

LUNAR ARCHITECTURE AND URBANISM

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Human civilization and architecture have defined each other for over 5000 years on Earth. Even in the novel environment of space, persistent issues of human urbanism will eclipse, within a historically short time, the technical challenges of space settlement that dominate our current view. By adding modern topics in space engineering, planetology, life support, human factors, material invention, and conservation to their already renaissance array of expertise, urban designers can responsibly apply ancient, proven standards to the exciting new opportunities afforded by space. Inescapable facts about the Moon set real boundaries within which tenable lunar urbanism and its component architecture must eventually develop.

THE LONG VIEW

Many decades still insulate us temporally from true lunar urbanism. Indeed, many years will pass before even inchoate lunar architecture is realized. Why, then, examine a field so embryonic that its real features cannot yet be known? Three reasons motivate this essay.

First, given the proof of Project Apollo, no one could defensibly pretend that human expansion to other planets is impossible. Even many nonspecialists are already thinking and anxious about prospects for lunar civilization; their inevitable projections will be most productive if grounded realistically in a few inescapable facts that will constrain life on the Moon.

Second, those hoping professionally to design the built lunar environment tend to be either space engineers who know little about urban history, or architects who know little about space. Responsible lunar planners, however, must be versed in both worlds. Preparing rigorously for that joint future will take much time, and appreciating the depth and range of both fields is a first step.

Third, and most central, refining the direction of the path that will bridge present thinking to future history depends on setting goals from the beginning. Without some tangible idea of what the far future must, should, and might be, we have no sound basis for making the many immediate decisions along our way toward it. Now is the time to begin earnest discussion of how people will use Earth's moon. Acknowledging eventual facts of offworld urbanism can save resources and, finally, remorse.

TRAVELING, STAYING, AND LIVING

To begin, we draw distinctions among three human activities, each of which has a special role to play in the growth of space civilization: traveling, staying, and living. Space architecture so far has been entirely vehicular, based on components launched from Earth. Atmospheric flight governs their form from the outside in. Like trucks and vans, they only grudgingly permit concerted

activity, being cramped, noisy, smelly, and too inertially jittery to permit precision work. The interior human environment of such capsules, shuttles, and modules is purloined from the available methods and familiar hardware of earlier atmospheric flight vehicles.

Because travel vehicles are inappropriate for lengthy stays, servicing longer missions with vehicular architecture requires either exrescent or modular approaches. The space shuttle uses the former, accommodating up to seven workers for roughly a week with ab-ware (Spacelab, Spacehab) installed in its capacious cargo bay. This allows but also enforces extensive ground support for every mission and is ultimately volume-limited. Mir, on the other hand, occupies the present stage in a modular space station lineage that began with Skylab. Distilling, as this approach does, the activities of traveling and staying allows much more growth, but is finally activity-limited by the dimensions of its units and connections.

A space architecture of linked, pressurized cylinders, even one that sprouts appendages and enormous exterior structures, is still vehicular in spirit. Such manned components on orbit are really like trains parked on sidings. Romanenko's recent 326-day record proves that, when specialized, such architecture can support individuals working and staying in space. While it is natural and common to envision even future space architecture based on this familiar vehicular vocabulary, however, only the very first stages of permanent construction in orbit or on planetary surfaces could in fact be sensibly vehicular.

Submarine and antarctic environments are frequently proffered as paradigms for space. Remote and hostile, all three are, after all, intrinsically deadly to people and thus require artifice to sustain life, promote efficiency, encourage conciliation, avoid conflict, and prevent disaster. From these urgent needs emerged human "factors" engineering, an attempt to quantify as completely as possible human behavior with the goal of designing more suitable environments. Such work holds great promise for enhancing our ability to stay in hostile places and will prove critical for long interplanetary manned missions and planetary outposts, which blur the boundary between traveling and staying. But Earth's oceans and poles, from which people eventually return, can only model space to a certain point.

Space cannot become the autonomous human economic arena widely regarded as inevitable until people establish their lives there. Travel time, expense, and risk will conspire to ensure that

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they eventually transform staying in space to living in space. Human living is an exceedingly complex activity, requiring much more than passably engineered accommodation because it includes all we do: working, resting, playing, and growing. Designing for living is a vastly messy problem, one not deeply solvable by Crays. People and their behavior cannot be reduced to factors in a numerical model of living. Instead, the sum of physical and abstract richness developed over all human history occupies the core and determines the aspects of human living.

The requirements and effects of environments that support human living are subtle and continue to be honed over millennia as society evolves. Manipulating those environments with skill and grace demands a fine multivariate balance that, as far into the future as we can defensibly see, only human experience and wisdom can feasibly provide, in space as on Earth. They demand in fact the practice of architecture.

FIRMNESS, COMMODITY, AND DELIGHT

We may define architecture succinctly as the professional activity of coordinating a set of specialty industries and services to make facilities that foster and enhance human living. To dissect the profession, we first need ways to evaluate its product. Then we can more critically review the specialties it coordinates.

Two millennia ago, the Roman Vitruvius proffered a clear, concise, and complete statement of the qualities defining good architecture: firmness, commodity, and delight. This tripolar standard covers anything that architecture can do or be. *Firmness* refers to structural integrity, appropriate material qualities, proper fabrication, and safety. Firmness addresses the question: Is it usable? *Commodity* subsumes all the ways a work of architecture serves the programmatic purpose for which it is built, accommodating the physical and abstract needs of its occupants and environment. Commodity addresses the question: Is it useful? *Delight* is often the diacritical signature of great architecture, frequently omitted in modern Western culture as a separable luxury. Delight addresses the subtle but penetrating question: Would people rather use this than other solutions? These three ancient principles apply to all ages and modes and styles of architecture, encapsulating distinct and complementary properties without any one of which architecture cannot be simultaneously structure, solution, and art.

At its best, architecture projects human values and aspirations; at the very least, it embodies human needs and behaviors. Because it depends on manipulating materials for human use, architecture has been called cynically the "second oldest" profession. The purview of architecture, even neglecting (as here) traveling and staying, is extensive and inclusive. We take all designed interfaces between human beings and their environment, from spoons to highways, gardens to sewers, and buildings, too, as architecture. Civil architecture, servicing and embodying human community, is convolved inextricably with civilization.

Archeologists generally define civilization as having begun about 5000 years ago in Mesopotamia, following two key inventions: writing and urbanism. The earliest applications of writing and urbanism must be considered artifacts of commerce, having used abstract yet practical formal design to facilitate efficient and dense intercourse. Subsequently, these permanently expressive media, both written and built, became intrinsically useful for encapsulating and stimulating human sensibilities. By thus transcending mere functionality, the recording arts of literature and architecture were born. Over the ages since then, civilization and its

cultural expressions have continued to define each other iteratively. We cannot imagine "civilization" (from the Latin root for citizen) divorced from its creative artifacts.

The city is architecture's grandest product, a built armature within which throngs of people can arrange discrete but linked lives. As a tool permitting societal evolution, the city must first provide enduring organization and sustain the individual and collective needs of the people living in it. By accommodating simultaneously most of the conflicting, singular services its citizens desire, the city can enable a population density possible no other way. The synergy of that populace animates in turn a social organism much larger, more resourceful, and more consequential than any individual could be. It is this strength, this capacity, this influence available to a civic culture, that drives humans together to make cities wherever they live.

A civilization sustained enduringly and efficiently by its culture can upon that foundation achieve great things, advancing the reach of the human spirit. As we know, however, the extreme density encouraged by cities cannot alone guarantee greatness; urbanism often falls far short of both commodity and delight. Disease, violence, exploitation, environmental devastation, and spiritual impoverishment have historically accompanied unbridled concentrations of people. As contemporary physical limitations are approached, atavistic biological controls resurface in human populations. Certainly there is a vast gap between what is biologically tolerable for the human species and what is spiritually desirable for human civilization. Urban design tries to mitigate the negative aspects of dense populations while still fostering their priceless benefits.

Architecture necessarily occupies a central role in building civilization, by linking and reconciling otherwise isolated fields that can only make a firm, commodious, and delightful environment if combined coherently. Traditional specialties contributing to modern terrestrial architecture include subjects as sundry as human programming, historical study, abstract and representational modeling, psychology, structural engineering, law, materials testing and development, environmental control engineering, negotiation, construction management, engineering geology, economics, environmental study, and of course art.

Designers of cities must in addition address mass transportation, civic logistics, waste management and pollution avoidance, industrial production, crime, commerce, power sources and distribution, spectator events, communication networks and media, public recreation, resource conservation, death, park management, health maintenance, and defense.

Architects and urban planners try to satisfy simultaneously the needs of all these diverse subjects by manipulating the proportions, character, symbolism, and scale of material assemblages. In so doing they add incidentally to the long history of built human environments. Their central, coordinating effort remains invariant despite material and social features unique to time and place.

ANOTHER CHANCE

The time is the next century, and the place is cislunar space, particularly on and under the surface of Earth's moon. Until then and there, the vehicular nature of all space vessels ensures that their design can be influenced by only a skeleton (the human "factors") of the tremendous array of architectural issues. Poised still at the threshold of inhabiting the first truly new environment since the dawn of man, and having only essayed tentatively into it, we are now understandably preoccupied with technical

challenges. Keeping people alive and physically healthy still dominates all other problems of manned space activity.

Orbiting a few people has consumed the best engineering effort the twentieth century could muster. Enabling several people to stay in orbit simultaneously for many months, served by a complete Space Transportation System (STS) permitting travel throughout cislunar space, will be much more challenging and expensive. Leaving behind the sustenance and protection of Earth opens a level of interleaved technical problems quite beyond anything we have tackled so far. Logistically, sustaining large groups for long times inevitably demands some form of Controlled Ecological Life Support System (CELSS). Long microgravity stays might require prophylaxis, whether biochemical or inertial, against bone demineralization; and protracted travel at and beyond geosynchronous orbit (GEO) demands careful shielding against both constant and acute radiation fluence. Solving just these problems reliably and elegantly will keep us busy well into the next century.

Yet, once those problems *are* solved, even primitively, they will cease to pose the dominant obstacle to space civilization. We can safely assert that before multitudes of people begin living in space, more ancient architectural issues will have superseded the technical dilemmas of putting and keeping them there. Establishing an offworld urbanism that can provide the spectrum of amenities, stimulation, and cultural support that people require of cities anywhere presents a really tough problem, beside which our incipient engineering challenges pale. The social complexities introduced by hundreds, thousands, or even millions of people living in space must come to dominate everything else. Technically on the verge of being able to keep communities alive on the Moon, we have barely begun to prepare for solving the total architectural problem engaged by doing so.

Extant but unconcerned preparation takes three forms. First, and least useful, are utopian images arising from contemporary "colonization" studies, which attempt to paint a picture of space civilization by projecting inconsistent and peculiar details. In presenting rather fixed images, they reveal more about their creators than about life in space. Second are the uncounted ideas explored in vignettted detail by science fiction. Albeit often technically bankrupt, these bring to the study of human futures beyond Earth the important advantage of having been conceived by writers generally driven to explore implications and meaning, rather than ways and means. Finally, but unwittingly, the profession of terrestrial architecture is better prepared for solving the eventually important problems of living in space than is space engineering. Only dedicated human planners supported by millennia of professional experience can hope to avoid the mannerist traps of simple visions, while still tapping the vibrant storehouse of potential futures, to realize viable and inspiring cities in space.

We must exorcise the common presumption that architecture has a "humanizing" role to play in engineering that urban landscape. We accomplish more by reversing the notion: Space engineering will in fact be but a new tool in the ancient panoply of architectural practice. Lunar urbanism must after all follow the human needs of its citizens, according to principles that no new technology, no new environment, no new gimmicks are liable to change deeply. Engineering realities of building on the Moon will provide the vocabulary but neither the diction nor syntax of lunar urbanism. Recognizing that human space engineering must eventually be absorbed by the inclusive profession of architecture allows us to see just how it will expand that profession.

Any offworld urban design will require attention to all the "conventional" architectural and planning subjects listed earlier, plus advanced CELSS, radiation management, gravitational biology, interorbital elemental mining, biomass production, material recycling, and of course the full complement of traditional disciplines peculiar to spacecraft engineering, including astronautics, propulsion, vacuum thermal management, attitude control, teleoperation, vibration and noise suppression, artificial intelligence, and redundant safety. Finally, actual planetary architecture must address further the dominant issues of launch and landing, alien planetology including local geology, weather, diurnal cycle and gravity level, and wilderness preservation. Clearly anyone intending to become conversant enough in the components of lunar architecture to perform it rigorously, responsibly, and well has an awful lot to learn. As a professional culture, we are far from ready to take on the task we so glibly imagine. Just putting people on the Moon is indeed child's play compared to establishing a mature and noble lunar urbanism.

The sudden technical and environmental enrichment with which space will infuse the second oldest profession heralds a great leap forward in human culture. For the five millennia of its civilized history, architecture has worked within a fairly parochial range of conditions. Space bursts those archaic boundaries, substituting an unprecedented set of freedoms and restrictions. Old planetary constants become parameters. Gone will be the easy dialogue between indoors and outdoors that humans have always enjoyed. Interior "exteriors" must arise, since the true exterior is lethal. The harsh rules of space and its startling allowances will change altogether the relationship between people and their environment.

By being forced unequivocally to rethink human living, we can remake urbanism beyond Earth if we proceed carefully, starting afresh with the 5000-year history of civilization as practice. Anticipating the most emphatic environmental transformation our species will undergo fuels our incessant designer's hope of improving the human condition. The promise of a pristine, indeed unsuspecting, realm affording utterly new opportunity lures us to try, yet again, generating a new standard of firm, commodious, and delightful urbanism. The Moon provides our first and most priceless chance to prove to ourselves that we can be wiser than the historical evidence shows. Most critically, the clarity with which we can treat human living on an alien world may, at long last, teach us how to protect Earth as the uniquely precious planet it is.

Given time and trial, of course, even the fuzzy problems of lunar human living would approximately sort themselves out, as they have done on Earth. We would hope, however, that foresight could limit error through planning, even though space is an utterly novel arena; not only should we aim to design there an urbanism better than any found on Earth, we must aim to do it hundreds of times quicker than the luxurious five millennia we had here. Otherwise the extravagant cost in human suffering, material depletion, and environmental destruction will be unconscionably high.

LUNAR REALITY

Having defined the scope of architecture and urbanism, and established why access to space must affect their evolution, we can look more closely at their necessary expression on the Moon. Outright lunar prophecy is a specious goal, and certainly premature. So rather than portraying arbitrary details that might

characterize one possible future, we limit instead some factual boundaries that contain all the possibilities. The abundance of misleading images of lunar civilization means that certain basic principles remain unobvious, so we outline the most probable rules that will constrain what lunar architecture must be. Not all these facts will dominate lunar life until real urban growth supplants the first vehicular and outpost phases. Nor will they necessarily remain dominant for more than a few centuries, as they neglect unpredictable material progress.

Lunar urbanism will be *densely populated* at virtually all stages of its evolution. The modern "cottage" culture allowed by Earth's environmental largess cannot be afforded in a place where every cubic meter of vital volume must be hewn (or poured, or sealed, or assembled) and sustained. Nor can suburban "homesteading" really make extensive logistical sense on the Moon. Resources for construction and life support will generally not be dissipated on anything except the densest of cities; lunar society will be almost fully urban.

The overwhelming majority of lunar civilization will depend on indigenous manufacturing techniques. Offworld imports must inevitably be rate-limited. Thus common objects will be made locally, not because supplying them from space is impossible, but because it is impractical. A specialized computer might come from space, but the chair in which the programmer sits, the snack she munches, the scrap paper on which she jots notes, and the light by which she sees must all somehow be produced on the Moon.

This pervasively local origin of lunar culture, with its corollary need to fashion a human environment from the bottom up, will excite and occupy designers for generations and prevents us incidentally from divining a complete image of it now. Some conclusions are unavoidable, though. Simplicity will favor urban transportation machines like bicycles over powered vehicles—if a few kilograms of composite can provide mobility and exercise unobtrusively, elaborate centralized transit systems are likely to be justified only for interurban traffic.

We can expect most surface buildings to be made primarily of lunar concrete reinforced with local metal, serving both structural and shielding needs with minimal industry. We can expect alloys of titanium and aluminum to be used as commonly as are steel and plastic on Earth, and we can expect glass to be everywhere. Among the easiest materials to fabricate from lunar sources, glasses of varying purities will make up everything from tunneled cavern linings and architectural elements, to structural and optical fibers. We must expect that ubiquitous products will be made as quickly, cheaply, and simply as possible from available resources. This might well mean a built landscape dominated by poured, masonry, fired, and vitreous materials. Again, these are not all the Moon makes possible, but they will be the most expedient.

Lunar architecture must be an *interior* architecture. Heavily shielded havens are required during anomalously large solar proton events (ALSPEs, or flares), and cosmic rays (which Earth's atmosphere attenuates) irradiate the lunar surface semi-isotropically and continuously; the best long-term countermeasures are not yet known. It may well be that, when not actually working, people living in space will quite voluntarily limit their unshielded exposure. No modern myth seems more immortal, yet more hollow, than the persistent image of miraculous crystalline pressure domes scattered about planetary surfaces, affording their suburban populace with magnificent views of raw space (and incidentally baking them in strong sunlight).

However, the natural landscapes of the Moon's surface and the antisolar sky will be especially attractive to human sensibility. A lunar lifestyle may evolve that restricts recreational viewing to very special times, spurring ritual, behavioral, and special surface architectures for that purpose. Primarily subterranean, then, lunar cities would be heavily top-shielded by concrete superstructures, by regolith overburden, and perhaps even by areas of untouched wilderness overlying tunneled city caverns. The planetary surface, both natural and engineered, will be the single most important architectural boundary on the Moon.

That boundary must in general also contain *atmospheric pressure*. While the enclosures inside lunar cities can be structurally rather conventional, every square meter of the hermetic city wall surface itself must withstand over 100,000 newtons of force exerted by the air within it. In fact, a regolith overburden with sufficient weight to counteract this pressure would exceed by many times the thickness required for safe shielding alone. Pressurized, lunar cities will in effect be spaceships; no other single feature argues more strongly for an economical, underground urbanism there.

Lunar life need not be troglodytic, though. Many ages of architecture, three of which provide contrasting programmatic examples, have been conceptually or explicitly interior. The urbanistic Roman Empire was conceived and executed as a sequence of controlled volumes and views that regarded all the natural landscapes it conquered and absorbed, from the Middle East to the British Isles, as alien. Imposing the same planning schemes everywhere, Romans created their own universe around themselves, civilizing it with gods of their convenience and arranging in it the ordered landscape of their choosing. Virtually all outdoor spaces in Roman cities functioned as urban "rooms" within which the public rituals of Roman society could be played out. The Roman invention of concrete allowed enclosed volumes of a truly public scale never before seen, and the legacy both of those volumes and of the street facades that surfaced and announced them remains alive today.

In the western medieval millennium following the Roman Empire, northern cold and frequent warfare conspired to produce a genuinely *interior environment*. Often little more from the outside than a densely shielded pile, medieval architecture peered out of halls and chambers through tiny slits recessed in thick masonry walls. The intellectualism of Christianity encouraged introspection, and even ornament shrank largely off the stone architecture to cloak the people instead. To the east, the old Roman extravagance became Byzantine piety, still with enormous and lavishly ornamented interior spaces but now in the service of religious mystery rather than a secular civic public. Eventually, belief inspired the West to refine its masonry construction technology to recover volume, stretching the old Roman basilica upward and flooding it with light from above. Gothic religion came to sustain an interior architecture as potent, grand, and influential as anything Roman.

Most familiarly, twentieth century North America has evolved the inclusive interior mall to compensate the automotive consumption of its natural landscape. Reverting indoors, public attention is occupied and stimulated by the mall's manufactured landscape. The consistency of its style is place-independent, making Toronto and Los Angeles essentially the same. Driven by capitalism instead of religion or conquest, this enclosed, pedestrian-scaled, and transient strip architecture will also find expression in lunar interiors.

The civic pride, inspiration, and commercialism whose built expressions we have just reviewed briefly will be among the old and new motives guiding lunar civic building. Referring eclectically to the rich human past, a pluralistic twenty-first century lunar culture will embody its own aspirations in the public interiors it builds. All types of lunar interiors will share two distinctive differences from Earth's, however. First, they must accommodate a larger scale of human movement. Although details await experience, a natural gait in lunar gravity will stride longer and hops will rise higher. Human "factors" will have a new problem to solve. Interior supporting structures, governed by economy, will be much more slender than Earth allows. Lunar architecture will therefore be lighter and seem more expansive than Earth architecture, despite its pressurized closure, its exterior shielding, and its urban crowdedness.

Lunar life will be *nonsterile*. Human beings are elaborate ecological hosts, having evolved in the septic biosphere of Earth a web of commensal and truly symbiotic interactions with other organisms. Our understanding of these relationships is too shallow, and utter sterilization too impractical anyway, to plan seriously a sterile offworld ecology. Pathogen management will be a difficult but real problem. Lunar cities themselves will host life as well. Some bacteria that metabolize by corroding metal and can live in environments extreme in temperature, pressure, radiation, and toxics will exploit niches in space. Feral pet and research animals will eventually coinhabit lunar cities, and it is inconceivable that urbanism could grow off Earth without bringing along the venerable cockroach (pigeons should be avoidable). Expansion will be too fast and quarantine too porous to prevent eggs and spores from colonizing the Moon with us.

Finally, the Moon must be a place of unprecedented demarcation between *wilderness* and human use. The ancient fixture of a town wall to distill urbanism from the countryside will recur there, not so much to protect inhabitants from the space environment, but rather to protect the natural lunar environment from human destruction. Fragile though the biosphere of Earth may be in the face of "development," we are nonetheless deeply spoiled by its resilience. The encroachment of living things, relentless weather, and finally even the inexorable tectonics of

Earth's geology condemn most signs of human action here to transience. Left alone, denuded forests and ravaged desert ecostructures can eventually recover despite appalling erosion and even toxic pollution.

The lunar wilderness, however, is truly fragile and effectively irrecoverable, despite its inanimate nature. Micrometeorite "gardening" takes millions of years to remake just centimeters of regolith. The forces that allow reclaiming strip mines and ruins on Earth simply do not exist on the Moon; the first trek through a pristine region of the Moon's unique "magnificent desolation" ruins its ineffable wilderness value practically forever. Surface exploration, strip mining, and construction will be facts of human activity on the Moon. So, sooner or later, will be human demands for utter preservation of untouched wild regions. The small planetary size of the Moon, which makes preventing its total use more urgent, also will aid that effort since its close horizon isolates areas visually. Wilderness appreciation cannot be participatory on the Moon the same way it is on Earth. The solace and renewal afforded by contemplating wilderness will induce radically new forms of urban design and specialized architectures to accommodate that human need on the Moon.

The few fundamental properties of lunar architecture and urbanism reviewed here grow directly out of facts as intrinsic to the Moon as weather is to the Earth. By accepting them as boundary conditions, our projections of the incipient, built human lunar environment can be more apt and more useful for planning our future. No rule, after all, prevents rigorous designs from being as exciting, as romantic, and as inspirational as specious ones. Many people, whether professional designers, authors, illustrators, engineers, explorers, leaders, or planners, are thrilled by thinking about living in space and on the Moon. Now is the time to inject realism into those thoughts. By starting from a few accurate principles—that lunar urbanism will be primarily *densely populated, interior, and nonsterile*; that it and the civilization it reciprocally defines will be pervasively *indigenous* in its materials and themes; and that lunar *wilderness* is irreplaceably precious—those who do plan can contribute meaningfully to realizing responsibly one of the grandest projects ever imagined in human history.

