The Shape of Space

What the orbital space habitats designed for NASA in 1975 can teach us about living in new geometries.

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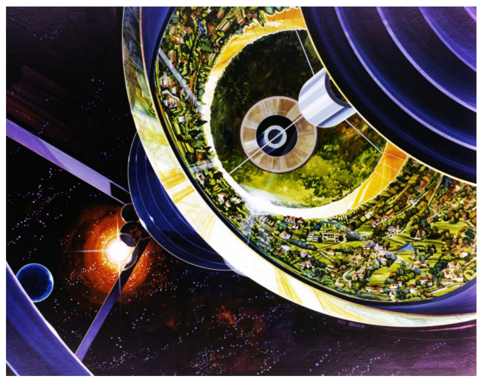

Bernal Sphere, 1975. [Rick Guidice/Nasa Ames Research Center]

"The sky starts at your feet. Think how brave you are to walk around."
— Anne Herbert[1]

"Space is not only high, it's low. It's a bottomless pit."
— Sun Ra[2]

Buckminster Fuller had an unusual way of talking about stairs. Instead of *downstairs* and *upstairs*, he encouraged people to say *instairs* and *outstairs*. "They all laugh about it," he wrote, "But if they try saying *in* and *out* for a few days in fun, they find themselves beginning to realize that they are indeed going inward and outward in respect to the center of Earth, which is our Spaceship Earth. And for the first time they begin to feel *real* reality."[3] Writing in 1970, at the dawn of extra-planetary space travel, Fuller identified a break in humans' spatial perception. Standing on Earth, we *see* the ground plane as flat, but we *know* the planet is a sphere. To describe motion and existence in a vast universe, where planetary surfaces are the exception, we would need a new language.

For centuries, the space away from the Earth's surface — "outer" space — has confounded attempts to make sense of it with terrestrial geometric schemes. Human occupation of and movement through space on our home planet has been dominated by the horizon and the apparent flatness of the ground plane. Meanwhile, the open sky has been conceived alternately as an unattainable place of infinite freedom or as a hard dome that limits the world, like a cake lid over a Flat Earth. For Nikolai Fyodorov and the Cosmists, in pre-revolutionary Russia, horizontality was the ultimate barrier. They believed humankind had to become vertical — had to resurrect the dead who lay flat in their graves, even — in order to escape the Earth's surface and achieve immortality.[4]

Fyodorov's most famous follower was Konstantin Tsiolkovsky, whose astronautic theory shaped the Russian (and later the Soviet) space program. A drawing in his 1883 manuscript *Free Space* might be the first depiction of humans in orbital weightlessness. Four figures float in a spherical spaceship, each pointed in a different direction, disoriented. Tsiolkovsky's ship seems better equipped than its passengers to operate in a fully three-dimensional environment. It has engines at both ends of a primary spine and gyroscopes on the other two axes, so that it can spin round and fire rocket thrust in any direction. This basic design — primary thruster, secondary retro rockets, axial gyros for orientation — has been used by all crewed Russian and American spacecraft to date, including the International Space Station.

Konstantin Tsiolkovsky, *Free Space*, 1883.
[via Russian Academy of Sciences]

In the counter-intuitive mechanics of orbital space, objects are continually falling on a trajectory that misses the spherical ground of the planetary body below. A spacecraft that accelerates forward moves to a "higher" orbit — up, or as Fuller would have it, "out." Firing retro rockets to decelerate, it moves "in." But these dynamics only apply to a dimensionless point. With a large, massy, complicated object like a spacecraft, we have to deal with gravity gradients and spin motion. Areas of the ship that are farthest from the planetary center are subject to less gravitational tug, and they move faster than the center of the ship's mass, so objects there drift outward with respect to Earth. On the side of the ship closest to Earth, objects drift inward.

The International Space Station, which orbits about 250 miles up (or out), is designed to mitigate these tidal complexities. Gyroscopes continuously modify the station's orientation, or "attitude," to keep its mostly flat grid of modules parallel to Earth's mostly flat surface, so that scientific instruments and observation windows look down (or in). Other gyros keep the station pointed forward. And as the station is slowed by the slight drag of the upper atmosphere, an engine periodically fires to keep it from falling in toward Earth.

Space is a place, but to be anywhere in that place is to be in motion. Astronauts on the ISS say "on orbit" instead of "in orbit," and they use the nautical terms *forward, aft, port,* and *starboard*. Fuller's "in" toward Earth is *deck* and "out" is *overhead.* These standard directions are labeled at every module junction, and they determine the uniform orientation of wall-mounted equipment. The ISS has ten main capsules, built in four countries, and their alignment on the same spatial axis helps avoid confusion, mitigate motion sickness, and promote community among the international crew.[5] This architectural scheme also reaffirms a connection to Spaceship Earth. Since the bodies of the crew are in a familiar relationship with the ground plane far below, we can imagine that they are in a very tall building with all the intermediate floors removed.

The International Space Station coordinate system. [NASA]

ISS Expedition 20, in 2009, the first time all five partner nations were represented on the space station. [NASA]

Cylinders, Toruses, and Spheres

A half century ago, the Princeton physicist Gerard O'Neill proposed a more radical break with the planetary surface. In the fall of 1969, after the Apollo 11 moon landing, he led a seminar of advanced freshman students to consider the spatial needs of an "expanding technological civilization."[6] The students evaluated different environments in terms of access to energy, materials, and waste disposal, and they concluded that high orbit would be the ideal location for new settlements. Orbital factories could use material from the Moon to make energy satellites, while orbital habitats could accommodate thousands of factory workers, and eventually a population of millions. They would occupy a relatively stable place in space, at the Lagrange Points, areas in high orbit where the gravity between large bodies balances out to create invisible hollows. O'Neill and his students worked out the engineering in rough detail, calculating material stress, light levels, atmospheric compositions, and the spin rate for producing artificial gravity through centrifugal force. They believed large-scale space habitats could be built within 25 years using existing technology.

In 1975, O'Neill convened a "summer study" at Stanford University to refine and visualize these proposals. With funding from NASA, he brought together engineers, space scientists, and physicists, along with artists, urban planners, and architects, for an "exercise in systems design." Among this group were the multitalented artist-designers Rick Guidice and Don Davis, whose collective experience included science-fiction film posters and book covers, video game art, advertising, and architectural design, as well as science illustration. Their renderings of O'Neill's space habitats included thirteen large-scale paintings in watercolor, acrylic, and gouache, showing both interior and exterior views, with an emphasis on the unnatural scale and perspective geometries of these new spaces and forms.

The O'Neill Cylinder, Stanford Torus, and Bernal Sphere, were, as their names suggest, volumetric primitives. The designs answered simple requirements: isolate a controlled interior from an alien and hostile exterior, enclose a large volume within a comparatively small surface, and spin on one axis to create a centrifugal force in lieu of gravity. Instead of the profusion of chambers and capsules that make up the ISS (and its Soviet predecessor, Mir), O'Neill and his colleagues imagined the interior as one large habitable environment.

Bernal Sphere, 1975. [Rick Guidice/NASA Ames Research Center]

The Bernal Sphere designed at the Summer Study had a 900-meter radius and spin rate of one revolution per minute.[7] If you were inside this habitat, standing near the sphere's equator, you would feel a sensation similar to gravity on Earth. You would see the landscape curving upward as the habitat rotates and, directly overhead, the roofs of buildings on the other side of the sphere, just over a mile away. The people there would appear from your perspective to be standing upside down. Away from the equator, spin gravity would approach zero, and at the center axis of the sphere's rotation, you could fly.

The authors of the Summer Study report were concerned about how inhabitants would be affected by this novel spatial experience. In an appendix on "Psychological and Cultural Considerations," they discussed "The Solipsism Syndrome in Artificial Environments." To mitigate feelings of isolation, they recommended that habitats have "a large geometry, in which people can see far beyond the 'theater stage' of the vicinity to a view which is overwhelmingly visible." And yet they recognized that such a long view could heighten feelings of unreality, so they suggested there should be even more, out of sight: "It is important to have 'something beyond the horizon' which gives the feeling that the world is larger than what is seen."[8]

To help weigh these considerations, the report included a chart comparing the proportion of a habitat's interior surface that could be seen from a given vantage point. For the Bernal Sphere and O'Neill Cylinder, this value is 1; the whole habitat is visible at once. For the Stanford Torus, it is less than 1/3. In fact, the restricted sightlines of the Torus were among the factors that led the authors to recommend it as the preferred option for a first built project. The Torus was also smaller than the other designs, accommodating only 10,000 people, compared to 75,000 in the Bernal Sphere, and 820,000 in the O'Neill cylinder.

Stanford Torus, 1975. [Don Davis/NASA Ames Research Center]

O'Neill Cylinder, 1975. [Don Davis/NASA Ames Research Center]

Research on human adaptation to spin gravity had started in the 1950s, when Dr. Ashton Graybiel conducted a series of experiments in "Slow Rotating Rooms" at the Naval Aerospace Medical Institute. Graybiel's subjects lived in a 22-foot diameter spinning room for up to one month at a time. Most subjects lived and walked upright, parallel with the axis of the room's rotation, but in some experiments the subjects were asked to walk along the wall for a short time, using centrifugal force, so that their perception of "down" was rotated by 90 degrees. An illustration of this spinning laboratory was published in the proceedings of a conference O'Neill organized at Princeton in May 1975. It showed the human subjects oriented in different directions, like the tiny floating figures in Tsiolkovsky's spaceship. Graybiel found that a period of one rotation per minute was tolerable by almost everyone. That number determined the spin rate, and therefore the size, of the space habitats designed at the Summer Study.[9]

All three habitats defied Bucky Fuller's coordinates. On the surface of a planet like Earth, we can imagine "down" (or in) as a vector passing through our body toward the planet's center. Down starts at our feet. But in spin gravity, down is a vector pointing *away* from a shared center. Spinning around the center axis of an O'Neill Cylinder, Bernal Sphere, or Stanford Torus, we lose track of the comforting presence of Earth's (illusory) ground plane. The Torus designed at the Summer Study had an aluminum skin less than three centimeters thick.[10] If that boundary were breached, anything lost through the hole would fall "out" at a speed of about 200 meters per second, likely ending up in an independent — and possibly unrecoverable — orbit around the Earth. Just thinking about that could be enough to induce vertigo among the inhabitants. As Sun-Ra said, space is a bottomless pit.

Ashton Graybiel's rotating room studies, ca. 1960. [Ashton Graybiel]

O'Neill and his colleagues debated whether human minds and bodies could withstand these conditions. Would living in a rotating environment — even one with a spin rate so low that it didn't disturb Graybiel's subjects — create long-term stress on the inner ear? Would working in zero gravity, even for short periods of time, tax the body as it alternated between no weight and a normal weight? Would exposure to background radiation affect general health and immunity? Would isolation, or more specifically the knowledge of that isolation, create emotional stress? Would these incremental stresses add up, or even create exponential feedback loops, causing inhabitants to collapse, physically and psychologically?

The researchers spent so much time discussing these concerns that they hardly considered the potential benefits of living within the new geometries. Yet the appeal was expressed vividly in the Summer Study renderings, which is partly why these extraordinary images have endured.

Superpowers

In 2009, Jack Schulze of the British design studio BERG created two maps of lower Manhattan that show the landscape curving up and over the viewpoint, as if New York were inside an O'Neill Cylinder. The simultaneous visibility of near and far is exploited here for wayfinding, which the designers call a "superpower," or "the ability to be in a city and see through it."[11] A version of this superpower shows up in Christopher Nolan's 2010 film *Inception,* in which characters trained as architects manipulate the space of dreams by folding cities up and over themselves, making connections between distant points. Space is also curved in the title sequence of the fantasy television series *Game of Thrones*, which establishes the geography of the show's imaginary world. The directors had initially wanted the camera to fly above a 3D rendering of a stylized tabletop gameboard, but that didn't work: "You couldn't really tilt the camera up very far because it raised the question, 'What's beyond the map?'"[12] The designers solved the problem by modeling a clockwork world wrapped around the interior of a giant sphere, which was lit by a fiery astrolabe lamp. Since the horizon always curved up and away, questions about where this world was located could be avoided.

BERG, *Here and There: A Horizonless Projection in Manhattan,* 2009. [BERG]

These examples imagine the "Solipsism Syndrome" as a constructive force, holding together miniature worlds whose legible, curved surfaces hide the nature of a hostile, unknown space beyond. The environment is graspable, manipulable. It can even be created from scratch by the perceiving subject. The landscape is there for you, the observer, to use and explore. In contrast, the strange and dangerous environment of "outer" space is unknowable without technological mediation.

An earlier use of wraparound surfaces to normalize and tame difficult or overwhelming environments can be found in cyclorama paintings from the 18th and 19th centuries. The dramatic Atlanta Cyclorama (1886) depicted a Civil War battle wrapped around the interior of a giant cylinder, 45 feet tall and 114 feet across. Visitors entered from a hole in the center, and as the cylinder slowly rotated around them, the carnage and confusion of the battle was turned into narrative — originally with live accompaniment by veterans. Hundreds of cycloramas like this were produced before the invention of movie screens, offering an immersive experience of environmental mediation. Similarly, the large-scale sublime landscape paintings of the Hudson River School presented a notional American wilderness to the gallery visitor. Today's analogue to the cyclorama is the virtual reality headset, which renders a scene in a 360-degree bubble around the perceiver, like a personal virtual Bernal Sphere.

Gettysburg Cyclorama, designed by Richard Neutra, Gettysburg, Pennsylvania. [Library of Congress]

Hollow Earth

Architectural history provides further precedents for the Summer Study. In Étienne-Louis Boullée's unbuilt Cenotaph for Isaac Newton (1784), the architect drew a single spherical volume, which visitors entered from the bottom, on a center axis below a suspended sun lamp. The curved surface of the floor rose smoothly to form a dome 500 feet high. Daylight streamed into this chamber through thousands of small holes, so that it resembled a planetarium. In another unbuilt project, Boullée imagined the Royal Library (1785) as a cylindrical space, with book stacks rising in tiers like building terraces, completing the interior curvature. Ceiling coffers picked up this rhythm and carried it to an overhead skylight that divided the cylinder into thirds. The bookshelves' relationship to this opening suggested that, in the Age of Reason, knowledge and light had a kind of equivalence.

A curved geometry is essential to these projects; it made the entire collection of the Royal Library visible from any point within, just as in the Cenotaph it enabled the communal experience of a represented universe. And in exterior view, the simple primitive forms of Visionary Neoclassicism — cone, cylinder, sphere, and cube — established a clear boundary between the architectural object and the background space. Like the Summer Study artists, Boullée saw the object as an artifact, a human fabrication within a wilder state of nature.[13]

"Space is hard," scientists tell one another when things go wrong.[14] Lacking air, filled with radiation, ranging in temperature from absolute zero to burning hot in the unfiltered glare of the Sun, "outer" space cannot be experienced by humans without mediation. We need constructed bubbles of warmth and comfort. We can imagine the spacesuit itself as a kind of personal spaceship, or a super-room. Similarly, the contours of the Summer Study designs represented a literal closure, sealing off a habitatable environment from the vacuum of space. Within the space of a Bernal Sphere or Boullée's

Cenotaph, what is outside no longer matters. It's a void — an absolute, infinite void — but it may as well be a hard solid.

Étienne-Louis Boullée, Cenotaph for Isaac Newton, 1784.

Étienne-Louis Boullée, Royal Library, 1785.

Stories of a hollow Earth abound in folklore and fantasy. The idea that the seemingly stable ground beneath our feet conceals huge caverns and voids — that the world contains other worlds — is powerful because it challenges our presumption of stability. Yet there is at least one version of hollow Earth theory that claims *we* are the ones inside. In the late 19th century, Cyrus Teed founded a commune based on his belief in "Cellular Cosmogony," which held that "the alchemico-organic (physical) world or universe is a shell composed of seven metallic, five mineral, and five geologic strata, with an inner habitable surface of land and water. This inner surface, as the reader already understands, is concave."[15] Some versions of this concept swap the infinite void above for an infinite mass of ground below, which may have world-bubbles embedded in it, waiting to be explored with tunneling machines.[16]

On our planet, within our visual field and relative scale, we are easily convinced that the world is flat. This is the illusion that Bucky Fuller warned against in "Man":

> He uses the words *up* and *down*,
> Which refer exclusively to a planar concept of the world and Universe;
> For all the perpendiculars to an infinite plane
> Must be parallel to one another ...[17]

On Earth, as on the International Space Station, the collective misperception of a flat plane helps build community and culture. We are all equal in our geometric relationship to one another. The reality, of course, is that we do not stand parallel. Each of our bodies corresponds with a distinct radial vector on the surface of a sphere, pointing away from a common center that we can never perceive or occupy. Our vectors diverge by imperceptible angles.

In "inside-out" worlds like the Bernal Sphere and the concave Earth, the situation is reversed. Our feet all point outward, into an inaccessible, but technologically habitable void, while our heads point inward, some of us apparently "upside-down." Standing, we rise toward a visible center, which can be reached simply by climbing a hill, strapping on wings, and jumping into the air, as low-tech as Icarus.

Hedwig Michel, president of the Koreshan Unity commune founded by Cyrus Teed, ca. 1961. [State Archives of Florida]

Inverse Perspective

On the convex Earth, the horizon is an unreachable asymptote; it recedes as we approach. But in practice it's the gateway to the rest of the world, through circumnavigation. "Traveling around the world" has become a cliché metaphor for personal change and development because of the immense effort the journey requires. Famously, Ferdinand Magellan, the first person known to have organized a trip around the world, did not survive the voyage, which astronauts orbiting on the ISS complete 15.5 times a day.

In the smaller concave worlds designed by O'Neill and his colleagues, circumnavigation is easy and convenient. In a Bernal Sphere, a walk along any straight path will return you to your starting point in under an hour. Decades before the Summer Study, science fiction writer Jack Williamson had incorporated those physics in his City of Space:

> It seemed very strange to Bill, to see these endless streets about the inside of a tube, so that one by walking a little over three miles in one direction would arrive again at the starting point, in the same way that one gets back to the starting point after going around the earth in one direction. ... As they stepped out, it gave Bill a curious dizzy feeling to look up and see busy streets, inverted, a mile above his head. The road before them curved smoothly up on either hand, bordered with beautiful trees, until its ends met again above his head.[18]

Visual futurist Syd Mead, whose design credits include *Blade Runner, Tron*, *Aliens*, and *Elysium*, called this the "inverse perspective," where "the ground plane goes up out of sight, up into the ceiling."[19] In Mead's interior view of a Stanford Torus, painted for *National Geographic* in 1980, space is continually warped. Lines on parallel planes converge not to a single vanishing point, but rather to a series of points on a vanishing line, which forms a kind of vertical horizon.

Syd Mead's Stanford Torus for *National Geographic*, 1980. [Syd Mead]

Rick Guidice's Stanford Torus for the Summer Study, 1975. [NASA Ames Research Center]

When Rick Guidice illustrated the Stanford Torus and Bernal Sphere, he rotated the painting surface while executing close details, so that small patches of local space roughly conform to conventional perception, even as the overall picture is defamiliarized. Space curves at the large scale, but each individual line is straight and ruled. In Mead's interior, by contrast, local elements follow the same subtle, flowing curve that animates the whole. (For example, look at the floating slab building with strip windows on the left side of the composition.) Guidice's view suggests that a person living in a Torus could interact with architectural components that remain individually unaffected and therefore familiar, while Mead imagines that even the smallest structures would bend to conform with the space's overall geometry. We know from experiments like Graybiel's that human vision does not always match bodily forms of perception. In a proper Torus, an inhabitant occupying any large flat element locally perpendicular to the spin axis would feel like each end was pointing slightly "downhill." Perceptual modes would decouple as the observer moved along the object, further from the center.

It's almost impossible to imagine living in such radical spatial conditions. It's hard enough to conceive the zero-dimensional vanishing point becoming a one-dimensional vanishing line, and the apparently flat, two-dimensional plane surface of everyday experience folding up to enclose a three-dimensional volume of space. But then we must further imagine that this volume is itself in motion, rotating about an axis and spinning in orbits, in four-dimensional time. This is the "vertigo of space and time," as artist Ralo Mayer put it.[20] From inside the orbital habitat, this motion is not perceived directly, but implied — and simultaneously denied — by the warping ground plane. Every aspect of the environment turns and folds the sightlines and spaces back in on themselves. Living here might be like living in a small valley, where the views all turn upward and hostile conditions block all paths to the next habitable space. Yet if we could make ourselves aware of this constant motion, we would understand that we are "on" a vessel instead of "in" a static place. One recent book project calls polemically for living in "ships not shelters."[21]

Construction of a Bernal Sphere, 1975. [Don Davis/NASA Ames Research Center]

Shells and Membranes

At the Princeton conference organized by O'Neill shortly before the Summer Study, Ludwig Glaeser, a curator for the Museum of Modern Art, delivered a paper on "Architectural Studies for a Space Habitat." Glaeser's approach was to treat the shell or boundary of the habitat as a given, and to assume likewise that the human needs of inhabitants would not change. The role of architectural design was to mediate between the two. He identified the small scale, peculiar curvature, and artificial nature of the habitat as problematic aspects that design could address. As noted by Felicity Scott in an article for *Grey Room*, Glaeser resisted the urge to think about the design of these structures as a visual exercise. "Tempting as it might have been to the architects in our group," he said, his presentation would not feature "fabulous interiors of space habitats," as that "would be premature and even misleading." For Glaeser (and for Scott) the problem of space habitats was first a problem of systems design. Glaeser also notably declined to sketch a "program for design," preferring instead to ask for "a catalog of questions."[22]

Some of the questions we might ask of the Bernal Sphere were articulated by its namesake, the British polymath and communist John Desmond Bernal, whose speculative 1929 pamphlet *The World, the Flesh, and the Devil, an Enquiry into the Three Enemies of the Rational Soul* influenced generations of space scientists and sci-fi authors. Bernal foresaw a medium-term future in which abundant energy and resources would pose new opportunities and challenges for humankind.[23] He imagined an expanding, curious, resource-hungry population building spherical space settlements.

Bernal's original spheres were much larger than what O'Neill proposed, many miles in diameter. They orbited the Earth or Sun but did not spin and thus had no gravity. And instead of treating the hard shell as an absolute enclosure, Bernal conceived the boundary area as a series of layers, each with different functions, some protective, others assimilative. His sphere lacked the absolute hermeticism that the psychologists and designers who participated in the Summer Study feared and hoped for.[24] The outermost layer was hardly even material; it was an energetic system that could detect and deflect incoming matter with "jets of high speed gas or electrons" and maybe even break this mass into component elements that could be used for construction and expansion.[25] The next layer in was a transparent shield that would keep out solid matter but allow sunlight and radiation to pass to a third layer, where food was grown. The fourth layer circulated matter and energy, and the fifth was for material storage, raw elements hardened into stock. Bernal envisioned that these layers would be made from the direct production of high performance designer matter, after a future breakthrough in materials science. Inside all those layers of biomimesis was the machinery that would regulate and produce human life. And inside that was the habitat itself, which could be an open public space accessible by humans with attached wings, or else partitioned off for privacy by reconfigurable smaller bubbles.

Perhaps no one has thought about spheres more deeply than the philosopher Peter Sloterdijk, who has written an erudite trilogy on *Bubbles*, *Globes*, and *Foams*. For Sloterdijk, spheres describe possible identities and possible worlds. The production of a sphere always involves the process of making some previously unseen background condition explicit, and the sphere in turn produces human life, both biologically and socially.[26] Sloterdijk considers structures like the ISS to be a particular kind of world in miniature, which, like a greenhouse or an island, must contain small versions of all the different spheres that humans require. As Bernal wrote, "the globe takes the place of the whole earth and not any part of it." Yet Bernal also anticipated the benefits of the type of arrangement that Sloterdijk calls foamy space, where the sphere is embedded in a system of "spatial colonies":

> Yet the globe would be by no means isolated. It would be in continuous communication by wireless with other globes and with the earth, and this communication would include the transmission of every sort of sense message which we have at present acquired as well as those which we may require in the future. Interplanetary vessels would insure the transport of men and materials, and see to it that the colonies were not isolated units.[27]

This is a paradox. The Summer Study habitats required isolation, and this isolation was figured in the form of a flat curve rotated in space around a center axis, enclosing the interior in an aluminum or titanium shell. And yet this formal isolation — along with other design elements that reinforced a common center — could create feelings of alienation, or solipsism, within an individual human or a human culture. Glaeser's understanding of a hard shell as a "given" within which humanity must be mediated and nurtured by architectural intervention is undermined by Bernal's conception of the possibilities opened up by altering human existence itself. Bernal's shell was not an enclosure but a permeable membrane involved in processes of mitigation, mediation, nourishment, and interaction with other shells.

Bernal Sphere, 1975. [Rick Guidice/NASA Ames Research Center]

"So you're the guy who's painting all of those red skies! Space is black!" Asteroid Miner, 1977. [Chesley Bonestell]

Red Skies

Around the same time that Guidice was working on the Summer Study paintings, he made a pilgrimage to visit the legendary space artist — and former architect — Chesley Bonestell. Known for strict scientific accuracy in his work, Bonestell had, in 1944, painted a view of Saturn from the moon Titan, showing a precise perspective reconstruction of the ringed planet's size, position, and inclination. Three decades later, Guidice was commissioned by NASA to illustrate the Pioneer 11 mission, tracking the space probe that produced the first close-up pictures of Saturn's system. He was known to add swirling red, purple, and orange nebulae in the backgrounds of his space paintings, among the splattered star fields. Guidice brought one of these pieces to show Bonestell, who chastised him: "So you're the guy who's painting all of those red skies! Space is black!"[28]

How we visualize "outer" space, and how we choose to talk about it, can influence how we think about environmental conditions on and off our home planet. Do we imagine space as a hard, uninhabitable solid? Or as a softer medium, a potential source of energy and matter, perhaps even an environment that is home to friends and neighbors? The membrane layers of Bernal's original spheres mediated and translated the purple, orange, red, and infrared medium of space into frequencies and resources legible to humans. Bernal imagined "spatial colonies," networks of spheres, connected by radio waves, transportation, and the transmission of sensory data not even invented yet. And those spherical interiors were wholly accessible and reconfigurable by occupants. His concept resists isolation and solipsism and retains the sense that play and manipulation are possible within a pocket world. If we know that there are friends and resources outside the sphere, and that we can do pretty much whatever we want inside the sphere, then we might feel better about living in a bubble far from our home planet. It's all just part of the foam. In this way, Bernal's spheres satisfy Glaeser's call for a systems approach, rather than a static image of the space habitat.

Too often, we take for granted the apparently solid, stable, planar ground of our home planet. We also take for granted that its spatial metaphors will translate to other states, forms, and spaces. On or near the surface of the Earth, we enjoy a correspondence between our spatial precepts and concepts. The nature of "outer" space questions those assumptions, and breaks apart those alliances. So do the strange geometries and spatial conditions of O'Neill's Cylinders, Spheres, and Toruses. If Bucky Fuller is right, that the spatial schema we use on Earth is inherently limited and limiting, then the conception of new "outer" spaces is vital. The split Fuller identified in his riff on *instairs* and *outstairs* is one of many fractures opened during the process of thinking about and designing spaces for humans off of Earth. Glaeser's position, which takes for granted the hard shell and the static nature of humans, might conceal still more splits yet to be explored. New images of space are necessary, but so are new systems, open-ended, within and without.

EDITORS' NOTE

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AUTHORS' NOTE

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NOTES

1. Quoted in Stewart Brand, ed., *Space Colonies: A Coevolution Book* (Sausalito: Whole Earth Catalog, 1977), 5. ↩
2. *Space Is the Place* (Plexifilm, 1974), directed by John Coney, script by Sun Ra with Joshua Smith. ↩
3. R. Buckminster Fuller, *Intuition* (New York: Doubleday, 1972), 103–04. ↩
4. George M. Young, *The Russian Cosmists: The Esoteric Futurism of Nikolai Fedorov and His Followers* (Oxford: Oxford University Press, 2012), 50. ↩
5. See Sandra Hauplik-Meusburger, *Architecture for Astronauts: An Activity-Based Approach* (Wien: Springer, 2011), 280. Hauplik-Meusburger notes, further, that the standardized

orientation of ISS modules and systems makes it easier to train astronauts on Earth, using mockups subject to gravity. ↩

6. Stewart Brand, interview with Gerard O'Neill, "Is the Surface of a Planet Really the Right Place for an Expanding Technological Civilization?," in *Space Colonies*, op. cit., 22. ↩
7. In a 1974 article for *Physics Today*, O'Neill had imagined a smaller sphere, but the physiology experts at the 1975 Summer Study argued that it would spin too fast, causing some people to get sick, so the dimensions were revised upward in the official report. ↩
8. NASA, *Space Settlements: A Design Study*, Richard D. Johnson and Charles Holbrow, eds., (Washington, DC: Scientific and Technical Information Office, National Aeronautics and Space Administration, 1977), 29. ↩
9. Jerry Grey, ed., *Space Manufacturing Facilities* (New York: American Institute of Aeronautics and Astronautics, 1977), 137–49. ↩
10. NASA, *Space Settlements: A Design Study*, 111–12. ↩
11. BERG London, "Here and There: A Horizonless Projection in Manhattan," 2009. ↩
12. Ian Albinson, interview with Angus Wall, "Game of Thrones," *Art of the Title*, May 11, 2011. ↩
13. For more on Boullee's Cenotaph, see Colin Rowe, "The Architecture of Utopia," *Granta* (1959), republished in *The Mathematics of the Ideal Villa and Other Essays* (Cambridge: MIT Press, 1995), 210. ↩
14. See, for example, Loren Grush, "Stop Saying 'Space Is Hard,'" *The Verge*, June 29, 2015. ↩
15. Koresh, *The Cellular Cosmogony: Earth Is a Concave Sphere, with Proof* (Central, Hong Kong: Forgotten Books, 2007). ↩
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