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THE ARCHITECTURE OF ARTIFICIAL GRAVITY: THEORY, FORM, AND FUNCTION IN THE HIGH FRONTIER

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Abstract

Previous papers have examined the physical differences between natural and artificial gravity, through mathematical derivation and computer simulation. Taking those differences as given, this paper examines: the role of gravity in architectural design; the extensions of architectural theory necessary to accommodate the peculiarities of artificial gravity; and the appropriateness of space colony architecture as illustrated in the "Stanford Torus", "Bernal Sphere", and similar proposals. In terrestrial gravity, there are three principal directions – up, down, and horizontal – and three basic architectural elements – ceiling, floor, and wall. In artificial gravity, due to inertial effects of relative motion in a rotating environment, east and west (prograde and retrograde) emerge as gravitationally distinct. Thus, there are not only three, but at least five principal directions: up, down, east, west, and axial. The grammar of architecture for artificial gravity should accommodate this fact. To be meaningful, architecture should have formal properties that are similar to other aspects of the environment. The goal is not to fool people into thinking they're still on Earth, but rather, to help them orient themselves to the realities of their rotating environment.

Introduction

Much of architecture, from the posts and beams of the Parthenon to the Pontiac Silverdome, can be seen as a struggle against gravity. Without gravity, such basic concepts as "floor", "wall", and "ceiling" lose much of their meaning. It seems reasonable to expect that the state of gravity in an environment should have a significant influence on its architecture.

The visionary work on artificial-gravity space station and space colony design has made allowances for such things as high population density, lightweight modular construction from non-organic materials, artificial weather and climate control, and even (minimally) the novelty of a concave toroidal landscape. But the unusual nature of the gravity itself does not seem to have had much influence. The assumption seems to have been that the differences between natural and artificial gravity could be ignored. The differences do become insignificant as the radius of rotation approaches infinity, but the first artificial-gravity habitats are likely to be significantly smaller than that. Furthermore, there is a philosophical issue: whether the architecture should deny the environmental oddities, or whether it should respond to them – perhaps even accentuate them.

Previous papers have examined the physical differences between natural and artificial gravity, with a heavy reliance on mathematical derivation, computer simulation, and reference to utilitarian engineering concerns.[1–2] Taking those differences as given, this paper examines:

- the role of gravity in architectural design, particularly with regard to "principal directions";
- the extensions of architectural theory necessary to create meaningful environments in artificial

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gravity;

- the appropriateness of space colony architecture as depicted in proposals such as the "Stanford Torus" and "Bernal Sphere".

The next two sections introduce relevant aspects of architectural design theory. Potential applications to artificial gravity are discussed in the final section. This paper is extracted from the final chapter of my doctoral dissertation (Arch.D., University of Michigan, May 1994).[3]

Meaning

The role of *meaning* is central to architectural theory. An important function of the built environment – beyond quantitative utilitarian concerns – is to make habitable space comprehensible. As Scully writes:[4]

> Human beings fashion an environment for themselves, a space to live in, suggested by their patterns of life and constructed around whatever symbols of reality seem important to them. Most of all, that environment and those structures invest the vast indifference of nature with meanings intelligible to, indeed imagined by, mankind.

Before we can design meaningful environments, we must understand how meanings operate. Hesselgren[5] describes three types of meaning, and three ways in which a meaning may arise from a perception. The types of meaning are:

- signal: that which triggers an action on the part of the perceiver, such as an alarm or a traffic sign. A signal tells us to do something.
- symbol: that which stands in place of something else, such as the graphic tokens used in schematic engineering drawings. A symbol represents something.
- expression – that which arises from the innate state or nature of something, such as a facial aspect. An expression reveals something about the expresser.

To use a linguistic metaphor, these meanings might be categorized as verbs, nouns, and modifiers. The links from perception to meaning are:

- convention – agreement. A red octagonal traffic sign means "stop".
- association – experience and learning. Low, dark clouds mean that rain is likely.
- spontaneity – natural reaction. A smile means happiness.

The distinction between associative and spontaneous meanings is open to discussion. In Hesselgren's scheme, associative meanings must be learned and may be local to a group or culture, while spontaneous meanings are "natural" and universal. But while certain expressions – smiles, frowns, laughter, weeping – may be universal and biologically "wired", it may be that infants must nevertheless learn their meaning. More to our purposes, gravity-related cues to meaning that seem natural and universal on Earth may turn out to be cultural and not applicable to micro-gravity or artificial-gravity environments.

Hesselgren devotes much attention to perception psychology, including tactile, haptic, kinesthetic, auditive, and olfactory perceptions, as well as visual. He describes "transformation tendencies" between these sense modalities. For example, a perception of visual texture gives rise to a mental image or expectation of tactile grain. Unmet expectations may lead to disappointment and negative aesthetic evaluations. The ubiquitous fake wood grain may be regarded as aesthetically inferior to real wood, because it fails to live up to its visual "promise" to feel and sound like wood (especially when applied to plastic or metal).

For a perception to carry a meaning, it must be recognizable. Hesselgren[5–6] and Prak[7] stress the importance of gestalts, both in composing the environment and in reading it. A gestalt is a structure, configuration, or pattern of phenomena that constitutes a semantic unit with a meaning that is not derivable from its parts. For example, a square is immediately recognizable as such; its perceived "squareness" does not depend on a rational analysis of discreet edges and angles. In fact, such an analysis often serves to contradict an initial perception: what was thought to be a square may upon closer examination turn out to be a rectangle or rhombus; its corners may be rounded, crossed, or unclosed. Within some small tolerance, a non-square stimulus may give rise to the perception of a "square" gestalt. Forms that are perceived to deviate just slightly from a suggested gestalt – for example, just slightly off-square – are often regarded as imperfect, erroneous, or ugly.

The gestalts are the "words" of the vocabulary of perceptions, from which higher-level meanings – sentences, paragraphs, and stories – are composed. The flood of perceptions that we receive from the local environment create what Norberg-Schulz calls the *genius loci* – the spirit of place: [8]

> Man dwells when he can orient himself within and identify himself with an environment, or, in short, when he experiences the environment as meaningful. Dwelling therefore implies something more than "shelter". It implies that the spaces where life occurs are *places*, in the true sense of the word ... Architecture means to visualize the *genius loci*, and the task of the architect is to create meaningful places, whereby he helps man to dwell.

This may explain the continuing public fascination with the torus as a space station form, even when its relationship to rotation and artificial gravity is satirized, misunderstood, or ignored. This is evident in posters produced by the International Space University and the Shimizu Institute, as well as sets for movies and television shows such as *Star Trek*. The torus is a simple form that is perceived whole, even if its rationale is not. In contrast, real space stations such as Mir and Freedom are complex assemblies of forms with configurations that appear arbitrary and meaningless to the untrained eye. To paraphrase Meyers: People "know" what a space station looks like – and it's not "Freedom". [9]

Principal Directions

An important organizing theme in architectural theory is the notion of principal directions, which imbue space with an inherent structure. The identification of these directions is powerfully influenced by gravity, which has – till now – been taken as a universal constant in architectural design.

Six directions on three axes are innately perceptible: up-down (height), left-right (breadth), and front-back (depth). In terrestrial architecture, the up-down axis is normally tied to the force of gravity – the plumb line; the other axes are free to rotate around it. The up-down axis is called "vertical", while all possible left-right and front-back axes are called "horizontal". The anisotropic character of this space is judged by the effort required to move in any given direction: up and down are distinct irreversible poles; left, right, front, and back are interchangeable simply by turning around. Thus, gravitationally, there are three principal directions – up, down, and horizontal – and three basic architectural elements – ceiling (or roof), floor, and wall. The walls, which bound the horizontal dimensions, are not inherently distinct. North, south, east, and west walls are all "walls"; none of them is a "floor" or "ceiling", nor are "floor" and "ceiling" interchangeable.

Distinctions between walls arise from higher-level analytical considerations that are not operative at the deepest levels of meaning. This is reflected in language: there is no simple linguistic term for the concept of "east wall" or "west wall". The cardinal directions acquired their distinct characters through observations of celestial phenomena, reflected in the etymology of "east", "west", "south", and "north" – respectively: "dawn", "evening", "sun", and "lower". [10] Those distinctions are not inherent in architecture. A building may isolate its occupants from all celestial cues to cardinal orientation, but it cannot isolate them from gravity.

Studies indicate that familiarity with gravity is not innate, but is learned in infancy. At 4 months, infants begin to realize that a rolling ball cannot pass through an obstacle, but are not yet aware that an unsupported ball will fall. At 5 months, they discriminate between upward and downward motion. At 7 months, they show sensitivity to gravity and the "appropriate" acceleration of a ball rolling upward or downward. By adulthood, falling objects are judged to move naturally only if they accelerate downward on a parabolic path. These judgments are based not on mathematical reasoning, but on visual experience; when asked to reason abstractly about such motion, many adults are prone to error. [11–13]

Misalignment with the vertical axis is psychologically disturbing in a way that horizontal misalignment is not. The perception of a picture hung awry on a wall produces an urge to straighten it. And, according to Thiis-Evensen, visitors at the Leaning Tower of Pisa "very seldom pause immediately beneath the leaning side. They feel safe only when at a certain distance and preferably on the opposite side of the tilt." [14] Again, this is reflected in the language: there is no horizontal equivalent of "lean" or "tilt".

These common-sense ideas, rooted in the experience of terrestrial gravity, permeate architectural theory. Thiis-Evensen builds his entire grammar around the three elements of floor, wall, and roof. [14] Architectural design for a gravitational environment distinctly different from Earth's requires a fundamental reexamination of design principles which until now have been taken for granted.

In a normal gravity environment, with the head up and the feet down, there are four principal body orientations. In micro gravity, without a strong up-down reference, there are twenty-four – four rotations for each of six orientations of the body axis. It is no wonder that such an environment can be disorienting. Again, it is misalignment or realignment of the perceived vertical axis (as compared to the horizontal axes) that is most disorienting. Skylab astronaut Ed Gibson reported that "being upside down in the wardroom made it look like a different room than what we were used to." [15] The wardroom furnishings provided a reference for that volume that was lacking in the larger workshop volume. In the wardroom, as a matter of etiquette when taking one's place at the dinner table, one did not float over the table, but instead squeezed past one's crew mates in an Earth-like fashion. Nevertheless, when looking out the window, the internal reference was abandoned in favor of an Earth-down reference, even if this meant floating sideways or upside down relative to the furnishings. [16]

As was mentioned above, the large workshop volume in Skylab did not provide any particular vertical reference. According to Oberg and Oberg, "the Skylab astronauts would sometimes become a little disoriented in it and preferred the lower [sic] decks with their smaller but more familiar spaces." [16] Even though micro-gravitational space may be amorphous and isotropic, the human body is not. It's difficult to collaborate with your crew mate when you're looking at his ankles and his task light is shining in your eyes. Modern space station modules, such as Spacelab and Freedom, are designed with a strong standard vertical reference – arbitrary perhaps, but beneficial.

On Earth, the normal stimulus to the perception of vertical is the plumb line. But even here there are exceptions. Hesselgren describes the case of a large concert hall in Gothenburg. By design, the walls are not plumb, but lean slightly. Apparently, there is a tendency in the occupants to misread this leaning as vertical perspective. Consequently, when light fixtures were installed to hang freely, they were perceived to be leaning the other way. This disturbing illusion was overcome by arranging the fixtures to hang parallel to the walls. [5] Once again, this shows that perception is not deducible from stimulus.

The Architecture of Artificial Gravity

In the twenty-one years since the Skylab workshop, micro-gravitational environmental design has progressed from an almost anti-terrestrial disregard for Earth-normalcy to a realization that some Earth norms can serve a useful coordinating function. We now see designs for Spacelab and Freedom that provide distinct "Earthy" floor, wall, and ceiling references and consistent cues for vertical orientation, without denying either the possibility of ceiling-mounted utilities or the necessity of foot restraints.

Exactly the opposite sort of progression is needed in artificial-gravity design. Virtually all concepts published to date have implied complete Earth-normalcy with regard to perceived gravity, stability, and orientation. A more appropriate approach calls for preserving those Earthly elements that serve a positive function while incorporating modifications that account for the peculiarities of rotating environments. This may require a reappraisal not only of artificial-gravity engineering studies, but also of architectural theory itself. According to Norberg-Schulz: [8]

> To be meaningful ... the inventions of man must have formal properties which are structurally similar to other aspects of reality, and ultimately to natural structures ... Natural and man-made space are structurally similar as regards directions and boundaries. In both, the distinction between up and down is valid, as well as the concepts of extension and closure. The boundaries of both kinds of space are moreover to be defined in terms of "floor", "wall", and "ceiling".

On the one hand, he testifies to the importance of reality and nature (whatever they may mean) in architectural expression. On the other hand, his characterization of the directions and boundaries of natural and man-made space must be reevaluated – if not refuted – in extraterrestrial environments.

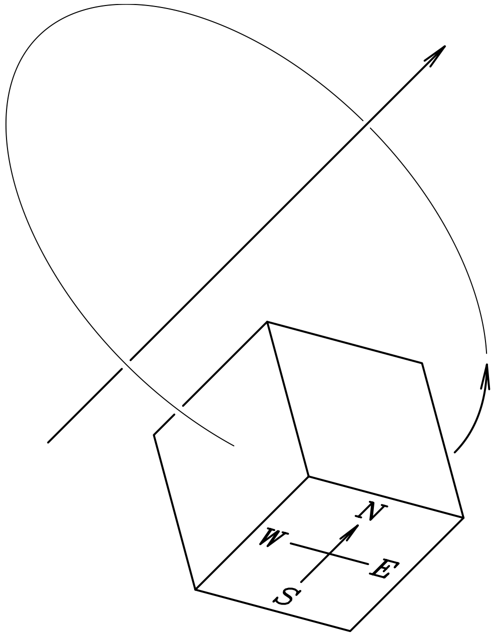
With regard to free-fall and relative motion, artificial gravity can be made Earth-normal within any finite tolerance, provided that the radius of rotation is sufficiently large. [1,3] However, to make the abnormalities imperceptible, "sufficiently large" may be ten kilometers or more. The alternative – more interesting theoretically, and the real focus of this research – is to adapt the architecture to the gravitational abnormalities associated with rotation at smaller radii.

In such an environment, falling objects follow involute trajectories and dropped objects deflect noticeably to the west, as if blown by a sort of "gravitational wind." East and west are gravitationally distinct in a manner akin to up and down. Therefore, there are not only three, but at least five principle directions: up, down, east, west, and axial. The smaller the radius, the stronger the distinction between east and west. It is as inescapable as the distinction between up and down, and cannot be masked by architecture. Perhaps it follows that "eastwall" and "westwall" must be introduced as new elements in the grammar of architecture.

As a secondary effect, axial is decomposable into north and south through derivation from east, west, left, and right. But, if inside and outside observers are to agree on the location of the north pole and south pole – important for rendezvous and docking maneuvers – then the handedness of north-south relative to east-west is reversed in artificial gravity. In that inside-out, concave landscape, north is to the right of east, and south is to the left, as shown in figure 1. While terminology may have a negligible effect on engineering, it is intricately tied to orientation, and this represents yet another adaptation required of people immigrating from a convex planetary surface.

North and south may also be distinguishable through cross-coupled rotations. If a torque is applied to an object about the up-down axis while the environment spins about the north-south axis, there is a cross-coupling effect about the east-west axis. In other words, turning to the left or right will cause a tendency to tip toward the north or south (about the east-west axis). The magnitude and direction of this effect depend on the object's particular inertia components, so it is a less consistent reference than the free-fall involute curve. Nevertheless, it should be consistent for rotations of the head – the most important object for gravitational orientation.

Unlike up and down, which are continuously distinct, east and west are intermittently distinct – only during relative motion within the rotating environment, in proportion to the relative velocity. While a person is stationary, he may forget that there is such a distinction – only to be rudely reminded of it when he rises out of his chair or turns to his side. Anything that keeps a person "passively" oriented relative to east and west would allow him to prepare himself for the consequences of his actions, aiding his coordination and adaptation to the rotating environment.



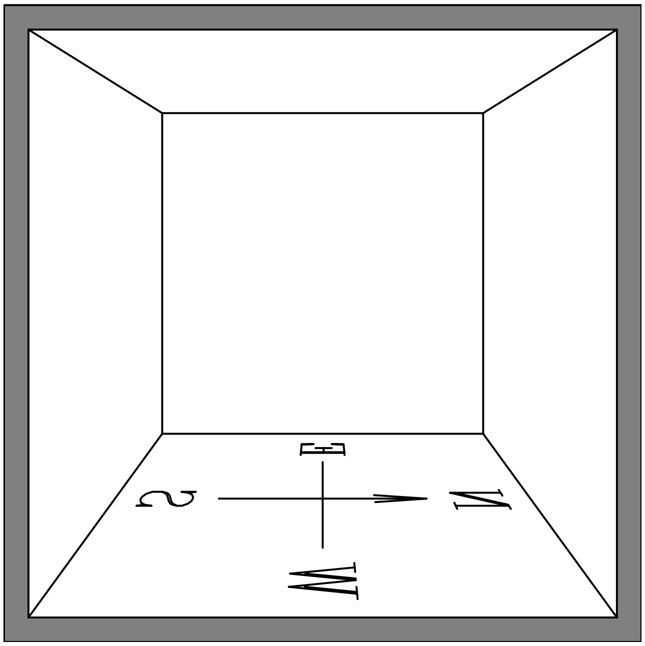


Figure 1: Cardinal directions in artificial gravity.

Hesselgren discusses the "transformation tendency", in which a perception in one modality may produce a mental image of a perception in another. One modality that he never discusses – that is taken for granted on Earth but cannot be in space – is vestibular perception. It may be possible, through experience in a properly designed environment, to acquire a transformation tendency to vestibular perception from visual, acoustic, haptic, or other perceptions. Not that we wish to induce motion sickness by the mere sight of some visual cue. Rather, we wish to provide visual or other reminders that motion relative to these cues will result in certain inescapable side effects, inherent in the artificial gravity. By doing so, we may be able to aid the inhabitants' orientation and adaptation to their rotating environment. Keeping with Hesselgren's system of meanings, these perceptual cues would act primarily as signals, triggering adaptive coordination in the inhabitants. From the designer's point of view, a consistent "vocabulary" of such signals would have to arise from convention. From the inhabitants' point of view, these conventions might to some extent be taught, but the unconscious transformation to a vestibular image would rely on association based on direct experience.

In designing signals, it is usually best to incorporate multiple perceptions. For example: stop signs are both red and octagonal; no other traffic sign posses either attribute. We may speculate on the use of color and form in artificial gravity to distinguish eastwall from westwall. Just as ceilings are usually lighter than floors in color, we may propose that eastwalls should be tinted with receding colors and westwalls with advancing colors. Hesselgren[5] and Thiis-Evensen[14] both note the receding character of cool colors tending toward blue and the advancing character of warm colors tending toward yellow. The forms of the eastwall and westwall may incorporate literal casts of the involute curve, or other symbolic shapes such as triangles for advancing (westwall) and circles for receding (eastwall). These forms may be merely chromatic, or they may be cast in bas-relief – convex for advancing and concave for receding.

Classical architecture is the premier example of a system of design rules for the proportion and placement of forms. Over the centuries, it has evolved a rich vocabulary – linguistic as well as formal – of pedestal, base, shaft, capital, architrave, frieze, cornice, triglyph, metope, fascia, and so on.[17] The classical orders specify the proportion and placement of these forms in minute detail with mathematical precision, reflecting the order in the Renaissance conception of the universe. One can imagine the invention and evolution of a new set of design rules for artificial gravity, involving, for example, pilasters with involute profile, and friezes composed from advancing and receding colors and bas-relief shapes.

I offer this Classical analogy merely as an example, certainly not as a specific recommendation or conclusion. Prak[7] is careful to distinguish between formal and symbolic aesthetics: the former deals with general rules of rhythm, proportion, balance, and consistency; the latter with heuristic aspects of style. What is important is that general rules of composition can be developed and applied to the architecture of artificial gravity – to impart, as Norberg-Schulz suggests, formal properties which are structurally similar to other aspects of the environment. The specific style in which this is done will evolve as a function of mission, population, and time.

Figure 2 is a sequence of computer images that represent simple experiments with architectural forms in artificial gravity. Starting with an unadorned room and the elements of floor, wall, and ceiling, forms are added or modified to express the rotation of the room in space and the consequent distinction between east and west. The involute curves on the back wall trace the path of a ball dropped from ceiling height, assuming a floor radius of 250 meters – the approximate proposed radius of the Bernal Sphere. The frieze (just below the ceiling) is punctuated with recessed blue circles on the eastwall and raised yellow triangles on the westwall. The scene through the window would appear to rotate clockwise at about 1.9 RPM.

The formal approach suggested here is relevant only to the extent that it is adaptive to function in a rotating environment. Forms of one sort or another are unavoidable, whether they result from apathetic adherence to Earth norms or proactive design for a new environment. However, formalism for its own sake – the triumph of style over substance – serves no purpose; to the extent that it interferes with adaptation, it may even be detrimental.

Apart from the gravitational peculiarities, the very geometry of artificial-gravity environments precludes Earth-normal design. This is especially true of the large space colony concepts that make the strongest claims for Earth-normalcy – such as the Stanford Torus, the Bernal Sphere, and O'Neill's "islands". Artists' renditions of these environments are often taken from points of view that minimize or obscure the concave upward curvature of the landscape – for example, "aerial" perspectives looking north or south, parallel to the axis of rotation. In these, the viewer is disconnected from the ground, the path ahead is flat and straight, and the curvature is relegated to peripheral vision – somebody

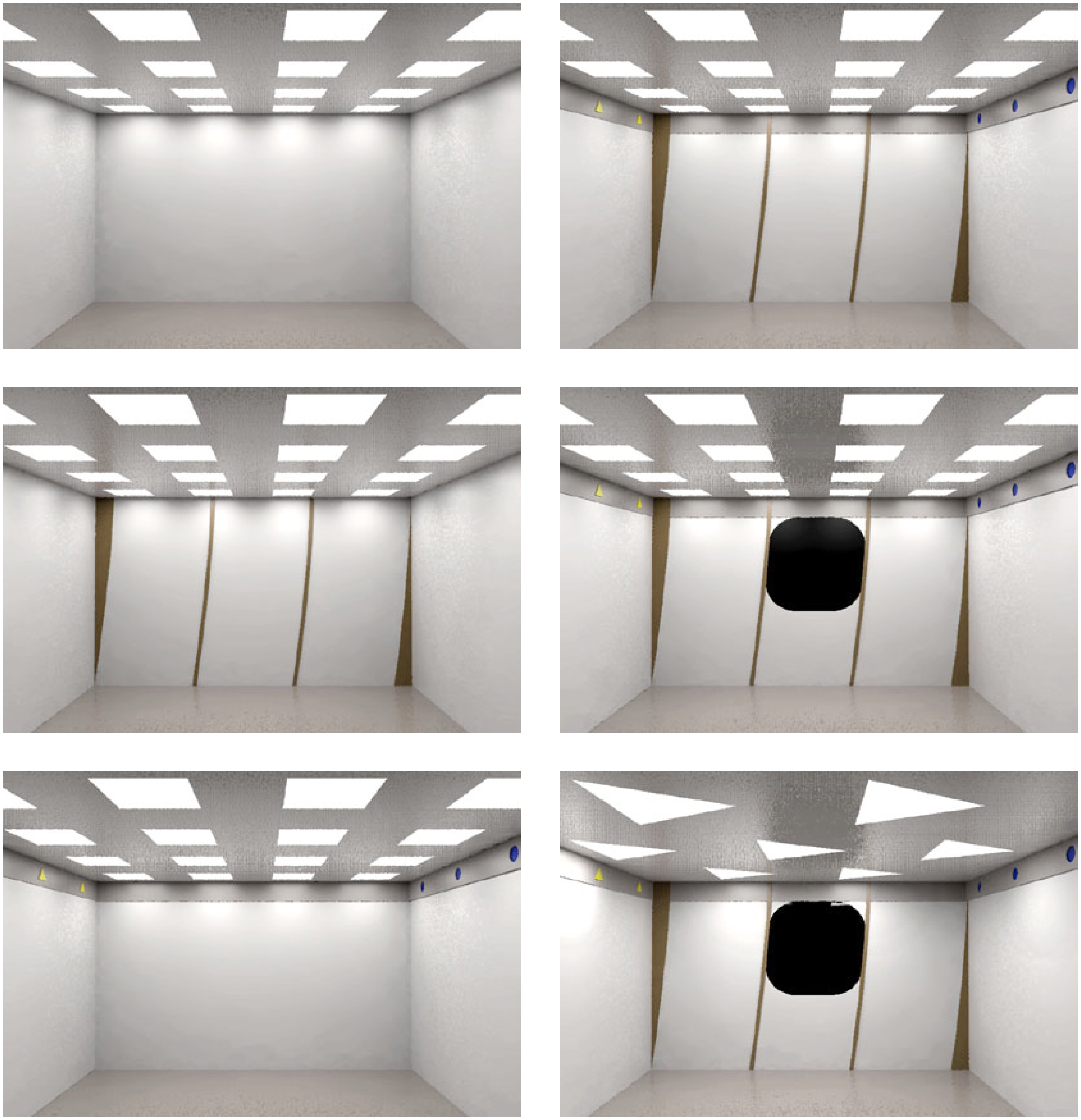


Figure 2: Experiments in the formal expression of east and west in an artificial-gravity environment.

else's problem. Ground-level views looking east or west, in which the curvature confronts the viewer head-on, are rare. Many of those that have been attempted are obviously flawed. For example, several views of the Stanford Torus depict sight lines much longer and flatter than the radius of the torus would allow. At a radius of 895 meters, a 1-kilometer arc would subtend an angle of 64 degrees; yet several views seem to show kilometer vistas with little or no curvature.[18]

A geometrically correct rendition of such a landscape is difficult to construct without the aid of a computer, simply because nothing like it has ever been seen. As an experiment in visualization, I developed a computer program for bending objects in a

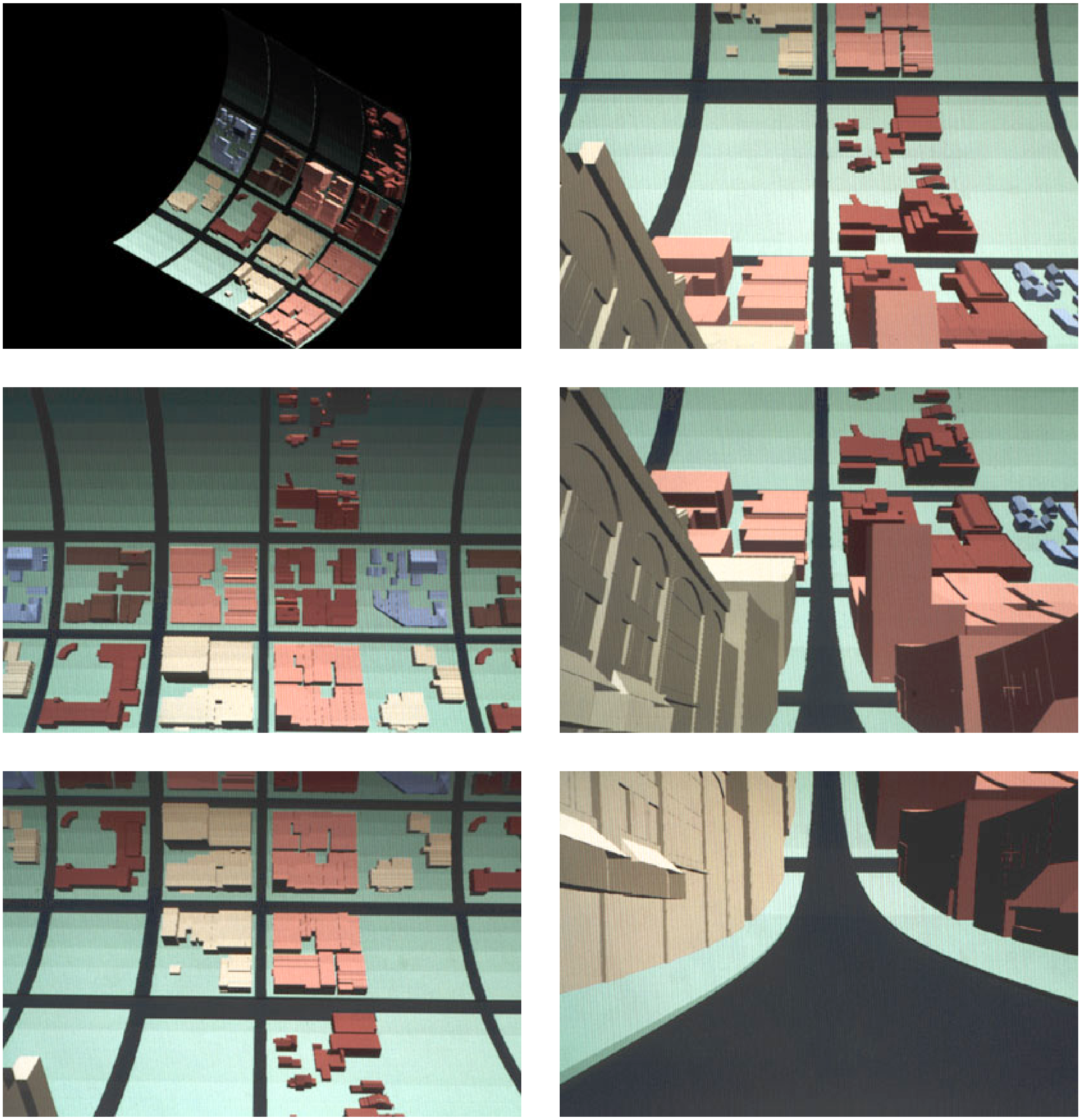


Figure 3: A neighborhood in downtown Ann Arbor, Michigan, bent at a radius of 250 meters.

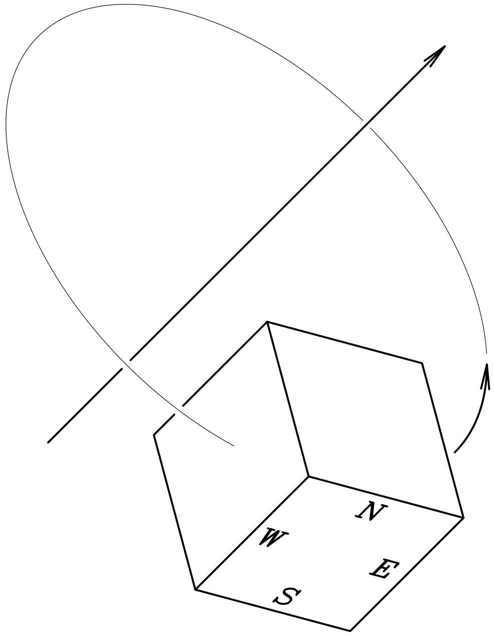
geometric modeler, and applied it to a model of a neighborhood in downtown Ann Arbor, Michigan. (The original “flat” model was developed by students in an architecture design studio, for other purposes.)

Figure 3 shows the results of bending the city at a radius of 250 meters – again, the approximate proposed radius of the Bernal Sphere. Standing at street level and looking straight east, the aerial view of roofs a few blocks away gives an impression similar to looking down from the top of a hill. Yet the upward curvature of the ground indicates that we are in a valley, not on a ridge. This incongruous vista is like nothing on Earth. The upward view of nearby roof soffits, arches, and awnings, and the downward view of distant buildings, yards, and streets, encompassed in a single frame, is impossible on Earth but would be inescapable in an artificial-gravity space colony – if the colony was composed from such Earthly forms. Even while east and west become gravitationally distinct, up and down become visually indistinct and ambiguous – especially when looking directly across the diameter of rotation. And, the flat computer-generated images give only a dim prediction of actual experience.

A recurring theme in the writing of Norberg-Schulz is that humans dwell between the earth and sky – the sky above and the earth below. In one of O'Neill's cylindrical colonies, one is nearly as likely to see the ground above and the sky below, depending on one's position relative to the large windows.[19] In fact, the best view of the heavens would be from a glass-walled observation deck in the sub-basement, protruding beneath the ground like a gondola beneath a blimp.

Windows continue to be a matter of disagreement. In addition to concerns about structural integrity, environmental control (including radiation shielding), and cost, rotation introduces the issue of dizziness. Payne[20] and others have suggested that, "to avoid disorientation," windows should not be provided in rotating environments. But depriving the inhabitants of an outside view would do nothing to alleviate the vestibular effects of rotation. On the contrary, it may promote the mismatch between visual and vestibular perception that leads to motion sickness.[15] Windows might provide an obvious, natural aid to orientation, in addition to the abstract, formalist cues discussed previously.

Figure 4 illustrates the apparent rotation of the star field. A celestial view to the north or south would rotate about the center of the window. (The parallax would be negligible.) To the south, the stars would rotate clockwise, while to the north, counterclockwise. To the east, the stars would move downward in the field of view, while to the west, upward. Looking up, the stars would move west-to-east, while looking down, east-to-west. Of course, as on Earth at night, the exterior view may be obscured by interior reflections.



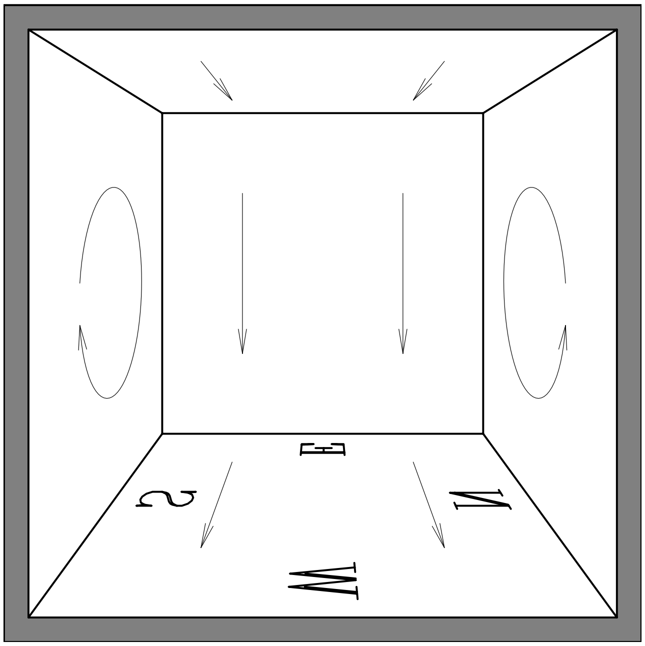


Figure 4: Cardinal directions and apparent rotation of star field.

Views are preferable, but direct sunlight is more problematic. Sunlight may be stroboscopic, or may "orbit" the room over the rotational period of the station, depending on the alignment of the rotation axis in space as well as on the placement of windows and mirrors. Unattenuated direct sunlight with virtually no diffuse light from sky or ground produces harsh contrasts, and ocular acclimation may be particularly difficult if the sun beam changes rapidly. Large colony concepts such as O'Neill's cylinders, the Bernal Sphere, and the Stanford Torus show particular attention to the problem of admitting steady sunlight, but most smaller concepts are silent on the matter.

The emergence of east and west as gravitationally distinct directions, the concave landscape, the inversion of earth and sky, and the rotating celestial scene, combine to present a profoundly abnormal environment that artificial-gravity design studies have yet to come to terms with.

Perhaps it is human nature for colonists to long for the old world while settling the new. Several centuries ago, many Europeans emigrated to America not because they wanted to be "Americans", but to escape political, economic, or religious oppression at home. Many tried to maintain their old ways of life, and starved in a land where indigenous people had prospered for thousands of years. Similarly, space colonization has been presented as an escape from over-crowding, resource depletion, and nuclear war. The architecture of artificial gravity has been conceived as an idealization of Earth, rather than a departure from it. Prak's views, on the relationship between architectural aesthetics and prevailing social conditions, seem relevant: "A person who knows that the road to a certain highly desirable goal is blocked, turns to wish-fulfillment in dreams. Analogously, the architecture of a society divided against itself becomes a dreamland, an image of the state desired." [7]

However, the persistence of Earth-normal concepts in space colony design need not be cast in such a negative light. The architecture derives from a global technological civilization that transcends national and cultural boundaries. It is the only architecture that most of us have ever known, and it is difficult for us to conceive of anything else. Perhaps our perspective can be widened by stepping back, returning to basics, and looking at nonconforming cultures – for example, the indigenous Zulu culture as described thirty-eight years ago by Allport and Pettigrew: [21]

> Zulu culture is probably the most spherical or circular of all Bantu cultures, possibly the most spherical of all native African cultures … The word "zulu" means heavens or firmament, and the aesthetic ideal of round rather than angular styles affects native art, architecture, and speech … It is commonly said in Natal that Zulus fresh from reserves cannot plow a straight furrow and are unable to lay out a rectangular flower bed … While it is possible to say "round" in Zulu, there is no word for "square". There is a word for "circle" but not for "rectangle". To speak of window, of square, or of rectangle at all, a Zulu is forced to borrow these terms from Afrikaans or from English – provided he is able to do so.

Allport and Pettigrew found that, compared to urban children, rural Zulu children were less susceptible to the "trapezoidal illusion", probably because their perceptions were not encumbered by the expectation of a rectangle.* "In this particular case, therefore, one might say that the primitive children see things 'as they are' more often than do the children of civilization." A spatial conception based on circles and spheres, rather than rectangles, may be particularly well suited to a rotating environment.

Conclusion

Artists' images of the Stanford Torus, the Bernal Sphere, and similar concepts are important icons in the pro-space movement. They embody the "proto-legends" of the "space culture", and define the culture to itself and others. To be effective, they should be realistic – or, at least, believable. The depiction of "Earth-normal" architecture in space colony concepts results from neither engineering nor architectural considerations. It indicates an uncritical adherence to terrestrial preconceptions that don't hold up under closer scrutiny.

Architectural design is not reducible to numeric calculation; psychology, culture, and philosophy must also be brought to bear. We can only guess as to the sort of culture that might one day be native to artificial gravity. In planning the first such environment, we may not be able completely to escape our terrestrial preconceptions, but we must make the effort.

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* The trapezoidal illusion is induced by a rotating trapezoidal window, proportioned and positioned such that the longer edge *always* appears longer than the shorter edge, even when the longer edge is farther away. Instead of appearing to rotate, as it actually does, the window seems to sway back and forth in an arc of 90 to 180 degrees.

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