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The Continuum of Space Architecture: From Earth to Orbit

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Space architects and engineers alike tend to see spacecraft and space habitat design as an entirely new departure, disconnected from the Earth. However, at least for Space Architecture, there is a continuum of development since the earliest formalizations of terrestrial architecture. Moving out from 1-G, Space Architecture enables the continuum from 1-G to other gravity regimes. The history of Architecture on Earth involves finding new ways to resist Gravity with non-orthogonal structures. Space Architecture represents a new milestone in this progression, in which gravity is reduced or altogether absent from the habitable environment.

I. Introduction

GEOMETRY is Truth[2]. Gravity is the constant.[3] Gravity is the constant – perhaps the only constant – in the evolution of life on Earth and the human response to the Earth's environment.[4] The Continuum of Architecture arises from geometry in building as a primary human response to gravity. It leads to the development of fundamental components of construction on Earth: Column, Wall, Floor, and Roof.

According to the theoretician Abbe Laugier, the column developed from trees; the column engendered the wall, as shown in FIGURE 1 his famous illustration of "The Primitive Hut." The column aligns with the human bipedal posture, where the spine, pelvis, and legs are the gravity-resisting structure. Caryatids are the highly literal interpretation of this phenomenon of standing to resist gravity, shown in FIGURE 2.

FIGURE 1. Abbe Laugier's "Primitive Hut"

Whether the column or the wall came first, certainly the wall led to the concept of solids composed of *face* that Plato first described in the Dialogue of Timeus, as shown in FIGURE 3. Plato ordered the five Solids by the number of *hedra* (faces) that derived originally from the flat orthogonal walls that he knew in his environment. Plato's ordering was: tetrahedron, cube, octahedron, dodecahedron, and icosahedron.

Leonardo da Vinci first drew the Platonic Solids in terms of *edges* or *struts*, dematerializing the wall-like faces into open proto-wireframe models. Leonardo's rendering proved highly influential for scientists, engineers, and architects who followed him.

Johannes Kepler explored the relationships among these "stick-built" solids, discovering the *duals* that he presented in his Harmonices Mundi. Kepler also advanced his interpretation of the solids – based upon Leonardo's stick figures – as a model of the Solar System.

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[2] Personal conversation with Hubert C. "Vic" Vykukal, hard space suit inventor, NASA Ames Research Center circa 1985.
[3] Personal conversation with Thomas Jones, astronaut, 2011, NASA Lunar Science Forum.
[4]

Buckminster Fuller took the transformation of the solids to the next level, reordering them by the number of *vertices*: tetrahedron, octahedron, cube, icosahedron, and dodecahedron. Fuller's reordering of the solids frees Architecture from walls and gravity-bound geometries. Fuller's transformation of the Platonic solids prepared the way for the author to create the triangular-tetrahedral space station architecture.

A. The Starting Point

At the time that the current ISS program started circa 1981-82, before even the Space Station Freedom period, NASA was looking at just recycling existing concepts from the 1960s and 70s. These concepts appeared under the rubric of the Space Operations Center or SOC (JSC/Boeing) and the Space Applications Manned Space Platform (MSFC/McDonnell Douglas). Both contracts used "multiple berthing adapters" as the key connective element. These "MBA's" consisted of long cylindrical modules sporting rows or rings of berthing ports. The MBA would neither accommodate substantive mission functions, nor allow any flexibility in the configuration, either during assembly or after completion. The design process was all about establishing control and keeping control. FIGURE 0 shows a Boeing rendering of the SOC for their NASA contract. The design thinking was strictly orthogonal. The rigidity and structural integrity of the system would depend upon resisting moment arms across the diameter of the berthing port. Installing or removing modules from between two MBAs would be difficult, especially if they involved needing to reopen the configuration.

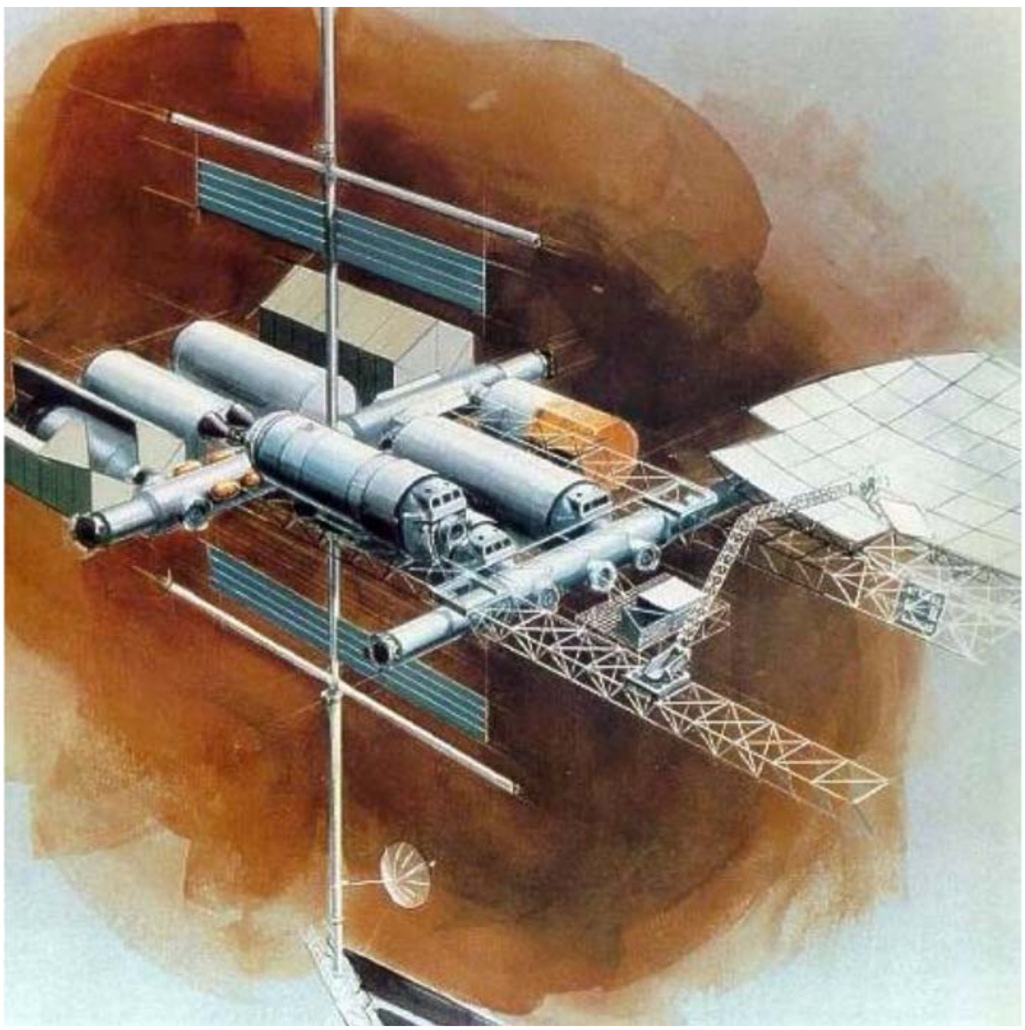

FIGURE 0. The 1982 NASA JSC/Boeing concept for the Space Operations Center.

B. The Point of this Paper

Nearly all people involved in space exploration and development look exclusively at the vast changes that occur when people venture from the familiar upright gravity of Earth to the floating microgravity of orbit and the partial gravity of the Moon or Mars. These perspectives focus on ways to compensate for *what people leave behind* when they go into space. In contrast, this paper addresses those elements *that people take with them* from Earth to orbit, including their perception and spatial cognition. These elements extend continuum of habitation in living and working environments, despite the change in gravitational acceleration.

Various spacecraft, lunar-planetary base, and space habitat concepts illustrate this transformation, not only the end-state, but also the precursors in terrestrial architecture that preceded and even anticipated them. Thus, this paper addresses three aspects of this continuum:

1) Gravity regimes, and how Earth Architecture is a response to 1-G; Space Architecture is a response to different gravity levels among all the other environmental stressors and threats in space.

2) Geometry developed within Western philosophical and mathematical thought in response to certain norms of environment, gravity, culture, perception, and society. Geometry and structure in Space Architecture responds differently to the microgravity and pressure-regime environments.

3) Connection between elements becomes a function connecting habitable atmospheres and joining the structures that contain them instead of a formal-visual connection.

This progression from planar wall/orthogonal geometry to non-orthogonal/nodal geometry blazes the path from Earth Architecture to Space Architecture as demonstrated on the ISS.

II. Key Definitions

This discourse entails three key precepts:

- A minimalist definition of architecture,
- The definition of Space Architecture, and
- The definition of a continuum.

A. *Minimum Functionality* Definition of Architecture

The sine qua non of architecture is that it consists of *physical problem solving*.[5] If it does not involve creating a physical solution to a problem in the human environment, it is not architecture. It may well be something else: art, applied social science, engineering, planning, or real estate. However, if it does not involve physical problem solving, it cannot be architecture and therefore it cannot be space architecture.

B. Definition of Space Architecture

At the Team 11/Millennium Charter Workshop during the World Space Congress in 2002, the Space Architects agreed to define Space Architecture[6]:

Space Architecture is the theory and practice of designing and building inhabited environments in outer space.

C. The Continuum

Defining a continuum is a challenge insofar as outside mathematics there are few if any smooth continua without any bumps or turns. A common dictionary definition (Farlex, The Free Online Dictionary) reads:

con·tin·u·um (Houghton Mifflin, 2009)
n. pl. **con·tin·u·a** or **con·tin·u·ums**
1. A continuous extent, succession, or whole, no part of which can be distinguished from neighboring parts except by arbitrary division.
2. *Mathematics*
a. A set having the same number of points as all the real numbers in an interval.
b. The set of all real numbers.

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[5] Personal conversation with Prof. Hanno Weber, Princeton University School of Architecture, Spring 1972.
[6] http://spacearchitect.org/ click on Resources.

Or alternatively (Collins, 2003):
continuum [kənˈtɪnjʊəm]
A continuous series or whole, no part of which is perceptibly different from the adjacent parts
[from Latin, neuter of *continuus* CONTINUOUS]

The *Continuum of Space Architecture* portrays a contrarian perspective. The all-too-common conventional wisdom in the space community that by definition "Everything we do is new. No one has ever done it before," even if they do not know what people did or why they did it. The *Continuum of Space Architecture* does not affirm comfortable and familiar perceptions, but confronts the tension between Space Architecture and the conventional wisdom. The *Continuum* explains how gravitationally responsive architecture came into existence to prepare space architects and the larger space community for the challenges of deep space, including permanent habitation on the Moon, Mars, asteroids, exoplanets, and beyond.

III. Geometric Transformation: From Primitive Huts to Space Architecture

The Continuum begins in one-Gravity (1-G) and moves outward to other gravity regimes: 0-G or microgravity in low Earth orbit (LEO) or in deep space, 0.18-G on the Moon, or 0.38-G on Mars. All humans to date were born and evolved on Earth in 1-G, and our architecture and structures co-evolved with us in response to the gravity regime. Although it is unknown what was the first rigid or permanent building for human shelter, probably it was comprised of walls. A column is a distillation of a wall down to a single vertical axis, resisting the acceleration of gravity toward the *nadir* at the center of the Earth.

A. Theory of Structure in Space Architecture

Given the Continuum as a conceptual framework, the central theory of this paper is that a continuing theme in the development of architecture and structure on Earth is finding new ways to resist gravity in non-orthogonal ways. These ways include the arch, vault, dome, and other non-rectangular structures. These structures evolved from 2 dimensions to 3 dimensions.

Although Abbe Laugier's sketch of the primitive house became an icon of the primordial notion of nature in architecture, in practice architects and builders quickly reduced wood construction's naturalism to near-universally standards of sizing and modularization.

FIGURE 2.1 Caryatid columns, Grotto of the Villa Madama, Rome (Author photo, 2005).

FIGURE 2.2. Caryatid Pilasters, Chernivtsi (Czernowitz), Ukraine. (Photo courtesy of Hardy Brier)

B. Columns and Walls

In terms of Architectural theory, the Renaissance opened largely with the painter, sculptor, and architect Leon Battista Alberti's *De re aedificatoria*, literally Edifices (also commonly entitled in translation as On the Art of Building or the Ten Books on Architecture). Alberti went further than Vitruvius in offering theories and principles of aesthetics, proportion, and ornamentation. His most famous quote – a misguided mantra for Architecture students the around the world -- is "The column is the principal ornament of architecture."

III. Solid Geometry

This section describes and illustrates the progression from orthogonal – planar wall geometry to the nodal geometry that liberates construction and habitat design from the surly bonds of Earth. It traces the progression from Plato to Leonardo to Kepler to Euler to Fuller and shows how Fuller reordered the Platonic solids by nodes instead of faces.

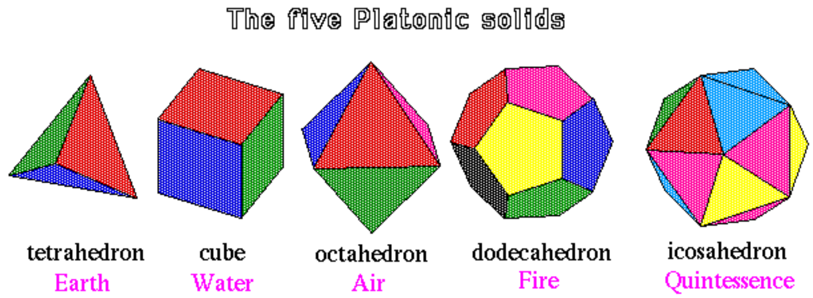


FIGURE 3. Representation of the Solids, as Plato ordered them by the number of faces (hedra).

A. Plato and the Solids

In Timeus, Plato describes the five "Platonic" solids. These solids served as a microcosm of the universe and he associated spiritual and cosmological properties to each. He ordered them by the number of faces: tetrahedron, cube, octahedron, dodecahedron, and icosahedron as shown in FIGURE 3. This ordering reflected his understanding of the wall as the principal element of architecture, which translates directly to the *hedra*, the faces of the solids. The cube, with its orthogonal walls, represented the normative way of building in Greece. The cosmological and religious implications of the solids may largely escape our understanding today. Plato attributed the properties of earth, water, fire, and air to the first four solids in that order. To the icosahedron, he attributed "quintessence" or the universe.

What is important about Plato's cosmology is the idea that these fundamental geometries can serve as ordering principles for matter, energy, and the universe as he knew it – and everything in it. He linked each of the solids to the four "elements" of contemporary science, with the icosahedron representing a kind of integration as "quintessence."

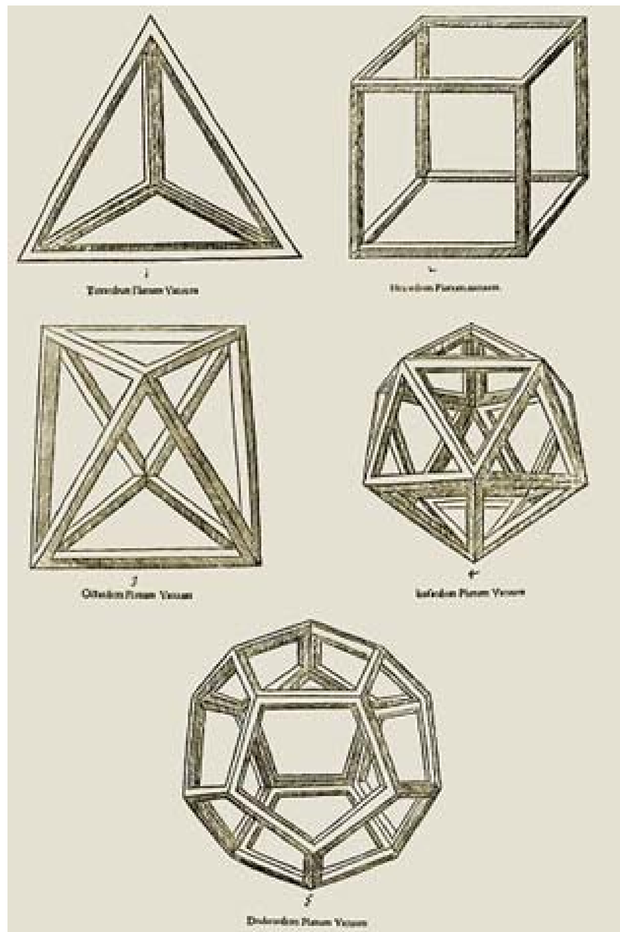


FIGURE 4. Leonardo's rendering of the five Platonic solids as edges or struts.

B. Leonardo and the Edges of the Solids

In 1509, Leonardo Da Vinci illustrated a book on geometry entitled De Devina Proportione (The Divine Proportion) for Luca Pacioli. He drew the Platonic solids, but not as made up of opaque, solid faces. Instead, FIGURE 4 shows how he drew them composed of their edges as struts. The walls dissolve as he reduces the solid to its structural frame. In reinterpreting Plato's solids as made up predominantly of edges or struts, he advanced architecture along the *Continuum* from planar, orthogonal walls to 3D frames, trusses, space frames, and geodesic domes (known also as space trusses).

Another observation is that Leonardo draws all five in perspective; all except the cube are clearly in emblematic Renaissance two-point perspective. These same four have the two points to the center *(+z axis)* and up *(+y* axis), but the cube is a skew to a vanishing at the right infinity point. The fact that the cubes front and back face-frames are perfectly square and only the "floor" and "roof" frames show a perceptible difference in foreshortening suggests that Leonardo considered the square plan normative with respect to face geometry.

He presents minimally distorted front faces that appear normal to the *z-axis* for the triangles in the tetrahedron, octahedron, and icosahedron. Similarly, the front face of the dodecahedron is a minimally distorted pentagon. However, only the cube stands out as vanishing to the side, as if to suggest the horizontality of the surface upon which it sits. The other four solids all skew to a vanishing point vertically, allowing the viewer to infer that they are not gravity-bound in the same way as the cube. Despite Leonardo's emphasis on the edges over the traditional faces, he cannot use edges as a way to order the solids because the cube and octahedron have the same number of edges (12), the icosahedron and dodecahedron have the same number of edges (30), and the tetrahedron is solitary.

C. Kepler's Duals

Johannes Kepler understood a phenomenon that may have puzzled Leonardo – the equality of edges in pairs of solids. In Harmonices Mundi (1619, Book 5, Chapter 9), Kepler identifies these *duals*, as the pairing of the cube with the octahedron, and the dodecahedron with icosahedron as having complementary relationships.[7] These pairings appear in FIGURE 4. With the discovery of the duals, Kepler was the first to begin *counting vertices* as part of arranging the solids. In so doing, he recognized them as a counterpoint to the faces.

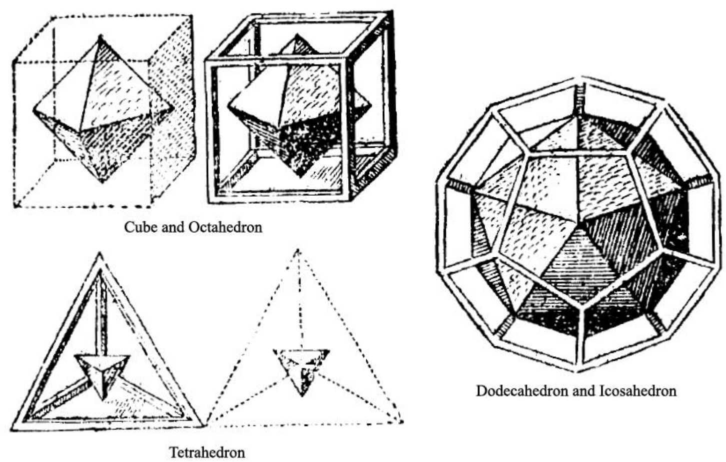


FIGURE 5. Kepler's drawing of three duals from Harmonices Mundi, emphasizing vertices and edges.

The tetrahedron is a dual with itself, four vertices touching four faces from the inside. The octahedron's six vertices correspond to the cube's six faces; the octahedron's eight faces correspond to the cube's eight vertices. Similarly, the icoshedron's twenty faces correspond to the dodecahedron's twenty vertices; the icosahedron's twelve vertices correspond to the dodecahedron's twelve faces.

Kepler renders the tetrahedron outside itself and the cube outside the octahedron as both a transparent solid and as a stick figure around an opaque solid. In the fifth dual, he shows a stick figure dodecahedron around a solid icosahedron. In these pairings, he places the solid with the fewer number of inside outside the dual with the corresponding number of vertices: the cube's six faces over the octahedron's six vertices and the dodecahedron's twelve pentagonal faces over the icosahedron's twelve vertices. Thus, in this representation, Kepler maintains the primacy of the faces over any other ordering principle. However, in the way he does it, he gives an equal if understated role to the vertices, which occur in the same number as the faces of their dual.

D. Euler's Formula of Polyhedra

Leonhard Euler (1752) discovered the first mathematical algorithm for the convex polyhedral solids. His formula defines the relationship between the number of faces, edges, and vertices. This formula made an important step toward bringing solid geometry into the domain of mathematics.

$$V + F - E = 2 = \chi$$

Where V = Vertices, F = Faces, and E = Edges, 2 = χ (chi) is an invariant value; all convex polyhedra give the result of 2 for X (chi) (Wolfram Math World). Euler's equation formed the foundation of much of topology and later for Fuller's geodesic math and geometry. Also known as the Euler characteristic or the Euler-Poincaré characteristic,

[7] The reader should be careful not to confuse Kepler's Duals in the Harnonices with his earlier Mysterium Cosmographicum (1596) in which he drew the solids as stick figures but proposed them as a Model of the Solar System to represent "the harmony of the spheres."

the result χ allows topologists to define entire classes of solids and surfaces. For example, χ 0 for a torus and χ 4 for two non-connected spheres.[8]

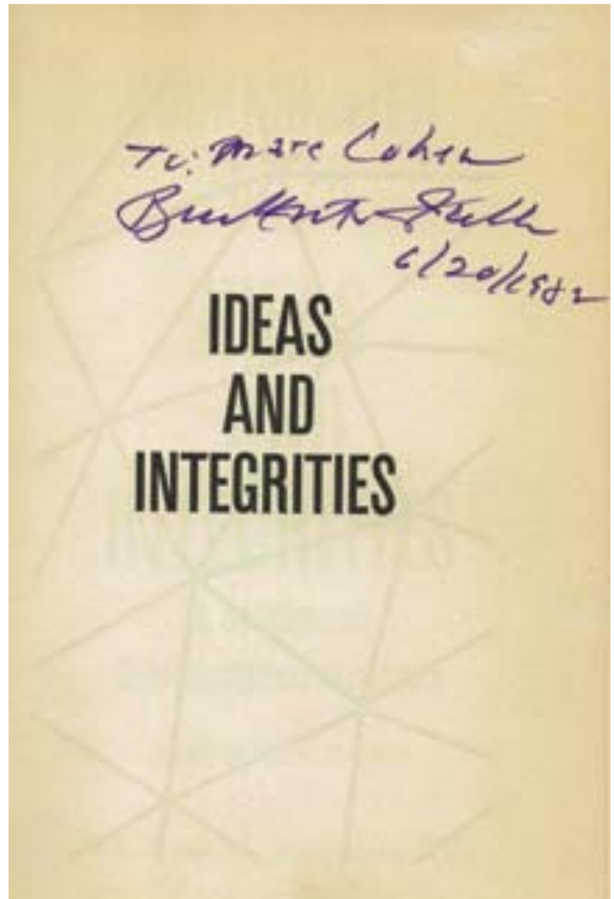


FIGURE 6. Title page of Ideas and Integrities autographed by Bucky Fuller on the day he and the author discussed the Comprehensively Finite Typology chart.

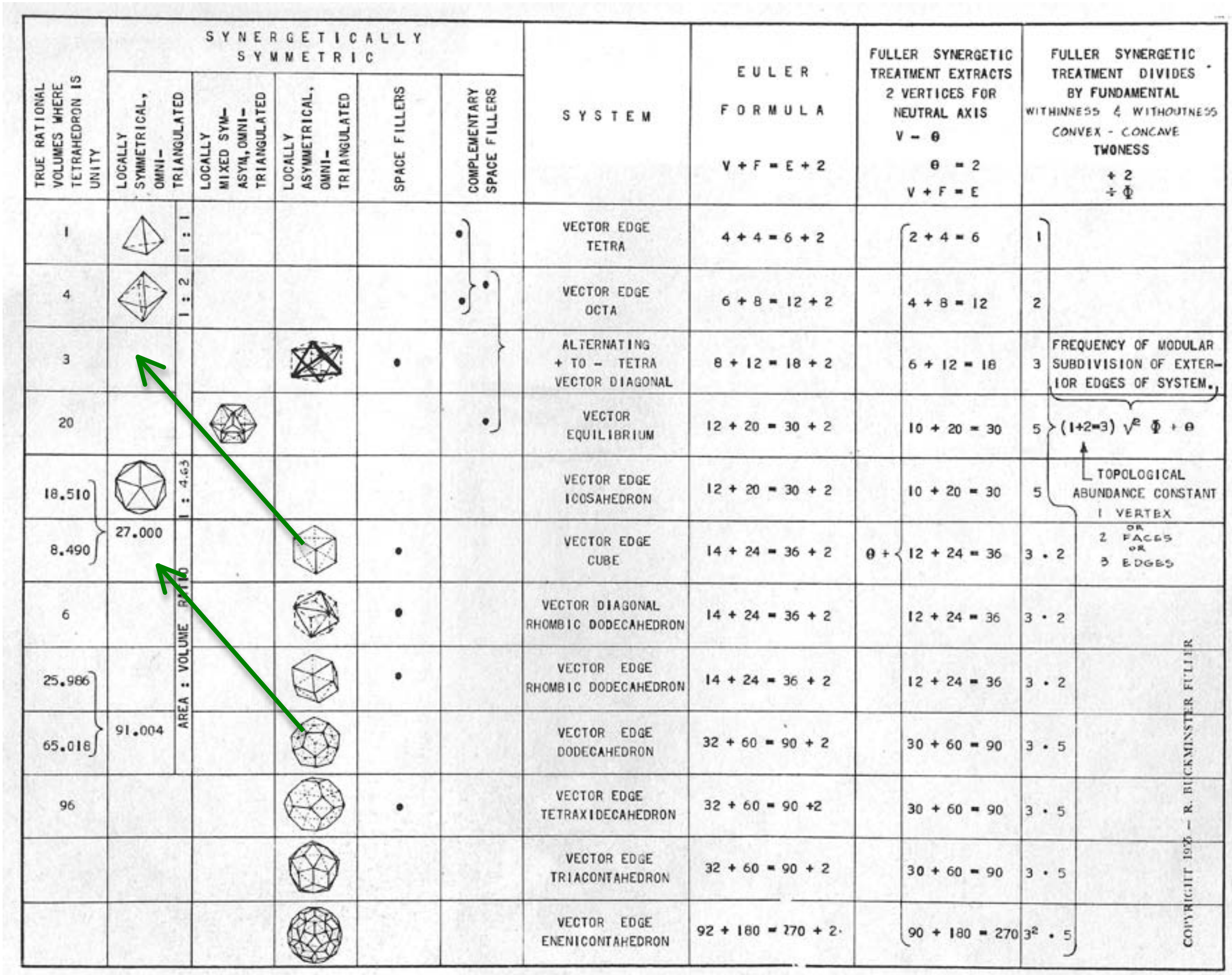
E. Buckminster Fuller

Standing "on the shoulders of giants," to borrow Isaac Newton's phrase, Buckminister Fuller achieved the most far-reaching conceptual advance since Plato. In Ideas and Integrities (Fuller, 1963, between pp. 192-193), reproduced in FIGURE 7, he reordered the solids by the number of vertices: tetrahedron, octahedron, cube, icosahedron, and dodecahedron. The decomposition between Column 2, the "Locally Symmetrically Omni-Triangulated" solids and Column 4, the "Locally Asymmetrical Omni Triangulated" ones is that Column 2 are all self-rigidizing but those in Column 4 are not. *Self-rigidizing* is the property that the solid will hold its shape with all vertices acting as pin-joints, free to rotate in any direction. If a solid is pin-jointed but not self-rigidizing, it will collapse under its own mass in a gravity field. For this reason, to act rigidly and not collapse, the construction of the Column 4 solids requires either a shear diaphragm – faces as walls, stellated and triangulated faces (works for dodecahedra), or moment-resisting corner joints.

Given this decomposition layout in the Comprehensively Finite Topology chart, the next question is: What would happen if the Platonic solids were recombined to repair the division into Columns 2 and 4? The cube would move from the fourth column/sixth row up and over to the second column, third row, as the upper diagonal arrow indicates. In the same way, the dodecahedron would move up from the fourth column, ninth row to the second column, sixth row, as the lower arrow indicates. This recombination of the two columns accomplishes the re-ordering of the solids by vertices.

The face or wall thereby becomes discounted as a tertiary aspect after the primary vertices and the secondary edges or struts. Fuller's rearrangement ***liberated solid geometry from gravity*** and its terrestrial implication of the wall or faces. TABLE 2 shows that the tetrahedron is the only solid that is both self-rigidizing and has the highest ratio of vertices to edges, which for the purpose of designing a space station configuration translate into vertices and modules respectively. To wit, the cube and dodecahedron have equal Vertex to Edge (V/E) ratios of 0.67 nodes to modules but they are not self-rigidizing; the octahedron and icosahedron are self-rigidizing but have inferior V/E ratios. The V/E ratio emerged as highly important because of the obvious need for as many available berthing ports and expansion points as possible while providing a structure of modules that does not require additional mass or complexity for stiffening. Please note that the *hedra* (faces) do not appear in TABLE 2; they are irrelevant to this analysis and so become de minimus: empty spaces between the modules.

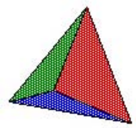
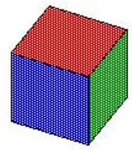
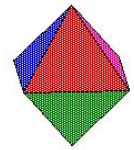
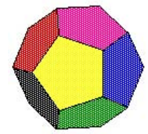
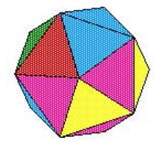
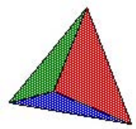
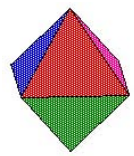
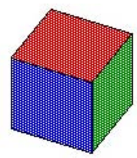
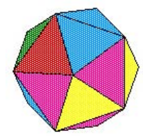
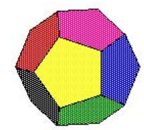
[8] Examples from Wikipedia, under the entry "Euler Characteristic."



TRUE RATIONAL VOLUMES WHERE TETRAHEDRON IS UNITY	SYNERGETICALLY SYMMETRIC: LOCALLY SYMMETRICAL, OMNI-TRIANGULATED		LOCALLY MIXED SYM-ASYM, OMNI-TRIANGULATED	LOCALLY ASYMMETRICAL, OMNI-TRIANGULATED	SPACE FILLERS	COMPLEMENTARY SPACE FILLERS	SYSTEM	EULER FORMULA V + F = E + 2	FULLER SYNERGETIC TREATMENT EXTRACTS 2 VERTICES FOR NEUTRAL AXIS V − θ θ = 2 V + F = E	FULLER SYNERGETIC TREATMENT DIVIDES BY FUNDAMENTAL WITHINNESS & WITHOUTNESS CONVEX - CONCAVE TWONESS ÷ 2 ÷ Φ
1		1 : 1				•	VECTOR EDGE TETRA	4 + 4 = 6 + 2	2 + 4 = 6	1
4		1 : 2				• •	VECTOR EDGE OCTA	6 + 8 = 12 + 2	4 + 8 = 12	2
3					•		ALTERNATING + TO − TETRA VECTOR DIAGONAL	8 + 12 = 18 + 2	6 + 12 = 18	3 FREQUENCY OF MODULAR SUBDIVISION OF EXTERIOR EDGES OF SYSTEM.
20						•	VECTOR EQUILIBRIUM	12 + 20 = 30 + 2	10 + 20 = 30	5 (1+2=3) √² Φ + θ
18.510		1 : 4.63					VECTOR EDGE ICOSAHEDRON	12 + 20 = 30 + 2	10 + 20 = 30	5 TOPOLOGICAL ABUNDANCE CONSTANT 1 VERTEX OR 2 FACES OR 3 EDGES
8.490	27.000				•		VECTOR EDGE CUBE	14 + 24 = 36 + 2	θ + 12 + 24 = 36	3 · 2
6		AREA : VOLUME RATIO			•		VECTOR DIAGONAL RHOMBIC DODECAHEDRON	14 + 24 = 36 + 2	12 + 24 = 36	3 · 2
25.986					•		VECTOR EDGE RHOMBIC DODECAHEDRON	14 + 24 = 36 + 2	12 + 24 = 36	3 · 2
65.018	91.004						VECTOR EDGE DODECAHEDRON	32 + 60 = 90 + 2	30 + 60 = 90	3 · 5
96					•		VECTOR EDGE TETRAXIDECAHEDRON	32 + 60 = 90 +2	30 + 60 = 90	3 · 5
							VECTOR EDGE TRIACONTAHEDRON	32 + 60 = 90 + 2	30 + 60 = 90	3 · 5
							VECTOR EDGE ENENICONTAHEDRON	92 + 180 = 270 + 2	90 + 180 = 270	3^2 · 5

The author's comprehensively finite Topology chart

FIGURE 7. Buckminster Fuller's Comprehensively Finite Topology from Ideas and Integrities (1963). Fair Use from the Estate of Buckminster Fuller.

TABLE 1: Buckminster Fuller's Reordering of the Platonic Solids by Vertices						
Author	**Metric**	**Ordinal Ranking**				
Plato, Dialogue of Timeus	**Faces**	**4** 	**6** 	**8** 	**12** 	**20** 
Fuller Ideas and Integrities	**Vertices**	**4** 	**6** 	**8** 	**12** 	**20** 

IV. The Triangular-Tetrahedral Space Station Architecture

In evaluating the conventional MBA-centered configurations that came out of Houston and Huntsville, it soon became obvious that NASA needed a space station that was unencumbered by orthogonal, 1-G mindset and conventional thinking. Given the primacy of vertices as an ordering system for a non-1-gravity field (microgravity in this case), the logical step was to design a microgravity habitable environment based on Fuller's reinterpretation of the solids. The selection of the tetrahedron for the optimal geometry for the configuration derived from an analysis of the salient characteristics of the solids, which appears in TABLE 2.

TABLE 2. Properties of the Platonic Solids for Selecting a Space Station Configuration				
Solid	**Vertices**	**Edges**	**Ratio of V/E**	**Self-Rigidizing**
Tetrahedron	4	6	0.67	YES
Octahedron	6	12	0.50	YES
Cube	8	12	0.67	NO
Icosahedron	12	30	0.40	YES
Dodecahedron	20	30	0.67	NO

The Space Station Architecture patent introduced the nodes as spherical, but also claimed the use of nodes generally as a connecting element in the space environment. The multi-port and multi-hatch intrinsic character of the node led to utilizing one of the hatch frames to hold a larger viewport, the cupola, which is part of the Space Station Architecture patent. Before the patent, the NASA space station module configurations consisted of all cylinders, some for berthing, and some for mission functions. The spherical nodes would prove far more efficient structurally and weigh much less relative to the job of supporting the berthing ports and hatch frames.

FIGURE 8 presents the configuration for the Triangular-Tetrahedral space station. The choice of a tetrahedron was based upon several factors that were both qualitative and quantitative:

- The nodes have high value as connecting structural elements and circulation hubs.
- The tetrahedron is one of the three self-rigidizing solids.
- The tetrahedron has a higher ratio of vertices to edges (nodes to modules) than any of the other self-rigidizing solids.
- The tetrahedron nodes offer the best geometry for the approach of a docking spacecraft, a "reverse cone of approach" in which the whole shape of the solid recedes away from the approach path (as opposed to presenting a flat façade).

- The larger node-to-module ratio means a higher incidence of berthing or docking ports to accommodate logistics modules to ensure sufficient supply storage capacity, so that for example, the crew would not run out of food if there was not sufficient and accessible logistics stowage volume.
- The larger node-to-module ration means future expansion of the geometry by the addition of more modules and nodes will be easier and have greater flexibility.
- The tetrahedron is self-rigidizing, which means that the node can behave as a pin-jointed truss joint and does not need to resist bending moments across the width of the connecting hatch-ports.
- This pin-jointed, self-rigidizing geometry would save substantial mass and structural complexity, and
- The triangular “racetracks” of the tetrahedron offer the shortest loop or path for dual distal access to any node or module.

The original impetus for the nodes was that they should be very low cost, simple, structurally efficient, highly reliable connective elements. The nodes constitute an element of infrastructure. There is a conventional wisdom tendency to view all infrastructure not as value to be enhanced but as cost to be minimized. However, in the extreme and unforgiving environment of space, having more and better infrastructure brings great value to the crew’s safety and mission success.

A Johnson Space Center cost estimate circa 1984 put the cost of the spherical nodes at $50,000,000 apiece, which was very low for any human spacecraft element.[9] With such a low-cost element, it would be possible to extend the configuration in any direction. At the same time, all the major operational functions would reside in the cylindrical modules. Utilities (power, water, data, life support, ventilation, etc.) pass from one module to another *through the nodes*, but the nodes themselves would remain as uncomplicated and uncluttered as possible.

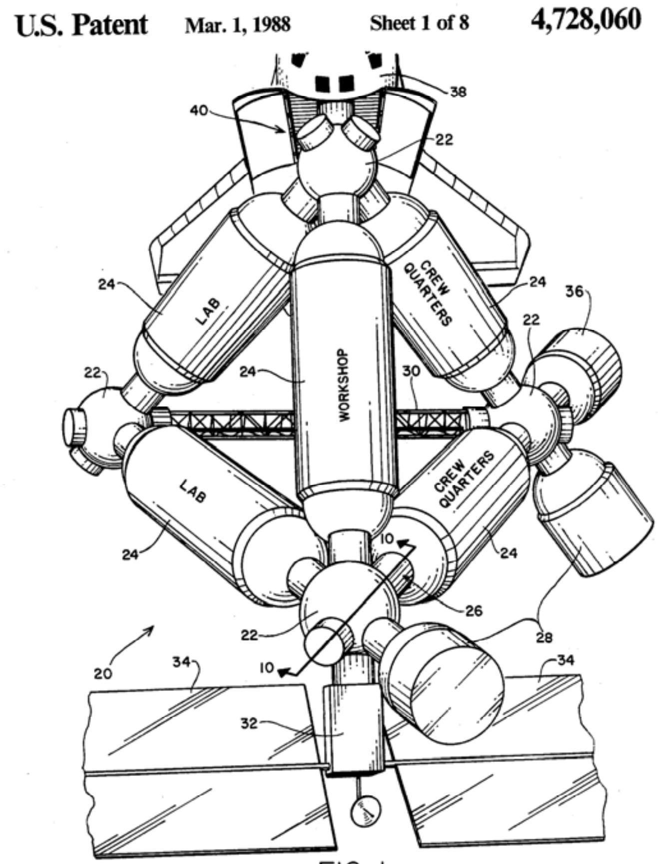


FIG. 1

FIGURE 8. Patent drawing for the Space Station Architecture -- Triangular-Tetrahedral Configuration.

Given these advantageous properties of the tetrahedron for a space station, it was the logical choice of geometry. Then, another level of design inquiry emerged: What should be the character of the module interiors and the nature of penetrations in their pressure shells? The patent uses hemispheres of the same construction and materials as the node to furnish the end-domes on the modules. FIGURE 9 shows how the spherical shells of the nodes and end domes on the module are essentially identical, with the option of emplacing several additional ports on the end dome in the same manner as the node. The presence and availability of these berthing port hatch frames is what makes possible the installation of a cupola into any of them. In FIGURE 9, the cupola is attached to an additional, off-axis port in a hemispherical end dome.

Another characteristic that appears in this patent drawing is the installation of an airlock into one of the hemispherical end domes. The idea was that these small pressurized units, either as nodes or as “half-nodes” in the end domes could provide a suitable or even optimal pressure vessel for an airlock. At the time, the space station configuration put the airlock as a unique, dedicated pressure vessel inside a conventional cylindrical module.

[9] Personal conversations with members of the Space Station Concept Development Group at NASA HQ, January-June 1984.

Installing an airlock inside a full module would mean building a pressure vessel within a pressure vessel, which would be redundant, make the module unnecessarily heavy, and be horribly inefficient. However, by using the naturally smaller shell diameter of the hemisphere, with the volume “cut off” from the interior by a flat or shallowly curved bulkhead, the airlock would have a more limited and manageable evacuatable volume of about one third of a “baloney slice” through the cylinder. An allied option would be to use one of the inexpensive, mass-produced spherical nodes, and use lightweight foam void-fillers to reduce excess atmospheric losses.

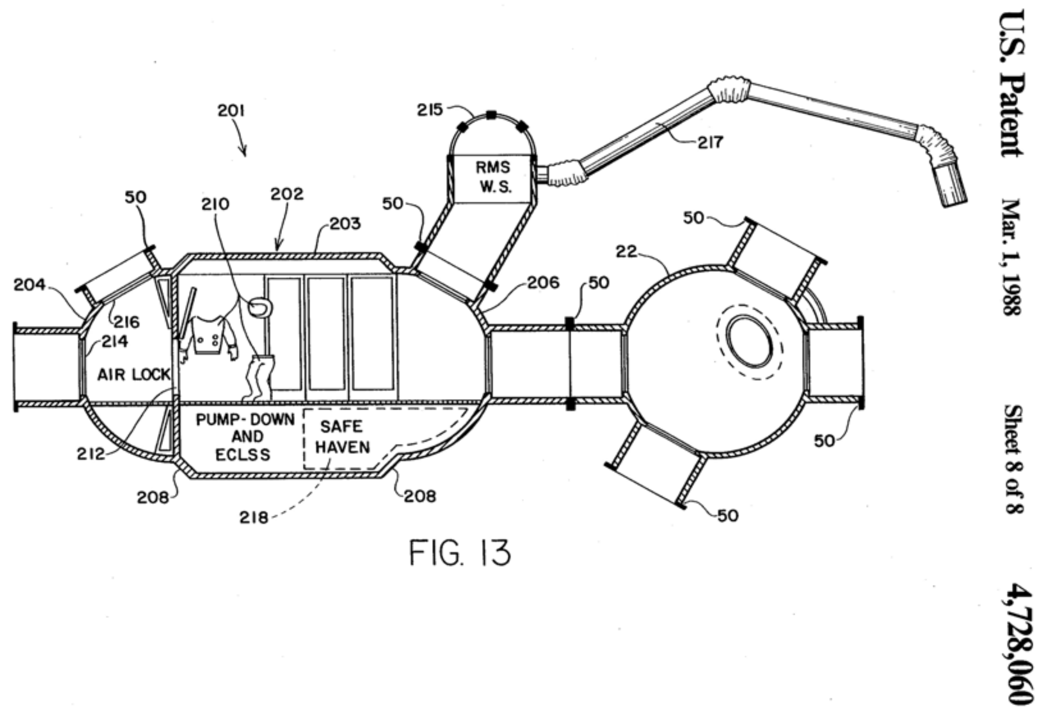


FIGURE 9. Longitudinal section through a spherical node, module with hemispherical end domes, airlock in an end dome, and the cupola mounted to a berthing port.

A pressure vessel primary structure compromise became necessary to fit the node in the Shuttle cargo bay. It was more advantageous dimensionally if the node (and module end dome) diameter is nominally 12 ft. (3.6m), while the nominal diameter of the cylindrical portion of the module is 14.25 ft. (4.275m). This differential outside diameter necessitates a frustoconical transition ring between the cylinder and the hemisphere. This ring adds to the parts count, however it allows much greater versatility by affording greater flexibility in the sizes of the pressure vessel shells.

Another important and far-reaching feature of the Space Station Architecture patent was the incremental, adaptable approach to the assembly sequence in FIGURE 10. This approach recognized a fundamental balancing act that would evolve as the assembly process progressed and the configuration grew. When the space station configuration was small, it could tolerate imbalances and asymmetries because its mass was smaller. However, as the configuration grew and added mass and longer moment arms from the solar arrays and extensions of modules, it could tolerate asymmetry and the accompanying imbalance less and less. Therefore, although the station might start out asymmetrical when it was small, it must build towards a larger symmetry and balance of mass and moment arms. Achieving this greater symmetry to achieve efficient and controllable flight dynamics meant relocating not only nodes or modules as the configuration grew, but also the solar arrays and trusses with their potentially huge moment arms and torques. An underappreciated feature of this assembly sequence is that it anticipates the need for continuing logistics resupply and takes into account the need to install, relocate, and remove logistics modules throughout the construction process and for the life of the Space Station.

V. Implementation: Nodes, Cupola, and Assembly

The conception and perseverance of the node and cupola show how architectural design research can contribute to spacecraft design and inform the final outcome. At the same time, once these designs or inventions enter the process of the System Engineering juggernaut, it is impossible to foresee what will be the final result or how the contribution will end up.

The first step in implementing the triangular-tetrahedral Space Station Architecture came in October 1985, when the NASA Space Station Control Board implemented spherical nodes into what was then entitled the Space Station Freedom (SSF). Johnson Space Center was responsible for the nodes, trusses, and everything on Space Station that would occur outside the cylindrical "Common Modules" that were assigned to Marshall Space Flight Center (MSFC). FIGURE 11 shows an illustration from the cover of NASA Tech briefs that shows a rectangular "racetrack" configuration of SSF modules. It employs four spherical nodes, one at each corner of the racetrack. The "racetrack" consists of two conventional cylindrical modules with frustoconical end domes, the four nodes, and two short tunnel connectors between each pair of hubs, front and back. On the right front node, a cupola is attached to a berthing port. This illustration depicts the "dual keel" configuration, in which two trusses run vertically up to about 250m high. This configuration would fly in "gravity gradient" mode, with the bottom of the vertical truss always pointing to the nadir, with the intention of balancing or cancelling orbital torques each orbit.

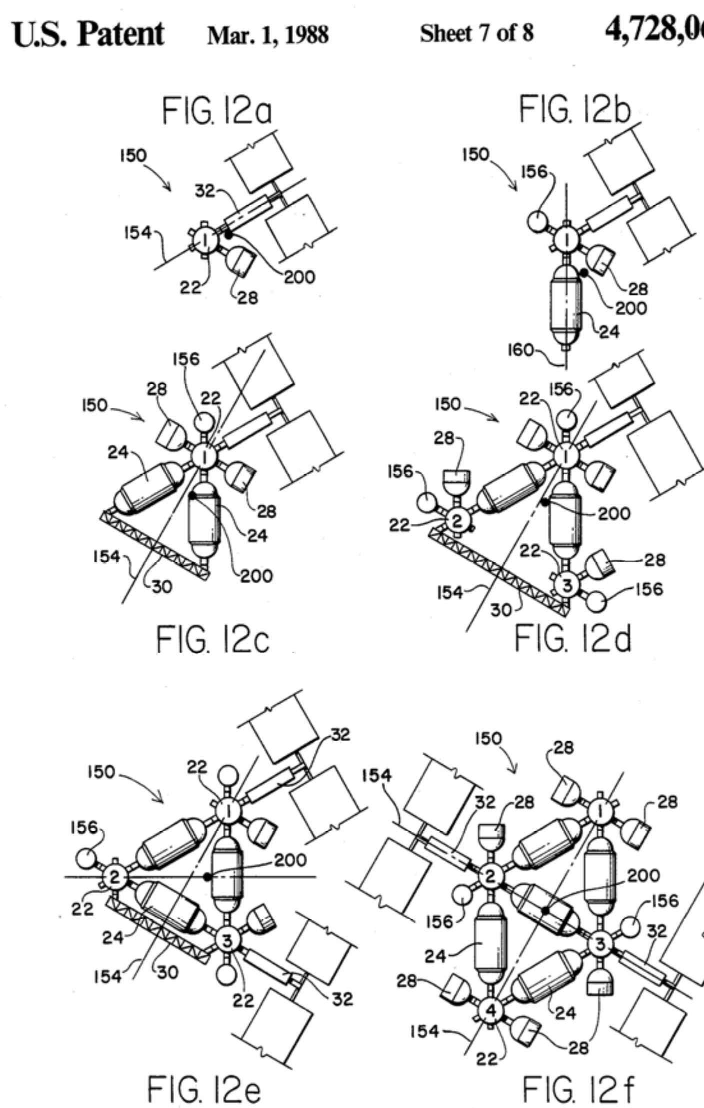


FIGURE 10. Space Station Architecture Assembly sequence for a representative triangular layout.

An additional purpose was to place Earth-observing scientific payloads at the bottom of the truss where they might be uninterrupted or unaffected by spacecraft traffic to the modules in the middle height. At the top, NASA planned a suite of sky-pointing instruments including telescopes and a variety of sensors at stars and other celestial phenomena. The main criticism of the Dual-Keel concept was that it involved far too much truss, and by some estimates, it would require up to a kilometer of truss to perform all these functions, plus support the solar arrays running horizontally through the space station center of mass, with the solar arrays outboard of the two vertical trusses

The spherical nodes accommodate logistics modules and other attached units or attached payloads, primarily at the two back nodes. Behind them appears a representation of the two partner labs aligned in parallel to adjacent nodes: the European ESA Columbus module, and the Japan Experiment Module (JEM) "Kibo."[10] Although there was excellent potential to use the spherical nodes as airlocks or low cost logistics modules, NASA did not advance along this line of development to implement them.

FIGURE 11. NASA Illustration of the Space Station Freedom with spherical nodes and cupola.

Instead, what happened was a period of retrenchment and conservatism in Space Station design. NASA experienced one of its greatest tragedies on 28 January 1986 with the loss of the Space Station Challenger and the death of seven crewmembers. The Rogers Commission that investigated the "accident" looked more to root causes for why the O-rings in the solid rocket boosters burned-through than trying to assign blame to the NASA center or contractor responsible.

What came next was a great surprise. The newly reappointed NASA Administrator, James Fletcher gave MSFC a much larger share of the Space Station program, including habitability accommodations, life support systems, and the nodes that formerly "belonged" to JSC. Once MSFC had control of the nodes, they declared that since they "owned" the Common Module with a set diameter of 4.25m, all pressurized modules should have the same diameter.

Architectural, functional, operational, and structural reasons for more efficient, versatile, and more effective design alternatives were no longer of concern to NASA. It was literally "one size fits all" from that time forth; rational discussion about optimizing the Space Station Architecture ended.

On the plus side, the primary function of the nodes and the cupola remained in the Space Station Program. Neither could NASA repeal the laws of physics to come up with a "one size fits all" configuration assembly sequence where it was never necessary to relocate an element, node, or module. Rod Jones (2000) describes these challenges for planning the assembly of the ISS, particularly how the limitations and asymmetries would change throughout the ISS buildup process. FIGURE 12 shows a full-scale mockup of Space Station Freedom in racetrack configuration with the short cylindrical nodes. FIGURE 13 shows a rendering of the Space Station Freedom racetrack module pattern. The redesign reduced the vertical dual keel truss to just the horizontal truss across the center to support the solar power arrays.

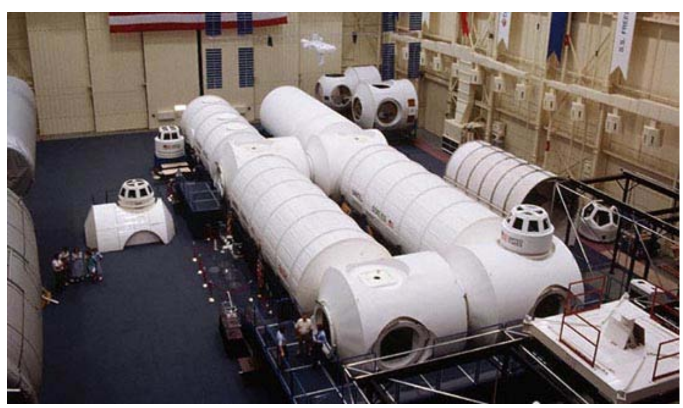


FIGURE 12. Full Scale Mockup of Space Station Freedom Racetrack Configuration. NASA image.

As part of this reallocation of responsibilities that drove the redesign, NASA started calling the nodes "Resource Nodes." This appellation directly contradicted the original Space Station Architecture precept of abundant, simple, highly reliable, and low cost spherical nodes.

[10] "Hope"

Making the nodes into resource or utility modules would drive up the costs, complexity, mass, and vulnerability – every thing the original Space Station Architecture tried to avoid. It meant that instead of having, say, two full size space station modules with these resource utility functions as integral parts of the Laboratory Module and the Habitat Module, there would now be six modules all requiring full multidisciplinary subsystem and system integration.

If there were inadequate volume in functional modules, the cost-effective solution would be to add more full size modules at the spherical nodes. That would minimize the cost of expansion (especially if a third module allowed a self-rigidizing triangle pattern with a 1:1 ratio of nodes to modules). What happened instead was that only one functional module – the US Destiny lab module – is installed between two nodes, Unity and Harmony. The other modules: Columbus, Kibo, Zarya, and Zvezda are all situated as a distal end of the closest node.

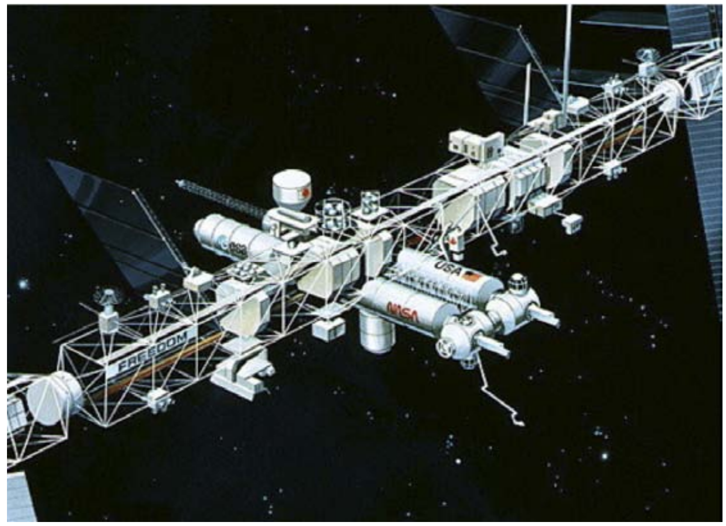


FIGURE 13. Artist’s rendering of Space Station Freedom Module Pattern with the full-size transverse truss.

FIGURE 14 shows an anti-nadir view of a temporary configuration that berthed Node 3 *Tranquility* temporarily to the side port of *Harmony,* the second node. This improvised asymmetry reflects exactly what the Space Station Architecture patent projected: temporary asymmetries and imbalances when the station was smaller, building toward a greater symmetry as the station approaches completion.

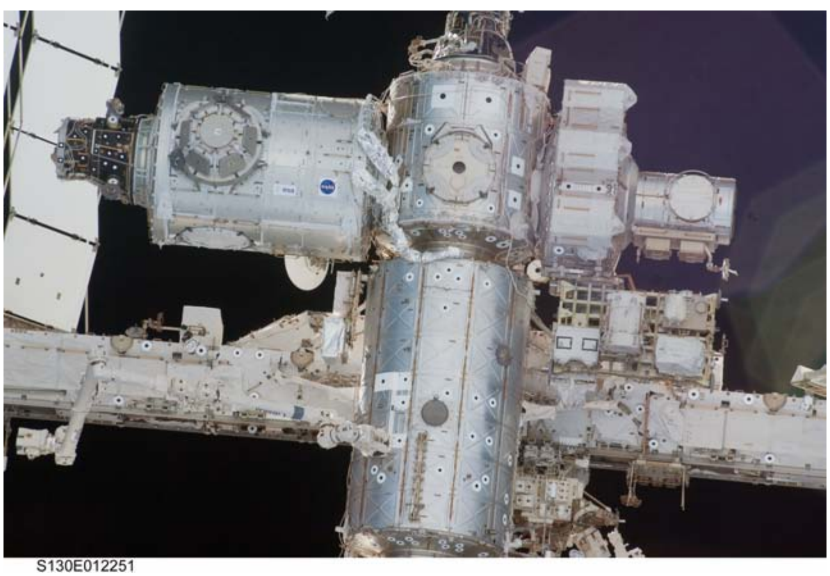


FIGURE 14. ISS during assembly process, Node 3 *Tranquility* with the cupola mounted on it is temporarily berthed to the side of Node 2 *Harmony,* which is berthed in term to the US *Destiny* Lab.

FIGURE 15 shows a side view of the cupola in its nadir-facing position on Tranquility, looking down at the Earth. In its final location, the cupola looks down at the Earth and along the velocity vector to enable the crew to see approaching spacecraft. It also enables the crew to observe the use of ISS’s robotic Canadarm over a fairly wide field of view. Despite the many changes in module and node design, orientation, and position, the cupola is a success because it achieves all the goals of the Space Station Architecture Patent.

FIGURE 16 shows the final “completed”[11] “Space Station Complete” configuration. The modules align longitudinally with the perspective of the photograph. The two longitudinally visible modules are *Tranquility* and *Harmony*. This adjacency between two nodes contradicts the Space Station Architecture patent because the purpose of the nodes was to connect the main functional modules – not to substitute for them in a compromised manner. To the left of *Tranquility* is ESA’s *Columbus* lab module. To

[11] Complete except for the absence of the Space Station Life Science Centrifuge in the Centrifuge Accommodation Module (CAM).

the right is Japan's *Kibo*, with its dedicated logistics module plus the external exposure facility. It appears that only JAXA took to heart the necessity for a dedicated logistics module capability for Kibo.

FIGURE 15. Cupola in Nadir-viewing position on the "bottom" berthing port location on Harmony, Node 3.

For the most part, the operations on ISS remain limited by resupply and the crew's ability to find a place to stow these supplies on board the station. Unfortunately, not only is the ISS extremely crammed and cluttered, but also once the crew stuff equipment or food into a rack or cargo bag somewhere, it is difficult to continue to keep track of it. Having most of the resupply in well-stocked external logistics modules would resolve these difficulties.

V. Conclusion

The gravity regime and its effects change from Earth to orbit and beyond. Yet, gravity remains a design driver and geometric form generator – but in micro-G or partial-G it is a different driver; it leads to different forms, geometries, and physical solutions. Clarity of geometry and the structure it embodies is a first order indicator of the quality of architectural thought, particularly in response to the space environment in all its hazards and threats.

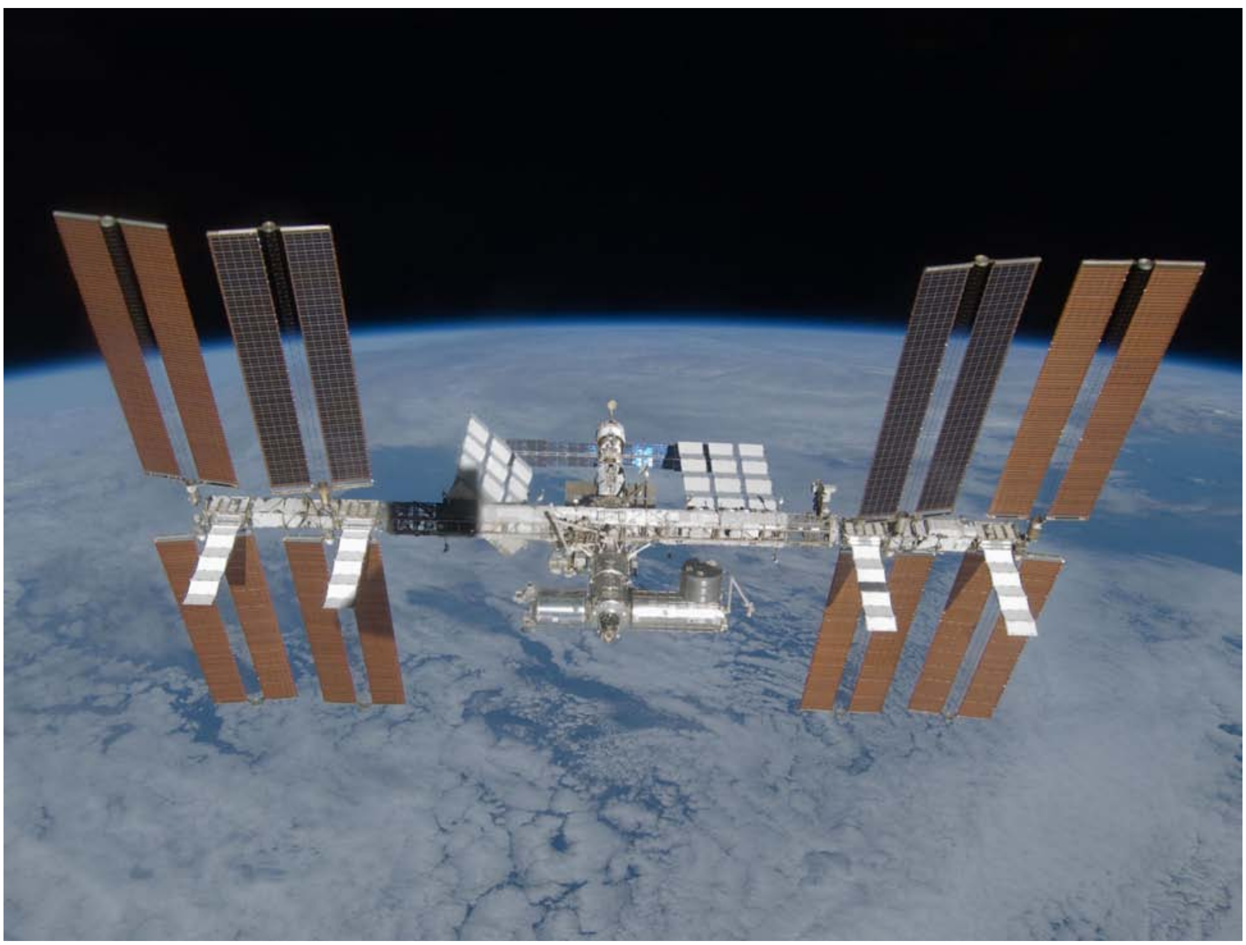


FIGURE 16. Completed International Space Station, 2011.

This odyssey of Space Station Architecture and the triangular-tetrahedral configuration demonstrates the importance of innovative and risk-taking architectural design research. It is almost axiomatic that when the Space Architect starts to do anything new, there will be an over-abundance of naysayers who will oppose the innovation, saying in essence “That way will never work because we have always done it this way.” The practice of Space Architecture always involves the battle to show that new designs can be better than the existing ways.

This Space Station Architecture took off on a different intellectual vector than the conventional wisdom at the time. Only by pursuing the design trajectory never taken previously, was it possible to conceive develop a set of inventions that would find their way into the Space Station Program, despite all the politics. In this case, necessity is only the great aunt of invention. The analysis that engenders a new view of reality comes first, opening a new channel to understand the design problem space. This new understanding, and the insights it brings about new possibilities and opportunities, makes all the difference. These new architectural design investigation and opportunities enable true advances in Space Architecture and other fields.

In this project, the new understanding and opportunities arose from the thorough analysis of traditional solid geometry and its implications for the orthogonal, 1-G-derived worldview. Understanding how Buckminster Fuller’s re-ordering of that worldview changed everything empowered the Space Station Architecture. The understanding must be comprehensive – as in Fuller’s Comprehensively Finite Topology. It is never about the superficialities of how forms look, who likes them, or what the politics may say. In this project, the success of Space Architecture came from following carefully and applying rigorously the design logic dictated by function, geometry, and structure.

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