill and his students into space studies in the first place.

But if not a colony, what should I call it? Certainly not a *habitat*, which connotes problems long-since solved. The word *biosphere* fit, but it also fit everything from sealed glass bubbles with algae and brine shrimp to the entire Earth itself. Paolo Soleri's *arcology*, Dandridge Cole's *Macro-Life*, Isaac Asimov's *spome* and the Artemis Society's *xity* each described space dwellings, sometimes employing biological metaphors. But all of these schemes were urban and human-centered, housing only selected species as necessary to provide food, water and air. If anything, these designs maximized our separation from living nature, sealing off its essential life support functions in vats and tubes, except where it was pleasing to the eye to have a pretty lawn or flower garden.

By contrast, my work was becoming increasingly focused on our physical, psychological and social need to live fully within nature in all of its wildness, diversity, robustness and efficiency. To call attention to the difference between this mode of living and the other schemes, I eventually coined a word for it:

> **Gaiome** ('gī'ōm) n, an artificial world in space that sustains itself using natural ecology. From *Gaia*, the theory of Earth as a living, self-regulating organism.

Gaiomes began as a modest attempt to update Tsiolkovsky and O'Neil's designs, which had been gathering dust for decades. But as question after question led back to ecology, I ended up with something unexpected: a direct challenge to the story of escape and conquest that drove space exploration for over a century. Where space colonies once promised endless growth for our current way of life, gaiomes, as living ecosystems, would require us first to find a new way to live. I also began to see how the same pattern of war and waste that threatens us on Earth has measurably begun to cripple us in space.

Make no mistake: human space flight is in jeopardy today. Despite mega-leaps in computer and materials technology since 1969, it has become more costly and dangerous than ever to send people into orbit. Neither money nor new technology nor political will has cracked the problem thus far. Nor, in my view, are they likely to. Working on what we must *do* to make space habitation possible is like asking what a caterpillar must do in order to fly. Wrong question! It can't fly. The important thing to ask is what it can *become.*

Are we the kind of civilization that can live large in the universe? Chapter 1 (*Far and Away*) dissects the space frontier myth to discover that for the moment, we are not. The evidence suggests that we aren't even qualified to live here on Earth, where we have all but spent the abundant inheritance of evolution. In order to survive beyond Earth, the chapter concludes that we first must embrace ecology here on Earth, where the lessons are easier and we have the most help from species that evolved alongside us.

Still, we have become conscious of the wider cosmos; it would be a shame to turn our backs on it. Long before we can become a cosmic species, we will need everyday space travel. Chapter 2 (*Space for Everyone*) borrows engineering and economic models from other transportation industries to establish the minimal criteria for safe, routine and sustainable passenger space flight. The chapter then proposes a strategy to achieve these goals.

Astronauts today echo our consumer culture by using prepackaged stores of food, water and air lifted at great expense to orbit. Ecologically speaking, this does not even qualify as life support. Chapter 3 (*Gaia and Her Children*) examines how life makes the connections necessary to support itself regeneratively on three scales: globally, in sealed terraria, and in thousands of permaculture farms and gardens world-wide. The chapter will extract from this discussion seven lessons and six heuristics that will help us to design self-supporting worlds.

Long before any settlers depart for lands beyond Earth, their choice of where to live will begin to shape their values. Chapter 4 (*New Worlds, Found and Made*) prospects the solar system for suitable places, revisiting numerous past schemes for settlement and their likely social consequences.

With the foregoing lessons in mind, the next two chapters discuss how we might design and build a living world. Chapter 5 (*Design*) describes the constraints placed on gaiome architecture by the space environment and lays out some traditional and original design solutions. As with Chapter 1, you may glimpse the occasional statistical reflection of your own being: as a consumer, as beneficiary of the vast web of life, as a composite organism. Chapter 6 (*Construction*) looks at who might build these tiny worlds, how they might do it, how soon and at what cost.

As I developed the detailed computer models for these chapters, it became clear that a "master plan" for space travel and habitation would be premature. Too many basic astronomical, biological and political questions remain unanswered or even unasked. Still, I have backed my work with the most accurate data I could find, so that hard engineering numbers can join the hard lessons from ecology as the basis for a new discussion. *Gaiome*, then, is not so much a proposal as a new way to talk about space; a challenge to get out of our present rut and take a fresh look at what it means to be alive in the wider cosmos.

What kind of civilization would build gaiomes? Who would live in them? How would they change with time? Chapter 7 (*Adaptation*) will discuss gaiomic life and its prospects, first on the scale of humanity's near future, then on evolutionary and cosmic time scales. As regenerative ecosystems, gaiomes would qualify as living organisms in their own right, with unique consequences for their residents. These extrapolations illustrate the advantage of biological and cultural diversity, rather than total energy use, as a measure of cosmic progress.

Throughout these pages, you will encounter space not as a frontier for human conquest, but as an evolutionary challenge for all of Earth life—including your own. Chapter 8 (*Homework*) invites you to seize the challenge of cosmic metamorphosis, not through esoteric practices, nor by joining or renouncing any organization, but through deliberate choices in your everyday routines and relationships. These "assignments" outline the work necessary to make a lasting home for ourselves on Earth and beyond.

Measures

Planning anything from backyard gardens to worlds requires measurements and estimates. Given the ease of modern global communications, it is completely inexcusable that space agencies and their contractors continue to use an archaic grab-bag of units of measure. Mars Climate Orbiter crashed, in part, because the contractor used imperial units, while the navigation team used metric. Let's not invite that type of error here.

Numbers in this text appear in short scale, grouping thousands with commas. In this system, a thousand million (1,000,000,000 or 10^9) is one billion. Since many of these numbers come from computer models, a few of them may contain rounding errors in the final digit. Financial figures appear in U.S. dollars, inflated to 2005 values unless otherwise indicated.[6]

For physical measures, I always specify the unit and stick to commonly accepted variants of Système International (SI)—the modern form of the metric system, recognized world-wide. Length appears in meters (m, the SI unit) or sometimes microns (10^{-6} m) or kilometers (1 km = 1,000 m); mass in kilograms (kg) or tonnes (1 t = 1,000 kg); time in seconds (s); areas in square meters or hectares (1 ha = 10,000 square meters or 1/100 of a square kilometer) and temperature in degrees Celsius (°C), which you can convert to Kelvin (K, the SI unit) by adding 273.15°. 0 K is absolute zero, the minimum possible temperature.

You will encounter three non-metric units of measure. First, gravity and acceleration appear in gees. One gee is the gravitation we feel on Earth. In a rocket or roller coaster with two gees acceleration, for example, you would weigh twice as much as you do on the ground. Second, it is sometimes convenient to express speeds in Mach numbers, or multiples of the speed of sound (330 m/s). A Boeing 747 airliner can fly as fast as Mach 0.95. Third, the average distance between Earth and the Sun is called an Astronomical Unit (AU). Mars orbits the Sun at an average distance of 1.5 AU, half again as far away as Earth.

If you're unfamiliar with metric units, here are some helpful conversions: A meter is 39 inches; a square meter is about 10 square feet; a hectare is about 2.5 acres, or a square the length of a football field on each side. There are 1,609 meters in a mile and one meter per second is about 2.2 miles per hour. A kilogram is 2.2 pounds and a tonne is 2,205 pounds. At sea level, water freezes at 0 °C and boils at 100 °C, while in Fahrenheit, it freezes at 32 °F and boils at 212 °F. A temperature of 300 K is about 80 °F.

Now let's begin.

Chapter 1

Far and Away

> "Viewed from the distance of the moon, the astonishing thing about the earth, catching the breath, is that it is alive."
>
> —Lewis Thomas[7]

December 24, 1968: A gray moonscape, framed by the metallic window of the Apollo 8 spacecraft, glides across the screen at a stately pace. A quarter of humanity has crowded around any available TV or radio to witness the broadcast—the first from another world.

For the past five orbits, the astronauts have caught sight of Earth, dazzling blue, rising over the cratered lunar plains. No one has ever seen our home world from so far away. Mesmerized, they snap pictures of it every chance they get. One image in particular stands out. The Earthrise photo soon will become the emblem of its time, appearing on magazine covers, newspaper articles, logos and even postage stamps for decades to come. The radio chirps and the voice of Command Module Pilot James Lovell struggles to bring this mythic sight home to 750 million listeners. "The Earth from here," he tells us, "is a grand oasis in the big vastness of space."[8]

Earth, so far as we know, is unique in the universe. Over the past fifty years, space probes have mapped dozens of Earths worth of new land among the planets and moons that orbit the Sun. Optical telescopes have found hundreds of planets around other stars. Radio telescopes have scanned thousands of stars for intelligent signals. Yet none of these efforts have found even a trace of life. Only here on this world of forest greens, ocean blues, delicate flowers and sunsets, have five to thirty million species made their home.[9]

Home. Does our world need any other name? All who live here are terrestrials, a word derived from the Roman Mother goddess Terra Mater, whom the Greeks called Gaia. Other languages from ancient Egyptian to modern English name the world for its soil. But far from profaning our planet's beauty, this humble name celebrates it. After all, a handful of Earth supports as many as 10,000 microbial species, and they in turn play an important role in supporting us. Though people push parts of it around and often treat it, literally, like dirt, there is no place like Earth, our undeniable home.

Walk awhile in a high desert, a quarry, a cave, a volcanic scarp, and the land's patterns will begin to hint at how they came to be. Spend time reading and walking with skilled geologists (*geo-*, again from *Gaia*), and the land will slowly surrender its secrets like an ancient text. In recent centuries, great libraries have filled up with geological observations, interpretations and debates. Gradually, through numerous lines of evidence, the threads of a planet-wide story vastly older than the human species have emerged and begun to knit together.

The story is incomplete and fragmentary, though, because geology, water, weather and life have reshaped Earth's surface many times over, erasing numerous lines of evidence. But Earth is part of a solar system in a galaxy literally filled with the scattered remnants of its formation and history. Many new clues have come to light in recent years as astronomers have combed the spectra of stars and planets, geochemists have analyzed the composition of meteorites and geologists have pored over 40 years of data from hundreds of planetary probes. Meanwhile, archaeologists and molecular biologists have made enormous strides in understanding the evolution and complexity of life. Together this work, some of it as recent as last month, has snapped the story of Earth into noticeably better focus.

Only this vast tale can properly frame the significance of space travel and the brilliant but flawed civilization that invented it.

The Book of Earth

If the history of Earth could be told in one million pages, it would fill 1,000 thick volumes. At twenty volumes per bookshelf and one hundred volumes to a bookcase, the whole set would take up ten bookcases. Even in such a massive history, each page would have to cover a lot of ground: about 4,570 years—

Mya	Page	Event
Hadean Eon		
4,750	1	Protosolar nebula collapses
4,550	4,377	Earth and Theia form
4,433	8,097	Theia collides with Earth; Moon forms
4,470	21,882	Sun turns onto the Main Sequence
4,000	124,727	Late Heavy bombardment
Archaean Eon		
3,800	168,491	First Prokaryotes
3,500	234,136	Photosynthesizing bacteria
3,000	343,435	Aquatic O_2 producers
Proterozoic Eon		
2,500	452,955	Oxygen Catastrophe
2,100	540,482	First Eukaryotes
1,200	737,418	Sex Invented
1,000	781,182	Multicellular algae and seaweeds
Phanerozoic Eon		
565	876,368	Cambrian Radiation
488	889,497	Cambrian-Ordovician Extinction
475	896,062	First plants
400	912,473	First insects (Devonian Period)
220	951,860	First dinosaurs (Triassic Period)
130	971,554	First flowers (Cretaceous Period)
65	985,777	C-T impact; dinosaurs extinct
35	992,342	First grasses (Cenozoic Epoch)
10	997,812	First monkeys (Miocene Epoch)
3	999,334	Australopithecus africanus
0.154	999,967	Mitochondrial Eve (Pleistocene Epoch)
0.100	999,979	First modern humans (Holocene Epoch)
0.074	999,984	Population bottleneck
0.027	999,995	Neanderthals extinct
0.015	999,997	Recent glaciation ends
0.011	999,998	Green Sahara; Dog and pig domesticated
0.008	999,999	Wheat crops; *Writing*
0.003	1,000,000	Iron tools; humans multiply 400-fold

Table 1.1: Selected events in the Book of Earth.

perhaps a decade per word. An abridged contents might read like Table 1.1, which lists times in millions of years ago (Mya). The table has been skewed near the bottom to emphasize human development, but the page count helps to put events back into proper perspective (note where written history begins). The Book's basic plot would go like this:[10,11]

In the first volume, a disturbance in the galaxy compresses part of a dark nebula of dust and gas. Evidence such as the presence of Magnesium-26 in grains found in meteorites suggests that the disturbance was a supernova, a known source of the very short-lived parent isotope Aluminum-26. The self-gravity of the nebula, now suddenly denser, overwhelms the gas pressure and galactic tides that previously prevented its collapse. Nothing challenges the momentum of its slight rotation and, like a figure skater pulling in her arms, the nebula spins faster as it shrinks. The parts with the greatest spin find orbits that resist gravity; the rest fall inward, flattening the nebula into a thin disk.

In the center of the disk, a dense knot of gas is forming a protostar. Glowing brightly from the heat of accretion, but not yet big enough to sustain nuclear fusion in its core, it grows as material rains down onto it from the collapsing nebula.

Grains of dust begin to stick together; some of the surrounding gases freeze to their surfaces, forming tiny motes that will grow to comet-like planetessimals. Gradually, a few of them, in the denser spiral knots of the nebula, get large enough for their gravity to start pulling in objects at a distance. Planets begin to form.

By about the fifth volume, Earth has formed, its volatiles (water, methane, other easily-boiled liquids) hissing violently into space as billions of huge planetessimals crash into it. Already molten from the impacts, Earth's heavier elements such as nickel and iron sink to form a core, converting enormous amounts of gravitational energy into heat. Short-lived radioactive elements decay in the same time frame, keeping the early Earth hot.

Near Earth, possibly in the same orbit but leading or lagging by 60°, a smaller sibling of sorts has begun to grow.[12] Astronomers have informally dubbed the planet Theia, for the ancient Greek Titan who in myth gave birth to the Moon Goddess.[13] Because Theia is small, her orbit is stable. But she and Earth continue to grow as impacts add to their bulk.

By the ninth volume, Theia, now Mars-sized, has too much gravity to remain in one place. Or perhaps she's jostled out of position by the planetessimals that continue to rain down on her. Whatever the cause, she falls, gradually, toward Earth.

The worlds collide at a glancing angle, greatly increasing Earth's rotation rate. As debris flies everywhere, the iron cores of the two molten worlds merge. Theia is gone. In fewer decades than the words of this sentence, the debris gathers and forms the Moon.

By the 22nd volume (we're finally on the second shelf of the first bookcase), the center of the growing proto-Sun has become dense and hot enough to sustain nuclear fusion. The Sun begins to shine with a light that will not go out for over ten billion years—twice the length of our massive history. The Sun is a G2 dwarf, a bright star that will, throughout its life, outshine 95% of the stars in its neighborhood.[14] Its intense light begins to sweep the young solar system free of gas.

By the 101st volume (at the top of bookcase 2), Earth has cooled enough for a solid crust to form and thicken. Between volume 125 and 170 (shelves 2 through 4), planetessimals rain down on the inner solar system, cratering the Moon and bringing volatiles such as water, carbon dioxide and methane to Earth. The cause of this Late Heavy Bombardment remains a mystery. Lunar craters from this event, undisturbed by wind or water, survive to the present day. Earth's craters, by contrast, typically don't even last ten pages.

Well before the end of bookcase 2, life appears on Earth. Because weather, geology and subsequent life have erased so much from this era, we don't know how it got here. The amino acids that form proteins occur naturally over a wide range of environments, including deep space. For all we know, life could have begun off-world and come to Earth as hardy cells entrained in the Late Heavy Bombardment. But this notion, called exogenesis, merely side-steps the central question: how did the simple building blocks of life get together to form cells capable of metabolism, reproduction, adaptation, movement and self-defense? In other words, which came first, the genes (DNA and RNA) that encode the instructions for building the cell, or the cell itself? To date, no one knows the answer, though like most living systems, the two may have evolved more or less in parallel.

The earliest life forms in the fossil record are prokaryotes: micron-sized cells with hard walls and no nuclei. Their world, the Early Earth, is one of extremes. The atmosphere, mostly made of carbon dioxide, is a hundred times thicker than it is today. Thermal vents perforate the ocean floor and the land oozes with hot springs. These environments host huge variations in temperature, salinity and acidity. As autotrophs (Greek for “self-nutrition”), early cells use these variations not for food, but to obtain energy, extracting carbon from CO_2 and oxidizing electron-donating substances such as sulfur to form acids.

Mutations occur, most of them fatal. Cells that use energy too quickly burn up or starve. Cells that use it too slowly are crowded out. In their dynamic environment, many cells find themselves challenged by scarcities of nutrients, extremes of temperature and other adverse conditions. Here, the occasional mutation proves advantageous, extending the range of the next generation. Each organism is a little experiment conducted under life-or-death pressure to adapt, repair, conserve or reproduce. Some 10^{30} organisms —quadrillions of quadrillions of them—come to occupy the Earth.[15]

Because prokaryotic cells divide on a time scale of minutes to hours, they tend to evolve tens of thousands of times faster than do modern mammals. The prokaryotes also exchange genetic information through a variety of means such as bacteriophages and direct contact, allowing communities to share beneficial traits within the same generation—further speeding their evolutionary development. Even so, it takes a full 65 volumes of this type of natural research and development to find a new source of energy: the Sun.

By volume 235, in water supersaturated with salt, a strain of halobacteria develops a new pigment (bacteriorhodopsin) in its cell wall. When struck by solar photons, the pigment flexes, pumping protons out of the cell. The chemical gradient thus generated provides the organism with a potent power source. This method survives to the present day as the only mode of proton-transport photosynthesis on the planet.

Electron transport photosynthesis as seen in plants does not appear for more than one hundred more volumes. By volume 350 (fourth bookcase), cyanobacteria, commonly called blue-green algae, have begun to use a pigment called chlorophyll to capture the energy in sunlight. In the somewhat complicated Calvin cycle of chemical reactions, cells store and use this energy to pull carbon out of the CO_2 atmosphere, producing oxygen as a waste gas.

This method of gathering energy becomes so successful that it begins to enrich the oceans with oxygen that, in turn, binds with dissolved iron to produce banded iron formations on the sea floor. But by about volume 450 (bookcase 5), oxygen production has overwhelmed the ocean and come to dominate the atmosphere. Most bacteria cannot survive this oxygen catastrophe, so the majority of Earth life retreats to anoxic environments—clays, deep ocean sediments and the like. Though the world has become harsh for them, the anearobes do not die off, but survive to find vital roles in the exotic ecologies to come. For example, with the emergence of plants 1.6 billion years later, some anaerobes will become nitrogen fixers in plant root zones. Thus even very primitive life proves its tenacity, adaptability, and ecological potential.

Not all life retreats, however. By the time of the oxygen catastrophe, the prokaryotes have undergone ten trillion generations of evolution comprising perhaps 10^{43} individual experiments.[16] Some cells have started to adapt to the new chemical environment, developing the citric acid cycle to utilize oxygen for energy. As these new aerobic organisms evolve, not only does genetic material continue to flow between them, but smaller cells sometimes find their way entirely inside some of their larger neighbors. Somewhere between volumes 540 and 650 (bookcases 6 and 7), a few of these tiny endosymbiotes evolve to become organelles ("little organs") that provide various services within their host cells. Among the many types of organelles are chloroplasts that use sunlight to produce Adenosine triphosphate (ATP: life's energy currency), mitochondria that put the ATP to work, and nuclei that protect the DNA within an inner membrane. Together these form a new domain of life, the eukaryota: strange composite beings-within-beings (the mitochondria retain their own DNA) that eventually will evolve to include all protists, fungi, plants and animals.

With the advent of aerobic eukaryota comes the dawn of the solar economy. From this point forward, nearly all natural wealth will derive from sunlight and the autotrophs (such as plants and algae) that harness it. Eukaryotes not blessed with chloroplasts are heterotrophs: they must get their nutrition by consuming other organisms.

By volume 740, as the first known supercontinent, Rodinia, begins to form along the equator, life has been passing genetic information to peers and offspring for 2.6 billion years. Finally, over the course of some 40 volumes, life discovers sex, a mode of reproduction that significantly increases genetic variation among offspring. Although it has its costs (a sexual organism may not be able to reproduce when stranded in a new environment), sex greatly increases the rate of variations so essential to the process of evolution.

In volume 782, metazoans (multicellular organisms) such as algae and seaweeds start to appear. Rodinia breaks up by volume 836. Sponges, jellyfishes and flat worms appear by volume 870, and the latter two evolve simple nerve cells. Seven volumes later, life begins a nine-volume surge in size, complexity and diversity known as the Cambrian radiation. By the end of this relatively short period, the world is filled with oxygen-breathing animals with nervous systems. Some of them venture onto land.

Life moves in fits and starts. Ten volumes before the end of the ninth bookcase, climate change kills a significant fraction of the world's species. Perhaps it was glaciation; perhaps depletion of oxygen in the ocean. Whatever the cause, it triggers the first major mass extinction event. To qualify as "major," more than 30% of the genera (groups of related species) must die off. Life will confront five more major extinctions before the end of our story, taking, in each case, millions of years to recover its former diversity.[17]

The first land plants appear by volume 897, and the first insects and sharks appear by volume 913. We're now in the tenth and final bookcase. Plants evolve seeds in volume 922, improving their ability to spread into new terrain. Reptiles appear in volume 935; dinosaurs in volume 952. Plants develop flowers by volume 972, co-evolving with their pollinators (mainly insects) to produce an enormous range of new species.

In volume 985—on the bottom shelf—an asteroid impacts the Earth, wiping out half of all species, including the large dinosaurs (a few of the smaller ones survive and eventually evolve into birds). This is the fifth major extinction. Mammals spread and diversify. Grasses appear in volume 993.

By the beginning of volume 1,000, the current book, early human ancestors have evolved away from the line that will become chimpanzees and bonobos and begun to walk upright. Proto-humans become completely bipedal with the emergence of Australopithecus in Kenya around page 344. By page 600, Homo Erectus is one of several proto-human lines that make their appearance in East Africa and, over the next few hundred pages, spread into Europe, Western Asia and Australasia, evolving adaptations to the local conditions.

Like all animals, humans inherit their mitochondria from the ovum. Geneological studies of mitochondrial DNA in people from every continent place the most recent female ancestor of modern humans—Mitochondrial Eve—at around page 670.

Isolated groups evolve rapidly and become distinct species. Homo Neanderthalensis, adapted to the cold, comes to live in Europe by page 972. The first modern humans, *Homo Sapiens*, appear in central Africa by page 979.

On page 984, the human population suddenly contracts, perhaps to only a few thousand individuals. The population bottleneck, as it's called, coincides with the Toba supervolcano eruption in Indonesia. Three thousand times more powerful than Mt. Saint Helens, the explosion and subsequent ash plume may very well have darkened skies over much of Earth, reducing global temperatures by 3 °C or more. While no big deal for life in the long run, this climate change spells disaster for itinerant human tribes struggling to survive in unfamiliar environments. Long winters and late blooms wipe out essentially all human settlements beyond central Africa.

Gradually, the population grows back. A new set of tribes begins to explore, reaching coastal Europe and Australasia by page 990 (around the time of Y-chromosomal Adam, our most recent male ancestor). By page 994, they have reached Japan, the Bering bridge and North America. The last known Neanderthals die on page 995, around the time that some of the human tribes learn weaving. A long glaciation ends around page 997, and sea levels rise, covering up the Bering bridge to North America and obliterating much of the fossil record along all coasts. Large mammals go extinct in prodigious numbers.[18,19]

By page 998, human migrations finally end at Tierra del Fuego, at the Southern tip of South America. Our global population reaches 5 million. Some tribes domesticate dogs; some set about domesticating plants. Agriculture shifts diets toward grains, and the energy thereby gained increases fertility. Human population grows, and with it, the demand for more arable land. On page 999, the first domesticated cereal, wheat, appears in the fertile crescent and domesticated food animals such as pigs begin to graze the green savanna of the Sahara. Plowing and weeding decrease biodiversity over large tracts of land, accelerating soil erosion and nutrient loss. The storage of grain blunts otherwise rapid ecological feedbacks, leading to land mismanagement. Vast tracts go barren, forcing migrations and expansion. Civilization appears and begins to keep records in ever more detailed and abstract systems of writing. By the end of the page, there are perhaps 15 million humans.

On the very last page, human intelligence seemingly triumphs. The gradual accumulation of knowledge beats back death in small increments; our population rises, doubling at first every millennium, then every century. Hebrew and Greek alphabets detach writing completely from pictographic depictions of the world, leading to a revolution in abstraction. Arabic numerals (including the all-important zero) enormously simplify computation. In the final, short paragraph, coal and oil massively amplify our power to move about and reshape the world. In fewer words than this sentence, ships span the globe, engines reshape the land, planes conquer the air, computers catalog the genome and space probes map dozens of new worlds. Our population has soared 400-fold on a single page, and doubles now every four to six words.[19,20]

In this sprawling epic, civilization occupies just two pages out of a million. A human life lasts just a few words. Yet somehow, we've arrived at the story's most dramatic moment. We can see it in the Earthrise photo: the sharp boundary between the endless void and life's blue sphere; the unseen photographer who has climbed beyond life's circle of gravity; a dawning sense of place in the wider cosmos; a moment pregnant with promise.

A Challenge to Evolve

Four decades before the Earthrise photo, a fourteen year-old boy glimpsed something of its promise. In an article published in the February 15, 1927 issue of *Deutche Jugendzeitung* (Journal for the German Youth), he wrote: "An age-old dream of mankind—to travel to the stars—appears to approach fulfillment."[21] The opportunity was unprecedented: a giant leap. With effort and good fortune, perhaps he could bring it into being.

The student's name was Wernher von Braun, the man who eventually would design the Saturn V rocket that carried the Apollo astronauts to the Moon. But he was writing long before the first satellites, indeed in a time when rockets were merely dangerous toys.

Three years later, von Braun joined the VfR (*Verein für Raumschiffahrt*: "Space Flight Society"), a 900-member amateur rocket club.[22] Perhaps its most prominent member was Hermann Oberth, whose self-published 1923 monograph *Die Rakete zu den Planetenräumen* (By Rocket into Planetary Space), had inspired von Braun and created an international sensation.

Learning of Oberth's work, the pugilistic Soviet government quickly announced that a Russian had long since invented everything in his book and more.[23] Oberth investigated. It turned out that a deaf Russian school teacher, one Konstantin Eduardovich Tsiolkovsky by name, had published hundreds of technical monographs and science fiction pieces about space travel starting as early as 1895. Not only had Tsiolkovsky long-since invented the fundamental equations of rocketry, he had, with uncanny detail and accuracy, anticipated many of the problems and sensations of modern space flight.[24] Oberth was so impressed that he became a lifelong fan of Tsiolkovsky and promoted his work abroad.

Tsiolkovsky's sweeping cosmic vision began with the Sun, which he recognized as life's primary energy source. Because Earth intercepted only one part in 2.2 billion of the Sun's total light output, life could only achieve a tiny fraction of its potential from the surface of the home planet. Tsiolkovsky reasoned, with an almost Marxian sense of inevitability, that humans eventually would have to "leave the cradle" of Earth. Only then could we truly make something of ourselves, using more energy than is available on Earth to live large in the universe.

To Tsiolkovsky, space was nothing short of a new evolutionary challenge. Beyond Earth lay lands so vast and varied that all of life's journeys by ocean, ground and air would pale by comparison. In his eyes, space travel was the grandest step evolution would ever take because it would unchain Earth life, after billions of years of confinement, to achieve endless destinies.

Tsiolkovsky then went on to show that rockets were the means to this end. This was where von Braun and his VfR colleagues would make their mark. Their goal, always, was interplanetary travel.

Their budget, however, was tiny, and so were their rockets. These they launched from a Berlin suburb, charging gawkers admission to defray costs.

Von Braun's fortunes changed in 1932, however, when the German army invited him and other VfR members to develop rocket weapons. Von Braun gladly accepted, using the army test range for his experiments, skipping the second half of his undergraduate course work and completing a doctoral dissertation on rocketry in a scant 18 months.[25] Others in the VfR dragged their feet, suspicious of an increasingly violent and paranoid regime. Two years later, after the Nazis had consolidated their power under Hitler, financial difficulties and ever-tighter regulation forced the VfR to disband. Some members, such as Willy Ley (who would become a prominent American author), soon left Germany altogether.

Rockets interested the Nazis because, as it happened, the Treaty of Versailles at the end of World War I prevented Germany from developing long-range artillery. But the treaty said nothing about rockets. So, in a strange twist of fate, the brutally repressive Nazi government became the first to sponsor the space dreamers.[21]

Thus a young Wernher von Braun found himself on the fast track as a Nazi, eventually joining the SS (*Schutzstaffel*: "protective squad"), a paramilitary organization that chose its members for their supposed racial and ideological purity. Before World War II was through, von Braun had attained the high rank of Major in the SS, overseeing a secret island factory called Peenemünde. Here, thousands of slave laborers from the nearby Mittelbau-Dora concentration camp built the rockets in a labyrinth of caves carved into a mountain. Despite aerial bombing, wartime supply problems and active sabotage by the laborers, von Braun oversaw the building of over a thousand V-2 rockets (V for *Vergeltungswaffe* or "Retaliation weapon"). Near the end of the war, the missiles rained down on England, killing over 2,700 civilians.[26] The greatest damage, however, occurred in Germany, where as many as 15,500 prisoners may have died building the rockets.[27]

Designed By a Nazi

When the war ended, von Braun and hundreds of other former Nazi rocketeers sought out and surrendered to the American army as it overran Germany. The U.S. Army seized Peenemünde, shipped all the V-2 parts it could back to the states and left the island and its production staff to the invading British and Soviet armies. The United States put the captured Germans to work on rockets at the Army's Proving Grounds in White Sands, New Mexico and Fort Bliss, Texas.[23 28]

Von Braun had been a quick study of the Nazi path to power, especially its manipulation of rich media images and spin control. As soon as anti-Nazi sentiment had cooled off somewhat in America, his dreams figured prominently in a series of lavishly illustrated articles in Collier's Magazine.

Here was his plan to conquer space: (1) Build huge rockets. Control them by radio from the ground. (2) Perfect the technology needed to get them into Earth orbit. (3) Put life-support systems in them and send monkeys, then men. (4) Build a re-usable rocket, or Space Shuttle, and make manned missions routine. (5) Build a giant, permanently-manned space station to study weather, relay radio signals, conduct experiments, spy on enemies, etc. (6) Build a permanent military base on the Moon. (7) Use the space station as a base to build a giant fleet of nuclear-powered space ships to send hundreds of military men to explore Mars.[29]

NASA adopted his agenda wholesale when it hired him to beat the Soviet Union in the race to the Moon. The U.S. Government and media turned a blind eye to the German rocket team's Nazi past, installing von Braun as Director of Marshall Space Flight Center and his associate Arthur Rudolph, who would later renounce his U.S. citizenship,[30] as program manager for the Saturn V rocket.

Standing 111 meters tall (seven times the height of the V-2 rocket), with a lift-off mass of 2.8 million kilograms, the Saturn V was the mightiest rocket ever built. Of the 13 launched, not one ever failed. On July 20, 1969, the Saturn V achieved the goal of putting Americans on the Moon, winning the "space race" once and for all.

With its primary goal achieved, NASA continued forward for a time on raw momentum. NASA's contractors now had the ability to crank out several Saturn V rockets per year, but only a handful more would be launched. On December 14, 1972, the last of six missions left the Moon. Money and political will had run out.

But NASA refused to die. By then, it had status, infrastructure and a cadre of super-educated dreamers with some unfinished business: items 4-7 of the von Braun playbook. And so, as political support waned and budgets dwindled, NASA got busy promoting the Space Shuttle, the Space Station, and planning permanent Moon and Mars bases.

Through much of its history, NASA's annual budget was decided in the U.S. House and Senate Appropriations subcommittees on the Veteran's Administration, Housing and Urban Development, and Independent Agencies. (The VA-HUD committees were disbanded on March 2, 2005, and NASA was reassigned to the Commerce, Justice and Science subcommittee.) Because its budget historically was carved out of appropriations that might otherwise house the poor or care for wounded veterans, the social relevance of NASA's activities fell under especially intense scrutiny.

How to convince the skeptics? Cold-war military necessity could no longer quite hold the day. What sold better was the frontier.

The Final Frontier

The American frontier had closed, of course, long before the dawn of space flight. The United States Census of 1890 noted its passing, remarking that the unsettled areas of the country, once large tracts that lay beyond advancing lines of civilization, had at last broken up into mere pockets of wilderness. Historian Frederick Jackson Turner, speaking on "The Significance of the Frontier in American History" at the Chicago World's Fair in 1893, advanced the view that the frontier had been the central defining feature of the United States and its citizens.[31]

Turner framed his Frontier Thesis in evolutionary terms: pioneers would regress nearly to "savagery" in order to survive the unsettled wilderness. Then, as civilization filled in behind them, it would progress steadily through ever more advanced industries toward modernity.

To Turner, the frontier explained not only America's rugged individualism, but also its paradoxically strong national identity. He wrote:

> "Nothing works for nationalism like intercourse within the nation. Mobility of population is death to localism, and the western frontier worked irresistibly in unsettling population...What the Mediterranean Sea was to the Greeks, breaking the bond of custom, offering new experiences, calling out new institutions and activities, that, and more, the ever retreating frontier has been to the United States...and with its going has closed the first period of American history."

From NASA's earliest days, Turner's paper circulated widely throughout the Agency.[32] Administrators and engineers alike readily perceived the Moon as the threshold to an infinite frontier that not only could recapture the central motive force of American history, but magnify it without limit.

American science fiction throughout the 20th century was rife with visions of a space frontier. Pulp fiction and movies filled the young minds of a generation with whole constellations of images: Astronauts bouncing buoyantly about in space suits. Rooms full of mission controllers with eyes riveted to giant status screens. A rocket pilot gripping the controls as the clock ticks backward toward ignition. The Earth looming large in a view port. Diners squeezing supper from plastic tubes. The incessant clatter of fans, pumps and actuators providing life support. Maverick tycoons mining the Moon for profit. Militaries planting flags and racing to control the "high ground" and orbital "chokepoints."[33] Rockets running gauntlets of extreme cold, isolation, orbital debris, solar flares and radiation belts to ply new trade routes between gigantic space stations and bubble-domed colonies in Lunar craters. Meanwhile, in nearby crevasses under black, star-speckled skies, growing mounds of trash neither rot nor rust away in grey wilds so still that a footprint there might last a million years.

Beyond its air-brushed glamor, adventure and novelty, the space frontier made three more promises: endless growth, escape from tyrants and disasters, and transcendence of the physical limitations of Earth and flesh. To cold-war America, these notions sold like instant hotcake mix. But were they accurate?

Growth

Increasing one's personal wealth is the central idea of modern civilization. To speak out against it is to be branded anti-progress if not anti-American. If you expect to have more than your parents, and your children to have more than you, then you are deeply invested in the concept. Investment itself implies growth.

The pattern of growth we're talking about occurs often enough in nature. Whatever increases by a fixed fraction of itself in a fixed amount of time will grow exponentially. At the moment you were conceived, you were a single cell. A few minutes later, that cell divided in two. A few minutes after that, those cells divided again, and so on. Early in your mother's pregnancy, you grew exponentially.

Populations grow exponentially when the birth rate exceeds the death rate. Not only is human population growing exponentially right now, but the rate of increase itself has been increasing (with only very short-term exceptions), for thousands of years.

The world economy is also structured around the assumption of continued growth. If your money is earning interest, growth is working for you: your nest egg will double in a finite amount of time.

The doubling time for anything that grows is about equal to 70 time units (such as years) divided by its percentage rate of increase (such as an annual interest rate). Human population has doubled in the 42 years since 1965, so the average annual growth rate over that period is $70 \div 42 = 1.67\%$. The growth rate varies somewhat from year to year and is currently about 1.17%. This would give a doubling time of $70 \div 1.17 = 59$ years.[20]

Growth would seem an absolute social good. For example, in the 20^{th} century, the population of the United States grew by a factor of 3.5.[34] Not coincidentally, over this time period, the rate of copyright registrations increased fivefold; patent registrations increased sixfold.[35–37] Many of these filings involve media (such as film and digital works) and physical phenomena (such as quantum mechanics and DNA) that were unknown in 1900. If civilization grew by a factor of ten, it seems fair to expect the sort of discoveries we now see every decade to emerge every year—almost as soon as new needs are identified. Now imagine what could happen if civilization grew by a factor of 1,000. Could it grow forever?

Not on Earth. The world has only so much land, and we depend on it for a lot more than housing and transportation. All of our food and most of the energy we use comes from the solar economy—sunlight converted by plants into the primary sugars that power the biosphere. Even fossil fuels—oil and coal—are stored (and substantially degraded) energy from a half-billion years of buried plant life.

Sunlight delivers a steady 1.8×10^{17} watts of power to Earth. Plants convert about a thousandth of that into biologically useful forms such as carbohydrates.[38] In 2002, human energy consumption came to 7.6% of the energy that plants stored that year, and half of that went to the richest billion of us.[39,40] If the remaining 5.5 billion rose to the same level of affluence (as China and India are working very hard to do), humans would consume 26% of Earth's total plant productivity. But this figure neglects the effects of habitat loss due to agriculture, construction and pollution. Even in 1992, when there were 1.2 billion fewer of us, Al Gore suggested that our total consumption had already reached 40%.[41] Ecologist H. T. Odum has pointed out that in stable ecosystems, no single animal species consumes more than 2% of the total plant productivity.[42] Clearly, our energy use alone puts us way beyond the point of natural balance with our environment.

To fill the energy gap, the global economy depends on oil, coal and uranium reserves. These may suffice for a time, but population continues to grow. Unlike an embryo, we have no built-in stopping mechanism short of exhausting our fossil and biological reserves like an overdrawn bank account. Then, as Thomas Malthus famously warned in 1798, war, famine, plague and pestilence would surely follow.[43]

But wait! This dreary picture ignores the existence of lands beyond Earth. The Moon and Mars combined have more land than Earth. The asteroids are rich in resources, from water to soil minerals to precious metals. For over a century, those who grasped the enormous bounty of space have wondered how anyone could believe in limits to growth. All the oil and coal on Earth is stored solar energy, yet as Tsiolkovsky showed, the Sun provides 2.2 billion times as much as reaches Earth. So why bother to save energy? The total amount of steel of all grades in use throughout the world would fit in a ball less than 1,800 meters across.[44,45] The asteroid belt has thousands of pure metal asteroids larger than this,[11,46] so why recycle? The galaxy has hundreds of billions of stars and probably trillions of planets. Beyond that, the best cosmological evidence suggests that the universe goes on forever. When would we ever run out of new material? Why not simply travel beyond Earth and clear new lands as we need them?

Suppose we could. By exporting all excess population to the Moon and Mars, we could avoid further crowding on Earth for a time. At an annual growth rate of 2% (which is low for an open frontier), the new worlds would become as crowded as Earth in 35 years. From that point forward, we would need more land still. By then, there would be twice as many people having babies, so in another 35 years we would need not one new Earth, but two, for a total of four.

Fortunately, the known asteroids contain enough material to build thousands of Earths worth of new land in the form of O'Neill colonies. We are only just beginning to discover the minor planets of the outer solar system, including Jupiter's Trojan asteroids and the Kuiper Belt, which includes Pluto and thousands of other small worlds. Together, these bodies multiply the available material by another factor of a thousand or more. Thus, at the same dry land population density as on today's Earth, the solar system could hold something like 10^{17} people.

At a 2% growth rate, it would take only 870 years, a fifth of a page in the Book of Earth, to fill up every piece of asteroidal, Trojan and Kuiper Belt real estate in the solar system. Even so, this falls far short of using the Sun's total output. To capture all of the Sun's energy, we would need to dismantle major planets such as Neptune or even Jupiter to get enough raw building materials. By capturing 2.2 billion times as much sunlight as Earth and taking care to maximize green spaces, our population may be able to grow to 10^{20} before again claiming an unsustainable fraction of plant productivity. Even so, growing at 2% per year, it would take us only 1,200 years to reach this enormous population. To continue our growth beyond that point, we would need to find

Scale:	Moon/Mars	Solar System	Galaxy
Population:	6.5×10^9	10^{20}	10^{30}
Doublings:	1	34	67

Growth/year	Years to reach Earth's present density		
2%	35	1,200	2,300
1%	70	2,400	4,700
0.1%	690	23,000	47,000

Table 1.2: Growth and overpopulation in the galaxy. The top section shows the populations and the number of doublings needed to match Earth's present dry land density on three cosmic scales. The bottom section shows the time it would take to reach each of these population levels at three different growth rates.

land beyond the solar system.

Of course, we could prolong the process by slowing our growth. However, doing so has proven extremely challenging even for strong central governments such as China. Across an open frontier, it's hard to see how even this modicum of restraint could be enforced. But even if growth does slow, as long as it remains above zero, our need for new land will rise exponentially.

Table 1.2 shows the total human populations needed to fill the Moon and Mars, the solar system and the Galaxy to the same density that we have on Earth today: 44 people per square kilometer of dry land. It also shows the approximate number of times our present population would have to double to reach that figure. Finally, the lower part of the table displays the number of years it would take to reach each population level, assuming various growth rates.

The figures are very rough, but this hardly matters. Even if the population needed to fill the galaxy (which assumes ten billion viable, empty solar systems) is off by a factor of 100, that's only a difference of seven doubling times (out of 67). The point remains that the Galaxy would fill up in a hurry.

Table 1.2 ignores travel times. Even moving at nearly the speed of light, it would take settlers 100,000 years to cross the galaxy, far longer than any filling time in the right-hand column of the table. The final limit to growth, then, is raw distance.

It may at first seem that the special theory of relativity provides a loophole:

viewed from a spacecraft moving at very close to light speed, the galaxy would appear foreshortened along the direction of travel. Thus travelers could cross it in perhaps only a few years of subjective time.

In practice, though, outrunning population growth by relativistic expansion would require the great bulk of humanity to remain in transit between the stars at any given time. As soon as a band of travelers slowed to settle a solar system, their reference frame would shift. The stars would return to their former imposing separations. From the perspective of any solar system in the galaxy, those still in transit would take 100,000 years to cross the Milky Way, their lives prolonged by time dilation. Even at a miniscule annual growth rate of 0.1%, solar systems would fill in 23,000 years, before travelers could get even a quarter of the way across the galaxy. Then populations would double, if unchecked, every 690 years. Thus even with relativistic expansion, all solar systems within the volume of settlement will fill at an exponential rate. Meanwhile, the surface of this volume can expand no faster than the speed of light. No matter how small its rate, exponential growth will overtake a volumetric expansion in a finite amount of time.

Perhaps we could get around this problem by somehow accelerating all new life to ever higher relativistic speeds. Our ever-faster progeny still would need power and materials for growth, of course, but they could never slow down to obtain them. Thus they would be forced (if they were able) to disassemble planets and stars for power and material without breaking stride. Fleeing outward from the solar system in all directions, their lines of communications would stretch ever thinner. Theirs would become a path of total destruction through a universe that speeds by in a blur. They would never know a moment's rest as they rush outward into deeper oblivion.

Long before growth reaches its limits, though, life gets hectic. A competitive economy with obligatory growth cannot avoid suffering. Because the wealth of individuals and regions changes at wildly different rates, a few get much richer faster, while most, especially agrarians, can't keep up with inflation. The wealthiest investor, Warren Buffet, has earned up to 40% a year for decades on end—doubling his wealth every fourteen months. Meanwhile, a third world peasant whose ancestors got by for millennia in the local ecology now may make two dollars a day or less. While that amount may have been fine a hundred years ago, today it is not even enough to open and pay the fees on an interest-earning account. With her government pressing her to grow exotic cash crops such as coffee rather than subsistence foods long adapted to the local ecology, her ability to eat becomes vulnerable to price and currency fluctuations on a global level. As a result, despite the world-wide cultivation of almost twice as much grain as needed to feed the human population, more than eleven million children die of malnutrition every year.[47]

For the many who struggle somewhere between poverty and wealth, the relentless pressure toward ever-greater visible prosperity increases competition, toil and hoarding to the point where these traits are lauded as innate social good. As resources and time dwindle, the incentive to try and rig the game in one's own favor becomes overwhelming. From the poorest sweatshop to the richest multinational, growth begets greed; greed begets corruption; corruption breeds violence.

There is no outrunning exponential growth. It will buck up against hard limits of resources and energy in finite time, no matter how boldly we go about extracting resources from the cosmos. As surely as tomorrow, the day will come when we cannot expect more wealth, power or children than yesterday. Conquering the space frontier would, at most, forestall that day, magnifying the cost to the majority of people who will be losers in the competitive economy along the way.

Escape

The frontier's second promise is escape from a world already feeling the pinch of growth. Today, a fifth of Earth's human population produces more carbon dioxide than plants can scrub from the atmosphere, and the remaining billions are striving to achieve a similar level of industry. Pollution, disease, guns and drugs cross borders continuously, and nuclear weapons continue to proliferate.

For those of us now richer in cash and energy than ever before, it can be hard to appreciate the enormity of the situation. The 1974 *Limits to Growth* study warned that, like an heir squandering his wealth, opulence has blinded us to our predicament.[48] During the oil gluts of the next two decades, the book was roundly criticized as anti-progress, but the story it told was as old as the hills. In *Collapse* (2005), biogeographer Jared Diamond showed that throughout history, societies that failed catastrophically generally did so within a decade or two of their highest levels of population and prosperity.[49] Through multiple crises of negligence, collapse catches civilizations by surprise. While a society's coping mechanisms (from royal tribute to free markets) may be sufficient to overcome any one crisis (such as pollution), the problem with growth is that it depletes all budgets simultaneously. Thus the society must face famine, energy and water shortages, loss of soil fertility and social turmoil all at the same time.

In the past, though, we lived in a world of many civilizations with separate economies. While some collapsed, others lived on. But now that world economies are knitting together into a single, interdependent whole, we live in deeply precarious times.

All the more reason, say spacers such as the theoretical physicist Stephen Hawking, to establish off-Earth colonies now. Hawking has been making the news lately by urging the construction of space colonies before something (such as a genetically engineered virus) has a chance to wipe us out.[50] He's in good company: Gerard O'Neill predicted wars and dark ages brought on by energy and resource starvation.[1] Astronomer Carl Sagan raised the specter of an asteroid impact such as the one that killed the dinosaurs.[51] Robert Zubrin warned against the rise of tyrannical world governments.[52] In each case, the authors felt that we had only the narrowest window of opportunity to get into space and dodge the apocalypse. (Science fiction author David Brin called this the "threshold effect"[53]). Even if our problems do fundamentally boil down to growth, they argue, going to space now would at least buy us time and resources while we hash out more durable solutions.

The idea is gaining traction. For example, at www.gaiaselene.com (slogan: "…saving the earth by colonizing the moon"), you will find dire warnings about global warming, melting ice caps and our rate of fossil fuel use ("millions of times faster" than nature produces them). The splash page claims that "By 2050 we will need three times as much power and it will have to be three times as clean." They're probably right. But what to do about it? According to their site, small-scale renewable energy production such as solar power and wind energy are not reliable and scalable enough to sustain any significant growth. So Gaia Selene proposes to build large solar arrays on the Moon's poles and beam the power back to Earth. If or when nuclear fusion becomes viable, they also advocate sifting the lunar regolith (soil) for Helium-3, a relatively non-polluting fusion fuel deposited by the solar wind. There's even a video featuring, among others, Dr. Alan Binder, designer and Principal Investigator of NASA's Lunar Prospector mission, which found evidence for water ice in the Moon's polar regions. According to Binder, permanent, self-sustaining lunar bases pose no problem: where there's water, soils and sunlight we can grow food. In Binder's words: "What could be easier?"

There's also the Lifeboat Foundation (lifeboat.com), a policy group concerned with limiting and defending against hazards posed by biotechnology, robotics, nanotechnology, and nuclear weapons. Lifeboat opened its doors online a few years ago with detailed renderings of a self-sustaining space station called Space Ark 1 on its splash page. The design consists of four von Braunian space wheels (each 300 meters in diameter) connected in parallel pairs at the ends of a cylindrical bridge. Power would come from solar panels and four fission generators—one in each hub. Space Ark is designed to support 1,000 permanent residents and 500 visitors. Its stated purpose is to provide a backup genetic stock of humanity "just in case."

As famous scientists have joined Lifeboat's board of directors, Space Ark 1 has left the Foundation's main page and buried itself among the links in the site's FAQ. The text that accompanies the many images briefly outlines the Ark's systems: Air (2/3 sea-level pressure and 60% oxygen), Design/Construction, Gravity, Heat, Location, etc. But the only column space devoted to biological life support systems is a brief mention of successful plant growth experiments aboard the late Russian Mir space station.

Is it really such a short step from a few zero-gravity sprouts to ecological life support? Most of us in the space community seem to think so. The prevailing view regards life as so much biomechanical gadgetry, easily and long-since mastered by the disciplines of agriculture and chemistry. O'Neill's colonies, for example, would place farms in sealed, glass-topped tanks outside the colony. By growing each crop in sterile soil, sealed off from the others and from the main habitat, their growth and nutrient needs could be monitored with perfect control and no risk of loss to pests or disease. Yields would be utterly predictable and regular, eliminating any chance of famine.

If only it were so easy. The crops in such a system would need air, water and fertilizer in quantities far too great to haul up from Earth. Thus it would be convenient to obtain them somehow from the habitat's wastes. The habitat itself would need clean air and water, nutritious food and sanitary waste disposal. Food crops by themselves aren't especially well-adapted to purifying raw sewage, so additional machinery would be needed to process materials flowing each direction. To date, Earth-side experiments (which we'll discuss in Chapter 3) have required an enormous amount of machinery and electrical power to provide these additional services, with only mixed success.

Engineering, Life and Life Support

Sooner or later, most science and engineering students realize that their tools, from resistor codes to mathematical formulas, are made to be as easy to use as possible: standardized, linearized, simplified, color-coded, cataloged and explained in every conceivable way in their text books and training manuals. Nature may at first appear to have something in common with human engineering: DNA uses four standard bases; organisms seem to have clear roles in ecologies, such as predator and prey. But this veneer of simplicity is really no thicker than our own perceptions.

The machinery of the living world operates on a molecular scale, so it would seem to be comprehensible through the tools of chemistry and thermodynamics. Yet unlike simple chemistry experiments, life systems down to the smallest organelle are characterized by an astonishing number of connections, many of them quite subtle. Unlike our tools, organisms exist for no external purpose except to live. And to do that, they have evolved what I would consider a defining characteristic of life: the ability to make new connections as needed. This creative aspect of life, coupled with reproduction and genetic variation, allows evolution to optimize organisms for energy efficiency, miniaturization, self-repair, ever-shifting niche roles and countless other traits. Life's technology is literally billions of years ahead of anything humans have invented. Its complexity and chemical interoperability came about through more than 10^{43} experiments optimized across millions of times more parameters and connections than the human mind can hold.[16]

If you asked a group of scientists from 250 years ago to reverse-engineer a cell phone, they would have no prayer of doing so. Even if they could somehow deduce from it the underlying principles of electricity and quantum mechanics, they would lack the manufacturing infrastructure to do anything with it. We are at millions of times less advantage when it comes to making sense of the living world. The only thing that should give us any hope of comprehension is that we, too, evolved as part of it. Thus instinct, intuition and tradition often rightfully guide our research trajectories.

Life abounds on this world because trillions of generations of every organism's ancestors (including our own) participated in the evolutionary process of sorting out and filling niches. This process provides all living beings on Earth with food and living space. The networks that emerge to accomplish this, and all the beings within them, together comprise complex and tightly interlinked ecosystems. Optimizing equations or electronic circuits is not at all the same kind of problem.

Not only does life not recognize intent (except to live), it does not recognize boundaries. Coral, for example, is a composite organism with animal, mineral and plant components. We may identify plants in isolation, but they did not evolve that way. For example, plants scrub carbon dioxide and provide food and shelter to numerous animals at various stages of life. Flowers and seeds co-evolved with birds, insects and their changing environment. Some plants such as sedges and hyacinths can even act in concert with microbes and fungi to purify raw sewage. Putting just one or two plant functions in a black box such as a space farm puts a plant out of several of its other customary jobs—and reassigns them to us. Soon enough, we discover that we are under-qualified. We do not understand life support. No species does. That hard-won knowledge is spread among the many thousands of species that comprise each of Earth's *biomes*, or climate-adapted ecologies.

From deep oceans to marshes to alpine forests, biomes are complex, detailed, interconnected, creative, non-linear and resistant to partitioning. This makes them poor candidates for the tools of engineering, which depend on linearity, predictability, simplicity and modularity. If, in the aggregate, we are not in a sustainable relationship with living ecosystems now, there is no definitive way to tell how much effort it will take to make them sustain us in space.

Indeed, the latest Earth escape club, the Alliance to Rescue Civilization (ARC; www.arc-space.org), acknowledges that any such project would be "very long-term."

Space lacks air, water, food and the ecosystems that regenerate and purify these essentials for us on Earth. We will never have a better opportunity to learn how to sustain ourselves through natural ecology than we have here and now on the home planet.

Since the dawn of civilization, our dreams of growth have put us at war with nature. The easy victories have ended; it's now a losing battle. Irrigated monocrop agriculture sows deserts, bacteria have evolved resistance to antibiotics, and if we don't change course now, up to half of all species will go extinct by mid-century—life's sixth and fastest major extinction.[17,54–56] Given the destruction we've wrought on Earth, our odds of preserving life meaningfully in a radioactive vacuum on a first attempt are vanishingly small. We have shown life so little regard for so long that we never learned the skills of life support. If we wreck the Earth, space offers no escape.

The Myth of Away

If building an ark is off the table, could there at least be a pragmatic middle ground? Could space tide us over with some valuable resources while we learn to live more sustainably? This seductive argument, often heard in space circles, smacks of Augustine of Hippo's ancient prayer: "grant me chastity and continence, but not yet."[57]

Even now, after sixteen centuries, Augustine's pious quip provokes a smirk: a virtue deferred is clearly no virtue at all. If it were convenient to mine space for immediate consumption, doing so would not so much buy us time as postpone the ecological virtues. Space exploitation (as it's called in the industry) would perpetuate a deliberate and possibly fatal ignorance that I call the Myth of Away.

Let's unmask this myth with a few quick questions. Where does your tap water come from? When you're done using it, where does the waste water go? Where do your electricity and fuel come from? Where do your clothes, your transport, your medicines, the building materials in your house or apartment come from? How about each item of food in your refrigerator? Where does your garbage go? Without extensive research, we don't know where most of the things in our lives come from or go to: it's just somewhere far away.

Indigenous peoples throughout the world, especially gatherer-hunters, know exactly where their food and water come from and where their waste goes. It is no coincidence that these "natives" consume dozens of times fewer resources than we do and, in many cases, waste practically nothing. Their economies are largely regenerative: food, body and construction wastes do not travel far in time or space before the local ecology reclaims and reconstitutes them into some other useful form. Surprisingly, anthropologists have found that most such peoples (prior to devastating encounters with consumer economies) enjoyed far more free time than we do and viewed nature not as hostile, but as benign and abundant.[58]

By contrast, our industrial economy is extractive. As consumers, we buy something, use it up and throw it away. Then someone far away mines the earth to make the next item for our consumption. We don't care where it came from or where it's going, so long as we can have it when we want it. Ours is a global culture of disconnection, filled with pipes, highways and media that come from and lead to that ubiquitous, fictional non-place called "away." By denying place and linearizing the once-cyclic resource flows of natural ecology, we automatically create both depletion and pollution. These problems are built into the physical shape of our assumptions about the world.

The Space Frontier is all about "away." By exporting pollution and population and moving resources across ever greater distances, it promises only to expand the extractive economy of commercial empires, not to deepen the regenerative ecologies of life. Buying time with space resources is a siren's song. It leads directly away from the ecological knowledge we need to live harmoniously wherever we are. It beckons us deeper into exactly the troubles of growth that we would most like to avoid.

Perhaps it is ecologically functional, then, that space is so expensive to reach. If you loaded the Space Shuttle up with straw, which then magically turned into gold in orbit, you would lose money due to the transportation costs. Would it be so surprising if recycling and conservation, already economical in many cases on Earth, hint at a better path to the cosmos? We will expand on this possibility in later chapters. For now, though, it's clear that space offers no escape from our problems and probably won't even supply us economically in the short run.

Transcendence

If a few humans somehow did manage to start anew far from Earth, new social forms surely would emerge. In space, where even the Law of Gravity seems optional, other Earthly constraints may no longer bind. Who could stop a distant space habitat, for instance, from engaging in human cloning and genetic engineering? Beyond reach of today's global civilization, humanity could find endless new directions for itself: new stories, new architectures and even new bodies. Thus we come to the Frontier's third promise: transcendence.

In space, sources of water, air and soil may be scarce, but solar power abounds. Recognizing this, Tsiolkovsky suggested that space dwellers ultimately would outgrow consumption and become autotrophs, deriving their energy from the Sun as algae do. He understood, though, that any such being would need both sides of the respiration cycle if it used photosynthesis, both producing and consuming oxygen within its own body. It would function like a world in its own right: a miniature version of Earth's entire biosphere. Just as the cells of your body embody mitochondria and other evolved symbiotes, Tsiolkovsky's autotrophs would include the metabolisms of both animals and plants.[59]

When Tsiolkovsky's hero interviews members of a species of intelligent autotrophs in his 1895 monograph *Dreams of Earth and Sky*, he learns that they originated on large planets. Upon reaching space, they gradually adapted to the weightless vacuum "just as your aquatic animals were gradually transformed into land animals, and your land animals into flying animals."[59]

Others since Tsiolkovsky have looked to technology for a much more rapid transformation. One of the earliest and most vivid post-evolutionary visions appeared in applied mathematician John Desmond Bernal's 1929 paper *The World, The Flesh, and The Devil.*[60]

In Bernal's view, science and technology were the only means to overcome the fundamental tyrannies of life. Advances in organic chemistry would provide humankind with ever stronger, safer materials, artificial foods with much more variety and nutrition than plant and animal flesh, and ultimately replace all metals and hence the need for labor-intensive mines. As processes were refined, all our physical needs would be provided for with decreasing expenditures of energy and materials (in sharp contrast to trends that have prevailed in the seven decades since his paper). Even so, he argued that human desire, "the strongest thing in the world," ultimately would prove too big for the Earth. To him, the conquest of space was inevitable.

Bernal's suggestions for how to approach this conquest have influenced the space community tremendously. His rocket boosters used beamed microwave power systems that anticipated the solar power satellite systems that O'Neill and Glaser would propose some 45 years later. His deep-space vehicles used solar sails, which we'll talk about again in later chapters. But more than any other idea, it was his space habitat that captivated the imagination of spacers over the decades. He proposed a 15-kilometer hollow sphere made of materials from the asteroids or perhaps Saturn's rings. Its transparent walls would admit sunlight, which would power its systems either using chlorophyll or photovoltaic solar cells. He likened his sphere to a phototrophic organism and, echoing Tsiolkovsky, recognized that everything within would be recycled: "the globe takes the place of the whole earth and not of any part of it, and in the earth nothing can afford to be permanently wasted." If ever space habitation had a Prime Directive, this was it.

Bernal declared that inside his sphere, “there would probably be no more need for government than in a modern hotel. . . Free communications and voluntary associations of interested persons will be the rule.” As the human population left the planet for Bernal’s stateless utopias, planet Earth, at last “free from the economic necessity of producing vast quantities of agricultural products, could be allowed to revert to a very much more natural state.”

But human desire would not be content with life around just one star. Bernal foresaw not only expansion outward into the universe, but also the possibility of improving the cosmos itself for human habitation. By carefully managing the energies of each star humans visit, he wrote, “the life of the universe could probably be prolonged to many millions of millions of times what it would be without organization.”

This theme resurfaced 54 years later when physicist David Criswell proposed a method to increase the lifetime of the Sun. He called it “stellar husbandry” or “star lifting.”[53] The technique involved siphoning mass from the Sun and using it to build new worlds. Enough new land would be produced to house some 10^{17} human beings. For every person now alive, Criswell’s civilization would have over 20 million people living at a level of affluence undreamed of today. Meanwhile the Sun, stripped of most of its mass, would shrink down to a white dwarf. By pouring a steady trickle of reserved material onto its surface, its lifetime would lengthen ten thousand-fold while still providing each citizen with some 200 kilowatts of power and light—comparable to the power level I will compute for gaiomes on page 151.

Even such grandiose conquest was not enough for Bernal. “Normal man,” he wrote, “is an evolutionary dead end.”

Bernal imagined improving on the frailties of the human form through what can only be described as the ultimate in elective surgery: removing the brain entirely from the body and placing it in an indestructible cylinder. Inside, machinery would circulate all the nutrients necessary to keep the brain alive, and the nerves would be grafted to conduits leading to external sensors and appendages. We would become immortal cyborgs, more machine than human, capable of living in open vacuum and seeing directly all the spectra of light now invisible to our eyes. We would communicate by radio-telepathy, eventually evolving such close associations with each other’s thoughts as to become hive minds. “The new life would be more plastic,” wrote Bernal, “more directly controllable and at the same time more variable and more permanent than that produced by the triumphant opportunism of nature."

These writings evoke a sense of rage at the happenstance nature of existence. Rather than bow to random mutations and evolutionary selection pressures, Bernal would have us take our destiny into our own hands, shaping ourselves and all the environments we encounter according our own conscious desires. Clearly, space would give us room to do that.

But what has shaped our desires in the first place? In all cases, it was our environment, whether natural or built. We have evolved together with millions of other species. Each turning point in our evolution was shaped by the presence of other beings, themselves shaped by our emergence. We belong to a natural democracy that long succeeded in matching our desires to our environment. We like greenery, nice weather and companionship not only because these provide for us, but also because we were, for most of our history, integral to the systems that maintain them. We once were native to Earth.

So it was for the first 20 pages of our story as a species. But on the 21^{st} page (the millionth in the Book of Earth), the dawn of phonetic alphabets touched off a process that gradually distanced us from immediate sensory experience.[61] As these have evolved into ever more immersive media such as film and video, we find we can manufacture experience, shaping desire and broadcasting it for profit. Not surprisingly, our desires increasingly come to be dominated by manufactured items, themselves extracted from the earth and discarded when spent.

As Bernal foretold, our chemistry has indeed advanced to the point where we manufacture tens of thousands of chemical compounds and alloys that are seldom if ever found in nature. Not surprisingly, ecosystems have not yet evolved ways to reclaim many of these substances. A discarded plastic spoon or carpet may sit in a landfill for many thousands of years, during which time its wooden counterpart could have cycled its vital nutrients through the ecology (including plants, animals and people) hundreds of times.

Building artificial bodies for ourselves in space would set us on the most lonely, arduous path imaginable. Not only would we have to re-invent a solar economy that took nature billions of years to develop, we would literally have to chop off the larger parts of ourselves and abandon them forever. I'm not merely talking about our bodies. Even a cursory study of living nature shows that our identity does not end at our skin. Life evolved simultaneously on all scales, from the sub-cellular to the largest ecosystems. Thus our being encompasses the taste of ripe berries, the warming rays of dawn, the brush of a breeze, the blue sky, the quenching downpour, the scent of wildflowers, the voices of crickets and birds, the lay of the land and the regenerative services of the soil microbes. All these parts of us preceded our hands and intellects by millions of years into every Earthly frontier.

The regenerative economy, the community of life, the truest friends we ever had: none of these await us in space. What's left of us once we transcend them?

The Finish Line

When Neil Armstrong's small steps on the Moon ultimately won the race for NASA, the Final Frontier seemed wide open at last. How strange, then, that over the next few years, the nation turned away from space. It wasn't simply that Presidents Nixon, Ford and Carter lacked Kennedy's vision. After all, the bold space proposals of Ronald Reagan and George Bush Sr. have also come to naught. Nor was it simply that space somehow was packaged in a boring manner. The problem was that to most Americans, the space frontier never opened at all.

Turner recognized that the central element of the American frontier was land that anyone could reach and claim with a plow and a gun. Its accessibility made the frontier something that nothing could repress: not legislation nor civic boundary nor even instances of compassion for indigenous people. Because it was relatively easy to reach, it physically absorbed and sustained many millions of settlers over the course of several centuries.

Space is not like that. You cannot just walk there. The Apollo missions, at a cost of billions of dollars, managed to put only twelve men on the Moon for a total of twelve and a half days. Only the best pilots and the most promising scientists in the best possible health could become astronauts—but only if they also looked good on TV. Under these circumstances, most people had a much better chance of winning a major lottery than ever going to space, and the lottery cost only a buck to play. The dry, technical, stressed-out life of the astronaut promised nothing to the average citizen.

If space is ever to achieve any tangible meaning for the rest of us, we must find a way to make it much easier and less perilous to reach. I discuss how this might be accomplished in the next chapter. Even then, though, space won't be a frontier and we would be foolish to try to make it one.

The world's heroic government space programs, built on the myth of "away," have fallen far short of our hopes for expansion, escape and transcendence, and always will. The hopes themselves are wrong. If we try to propagate our pattern of obligate growth throughout the cosmos, we would succeed, at most, in greatly expanding the anxiety and misery it already exports. If our extractive economy wrecks Earth for us via resource wars or environmental crises, it also leaves us even less prepared to survive anywhere else. If we surgically sever all relations with our world and our bodies, we'll find ourselves friendless, estranged and hollow.

Yet space is rich in promise: not as a venue for conquest or escape, but as a challenge to evolve, a challenge not for one isolated species but for whole biomes. Life should try living beyond Earth, just as it tried to grow on land many times over until at last finding its stride through massive coevolution in the Cambrian period and beyond. Gaiomes are worth building in their own right, if only just to see what happens next.

We have tried building sterile, submarine-like habitats such as Mir and the International Space Station (ISS). While efficient for short trips with a few people, in the long run that's the hard way. It will always be dangerous, expensive, depleting and elitist. It ignores the great challenge of evolution because it excludes the vast community of people and species with whom we've evolved.

Alternatively, we could bring as much Earth life as we can along with us into space and do all we can to help it thrive. But first we have a lot to do and a lot to learn. We need to let life become a circle again here on Earth. We need to do away with "away." We need to re-learn the art of locality, of being native to a place and aware of its cycles. Nowhere will we need these vital skills more than in the deep vacuum of space, where, as Bernal said, "nothing can afford to be permanently wasted." Only when our relationship with Earth and all its species is mutually secure, abundant and joyous will we find ourselves—our larger, ecological selves—able to experiment meaningfully with living beyond.

Astrophysics meets permaculture in a book about the design and construction of gaiomes: artificial worlds in space that would sustain themselves through natural ecology. Discover how living beyond Earth challenges not just technology, but our very identity as a species.

Gaiome: Notes on Ecology, Space Travel and Becoming Cosmic Species