

THESIS REPORT  
2026

# Biomorphed

Lunar Lava Tube habitat

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Computationally based Biophilic Design  
for Astronaut Well-being

**Project Title**

E.D.E.N. | Extended Duration Extraterrestrial Nest

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# ABSTRACT

In anticipation of humanity's return to the moon and broader pursuit of space colonisation, extraterrestrial architecture is becoming increasingly relevant. Lunar habitat design faces significant hurdles, mainly prohibitive transportation costs, extreme environmental hazards (such as vacuum exposure, extreme temperature fluctuations, radiation and abrasive dust), as well as the significant psychological toll of long-term isolation in high stress environments. This thesis project addresses these challenges by synthesising structural resilience with inhabitant well-being.

This research explores how biophilic design principles can be integrated with In-Situ Resource Utilization (ISRU) additive manufacturing in the design of a Lunar lava tube habitat on the Lunar South Pole, with the aim of improving astronaut well-being. The lava tube acts as a natural barrier against some of the environmental hazards, while ISRU through Selective Laser Melting (SLM) reduces the reliance on terrestrial resources.

The habitat's morphology is generated through computational L-systems, producing an organically branching spatial hierarchy that facilitates efficient circulation, life-support integration, and compartmentalisation for safety. This system is enclosed within metaball volumes that are optimised using Karamba to manage internal atmospheric pressure while providing a dynamic and organic interior landscape. Internally, the design maximises Indoor Environmental Quality (IEQ) through circadian lighting and the integration of plant life to resemble Earth's environment.

By synthesising biophilic design principles with additive manufacturing, this project proposes a human-centric approach to lunar habitats that prioritises astronaut well-being.

## Keywords

Lunar Architecture, ISRU, 3D Printing, Biophilic Design, Mental Health, Habitat Design

## FOREWORD

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## AI STATEMENT

In the production of this report, AI tools like Gemini and ChatGPT were used. Their tasks include: Literature research, proofread for spelling and grammar, improving readability and structure. These tools also provided some technical support for Rhino and Grasshopper scripting logic. However, all ideas, models, and project images are my own.



“I know the sky is not the limit  
because there are footprints on the Moon”

Buzz Aldrin - Second man on the moon

# TABLE OF CONTENTS

## INTRODUCTION 8

Problem Statement 10

Relevance 11  
International Missions 11

## MOTIVATION 12

Objective 12

Research Question 12  
Sub-Questions 12

SCOPE 13  
Mission Context 13  
Construction 13  
Architectural Design 13

## APPROACH 14

Method 16

site research 16  
Lunar South Pole - Water Ice 16  
Shackleton Crater - Sunlight 17  
Site Conditions 17  
Lunar Lava Tubes 19

Lunar Movement 20  
How does Lunar Movement compare to on the Earth? 20  
How might this affect the design? 20

Isru 22  
Soil Composition 22  
Regolith Collection 23  
3D Printing Method 23  
Case Study - TECLA 24

Biophilic Design 26  
Definition 26  
Nature in the Space 26  
Nature Analogues 26  
Nature of the Space 26

Mental Health & Comfort 28  
Astronaut Mental Health 28  
Sick Building Syndrome 28  
Indoor Environmental Quality 28  
Biophilic Integration 29

<b>L-System</b>	<b>30</b>
Definition and Computational Logic	30
Biophilic Integration	30
Organizational Benefit	30
Case Study: Greg Lynn – Cardiff Bay Opera House	31
<b>Metaballs</b>	<b>32</b>
Definition and Computational Logic	32
Biophilic Integration	32
Structural Optimization	32
<b>RESULTS</b>	<b>34</b>
<b>Programme</b>	<b>36</b>
<b>Bubble Diagrams</b>	<b>37</b>
Text	37
<b>Fragment</b>	<b>38</b>
L-system & Metaball integration	38
<b>Form Finding</b>	<b>40</b>
Kramaba Metaball Analysis	40
Window / Porosity	41
<b>Interior Case Studies</b>	<b>42</b>
Chapel of Sound - OPEN Architecture	42
Fondazione Luigi Rovati - Mario Cucinella Architects	42
<b>Interior Studies</b>	<b>43</b>
<b>CONCLUSION &amp; DISCUSSION</b>	<b>44</b>
<b>REFERENCES</b>	<b>46</b>
REFERENCES	48
Literature	48

PART 1

# INTRODUCTION





National Aeronautics and Space Administration. (1969, July 16). Apollo 11: View of Moon limb with Earth on the horizon [Photograph]. <https://images.nasa.gov/details/as11-44-6550>

# PROBLEM STATEMENT

Humanity stands on the precipice of space colonisation. The NASA and ESA Artemis missions serve as a critical precursor to long-term lunar habitation (NASA, 2025). With it comes the architectural challenge of moving beyond basic habitats for survival and towards the creation of homes amongst the stars.

This transition, however, comes with an abundance of challenges. Firstly the logistics of building and maintaining lunar habitats is extremely costly. At a price estimation of \$1,000,000/kg (SOURCE), transporting material to the moon is impractical. To achieve economic viability and sustainability, we must pivot towards In-Situ Resource Utilization (ISRU). This allows us to leverage materials found on site to reduce reliance on Earth.

Secondly, the Moon's inhospitable vacuum environment lacks atmospheric protection. Subsequently, the surface is plagued by abrasive lunar dust, moonquakes, micro-meteorites, deadly radiation, solar wind, long lunar nights and intense temperature fluctuations (SOURCE).

While Lunar lava tubes offer natural shielding against some of these threats and temperature fluctuations, careful design considerations will have to be made to insure survivability.

Lastly, the psychological toll of long-term isolation in high-stress, cramped environments poses a significant threat to mental health, necessitating a move towards human-centric design. Research indicates that long term space missions can impact mental health through emotional dysregulation, disrupted sleeping rhythms, cognitive dysfunction, etc. (Arone et al., 2021). This is where biophilic design principles can be incorporated in the architecture to help improve well being.





# RELEVANCE

## International Missions

The Artemis missions (NASA, 2025) and the ESA's Terra Novea 2030+ Strategy (European Space Agency, 2022) mark humanity's long-awaited return to the moon since the first landing in 1969. Unlike the short-term exploratory sorties of the Apollo era, these missions aim to establish a sustained presence on and around the lunar surface, serving as a critical 'stepping stone' toward the eventual colonization of Mars.

To ensure we are ready when the time comes, a shift is needed in the architectural language of space habitats. Fundamentally, the ISS is utilitarian and sterile, focused mainly on survival and functionality. However, simply 'surviving' should not be the sole metric of success for a habitat, we want to create permanent homes that allow users to thrive. By focusing on wellbeing through biophilic design we develop the technical and psychological knowledge necessary for humanity to become a truly multi-planetary species.

## UN Sustainable Development Goals

Looking a little closer to home, the UN Sustainability Goals (United Nations Development Programme, n.d.) offer a lens through which the project also gains relevance back on earth. In the past innovations in space have been applied directly to everyday life on Earth.

The extreme constraints of the lunar environment act as drivers for innovations that can be implemented across the built environment and beyond. Innovations in space remain highly relevant and applicable to Earth, the ball point pen for example was originally developed for use in space.

**UNSDG 3 (Good Health and Well-being):** The isolation of space necessitates a mastery of biophilic design to improve indoor comfort and mental health. These design principles can help provide a framework to improve health in high-density or isolated urban environments.

**UNSDG 9 (Industry, Innovation, and Infrastructure):** The shift toward Design-to-Robotic-Production moves the construction industry away from manual and towards automatic construction. An innovation that could make the industry much more efficient and broaden construction possibilities.

**UNSDG 11 & 12 (Sustainable Cities / Responsible Production):** Using In-Situ Resource Utilization (ISRU) is the ultimate form of circularity. By eliminating the waste from transporting materials from Earth and utilising 3D-printed regolith, we model a construction philosophy that prioritizes material efficiency and zero-waste manufacturing. Moreover, the net-zero nature of the habitat ensures circularity in the resource usage during the building's use as well.

# MOTIVATION

The challenge and novelty of lunar architecture is what drove me to do this graduation course. Space is the ultimate frontier and can be a driver for architectural innovations. Specifically the advancement of ISRU 3D printing and robotic manufacturing are methods that can be transferred here on Earth to help combat the housing crisis and make architecture more sustainable.

Moreover, my focus on biophilic design grounds the project in tangible design practices that are directly applicable in terrestrial projects. In the aftermath of Covid-19 the importance of healthy indoor environments has become increasingly apparent for both mental and physical health of users.

# OBJECTIVE

The primary objective of this thesis is to design a lunar habitat within a lava tube that promotes long-term habitability and astronaut well-being through biophilic design principles. This research explores the synthesis between biophilic design robotic manufacturing and In-Situ Resource Utilization, aiming to contribute both to the future of space habitation while providing transferable insights for terrestrial projects. Some sub-objectives include:

1. Identify how organic shapes can be 3D printed on the moon and outline the construction steps using robotic manufacturing.
2. Optimise circadian health and psychological wellbeing through the biophilic design of lighting and spaces.
3. Incorporate design considerations to leverage low gravity construction and make human movement more intuitive inside the habitat.
4. Design a habitat that can support a 6 astronaut team in achieving their research missions and staying both mentally and physically healthy during the mission.

# RESEARCH QUESTION

How can biophilic design principles be adapted to a lunar lava tube habitat using ISRU 3D-printed architecture to support astronaut mental health and well-being?

## Sub-Questions

- What is biophilic design?
- What is ISRU and why is it important for lunar base development?

- How can 3D printing be leveraged for biophilic design?
- How does biophilia improve mental health and wellbeing?
- What are the challenges of living on the moon?
- To what extent do lava tubes provide protection against the moon's environment?
- How can computational design be applied when modeling the structure to get a more biomorphic design?

## SCOPE

The scope of this thesis is defined by the architectural and technical requirements of a second-generation lunar settlement, specifically moving towards long-term habitation.

### Mission Context

**Location:** The site will be located at the Lunar South Pole near the Shackleton crater. The design is situated inside an undefined lunar lava tube.

**Timeline:** This project focuses on long-term missions and occurs after the first lunar bases have been established. It therefore moves beyond utilitarian survival-focused design of short term missions and more towards human-centric design.

**Occupancy:** The habitat is designed for a 6-person crew, staggering rotation of 3-person teams to ensure continuous knowledge transfer.

### Construction

**Robotic Manufacturing:** The design will assume a full reliance of robots for manufacturing on site. Although the project will outline the steps and design considerations for construction, its focus does not lie on robotics and their exact workings.

**ISRU:** The construction materials are limited to what can be harvested on-site. Therefore, the main construction material is lunar regolith

**3D-Printing:** The building will be constructed using the Selective Laser Melting (SLM) of lunar regolith as its primary manufacturing process.

### Architectural Design

**Biophilic Design:** Primary focus of the design is to integrate biophilic design principles and mitigate mental and physical health degradation

**Technical Systems:** The scope includes essential elements like Life Support Systems (LSS) ensuring that the habitat meets the requirements for lunar survival.

PART 2

# APPROACH





National Aeronautics and Space Administration. (1969, July 20). Apollo 11: Close-up of astronaut's foot and footprint in lunar soil [Photograph]. <https://www.nasa.gov/image-detail/amf-as11-40-5880/>

# METHOD

To answer the research question, this report will start by collecting background knowledge through literature and case studies. Literature will be collected through recent sources due to the fast developing nature of robotic manufacturing. However, for lunar soil data may be sourced from older papers as we have not yet been back to the moon.

Once the theory is established, they will be utilized in the design stages. By exploring through sketches, maquettes, digital models and computational workflows, this project wil aim to answer the research questions.

# SITE RESEARCH

## Lunar South Pole - Water Ice

The Artemis missions aim to land on the Lunar South Pole because of the presence of exposed water ice. Due to the tilted rotational axes of the Moon the sun sits quite low on the horizon. Subsequently, crater floors become permanently shaded regions that act as cold traps with temperatures under 110 K, preventing the sublimation of water and allowing for accessible accumulations of water ice (Li et al., 2018). These deposits are essential for Lunar Missions as they are a vital resource for both life-support and fuel through hydrogen.

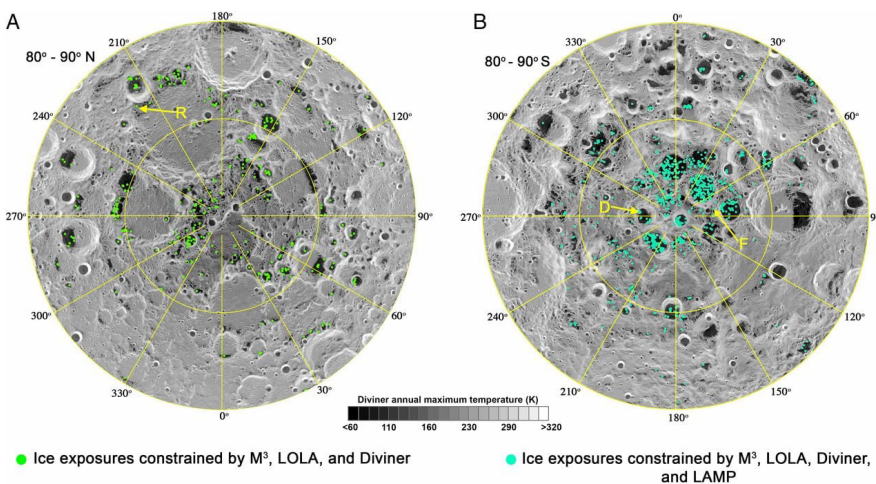
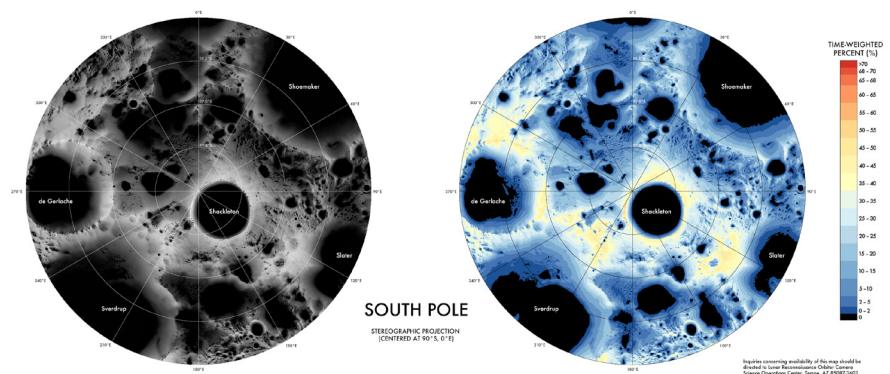


Figure x: Distribution of water-ice-bearing pixels on the Lunar South Pole (Li et al., 2018)

## Shackleton Crater - Sunlight

Another critical resource is sunlight, without it the habitat can't be powered through solar energy. Due to the low horizon sun, there are no permanently illuminated areas in the South Pole (Speyerer et al., 2013). However, select sites, like the rim of the Shackleton Crater, are situated high enough to receive longer periods of solar illumination. These sites are ideal for future bases and research as they have both a proximity to shaded and unshaded regions.

Figure x: Illumination on the Lunar South Pole (<https://roc.im-ldi.com/images/downloads>)



## Site Conditions

Establishing lasting lunar habitats requires protecting the astronauts from the hostile environment.

### Vacuum:

The absence of atmospheric pressure results in the moon having a vacuum environment. Subsequently, the habitat will require pressurisation and must be resistant to the resulting forces acting on the building's envelope.

### Temperature fluctuations:

During the day the mean surface temperature is around 107°C, while at night it drops down significantly to -153°C (Heiken et al, 1991, p. 28). These extreme fluctuations will require habitats to have good thermal insulation. Moreover, any material or building process used will have to be resistant to these extreme fluctuations.

### Radiation:

Without magnetic or atmospheric shielding, the surface is fully exposed to UV radiation, galactic cosmic rays (GLR) and solar particle events. This poses a significant threat of increased cancer risk and necessitates the need for protective radiation shelters (Reitz et al., 2012).

#### Micrometeoroids:

Without air resistance meteoroids don't burn up or slow down like they do on earth, allowing them to strike at full velocity and risk damaging structures. Estimates suggest that micrometeoroids are expected to hit large structures almost yearly, with strikes from bigger ones being less frequent than smaller ones (Heiken et al, 1991, p. 46). The velocity of micrometeoroids can range from 3-70 km/s, averaging with an impact velocity of 20 km/s (Allende et al., 2020).

#### Seismic Activity:

Seismic activity on the moon is relatively low, but long lasting. Data from the Apollo missions registered quakes at a Richter equivalent magnitude of 1.5 up to a 5.5 maximum (Watters et al., 2024). These can be felt but leaves relatively little damage. For well designed structures this should pose a low risk.

#### Gravity:

The mass of the moon is significantly smaller than the earth. Subsequently, the force of gravity on the moon is only 1.62 m/sec<sup>2</sup>, which is about 1/6th of what we experience on earth (Heiken et al, 1991, p. 28). This can unlock some opportunities in constructions as the compressive force on materials will be much lower, allowing for taller buildings and longer spans.

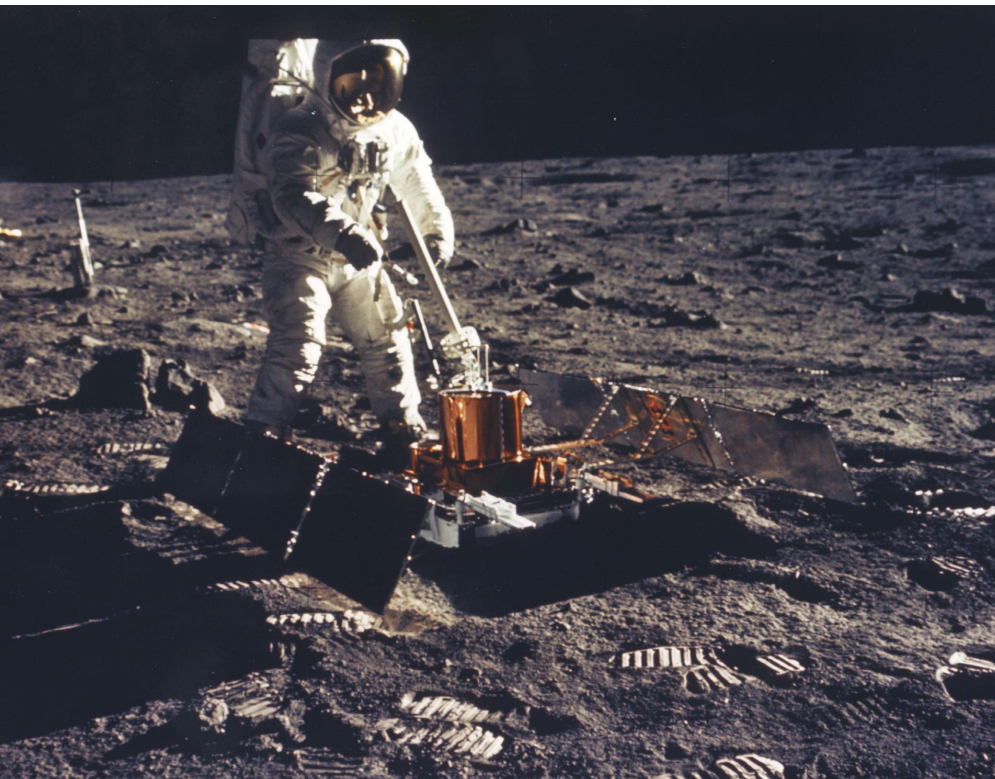


Figure x: Deployment of the Passive Seismic Experiment Package (PSE) to gather data on moonquakes, landslides and micrometeorite impacts

## Lunar Lava Tubes

Like the first humans on Earth, those on the Moon may also inhabit caves. Although yet unexplored, lunar lava tubes are theorized to be present underneath the surface. Lava tubes on the moon are much bigger than those on earth, with tubes theoretically being stable at 1 km wide with only a 2m thick roof, the largest theorised ones can go up to 5 km wide (Blair et al., 2017)

Entering these tubes through collapsed openings offer a place to build with natural shielding against radiation and micrometeorites, drastically reducing the required thickness of the habitat walls. Moreover, due to the thermal massing and protection these tubes have a much more stable temperature than on the surface at around  $-20^{\circ}\text{C}$  (Angelis et al., 2002).

Figure x (Right) : Diagram showing the spatial distribution of the effective dose equivalent (radiation risk) is a Lunar lava tube. (Naito et al., 2020)

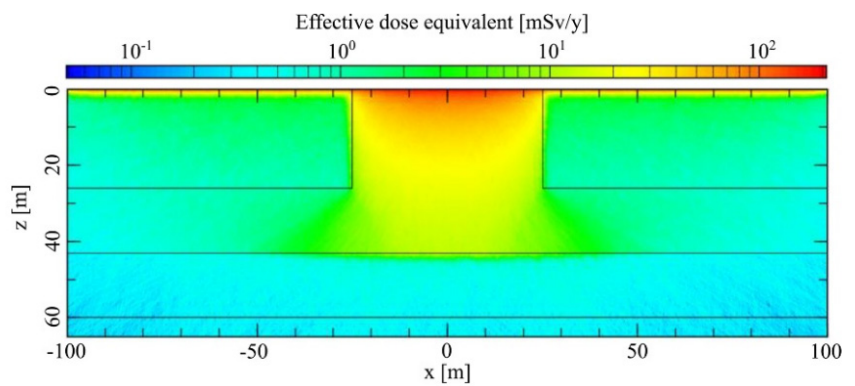
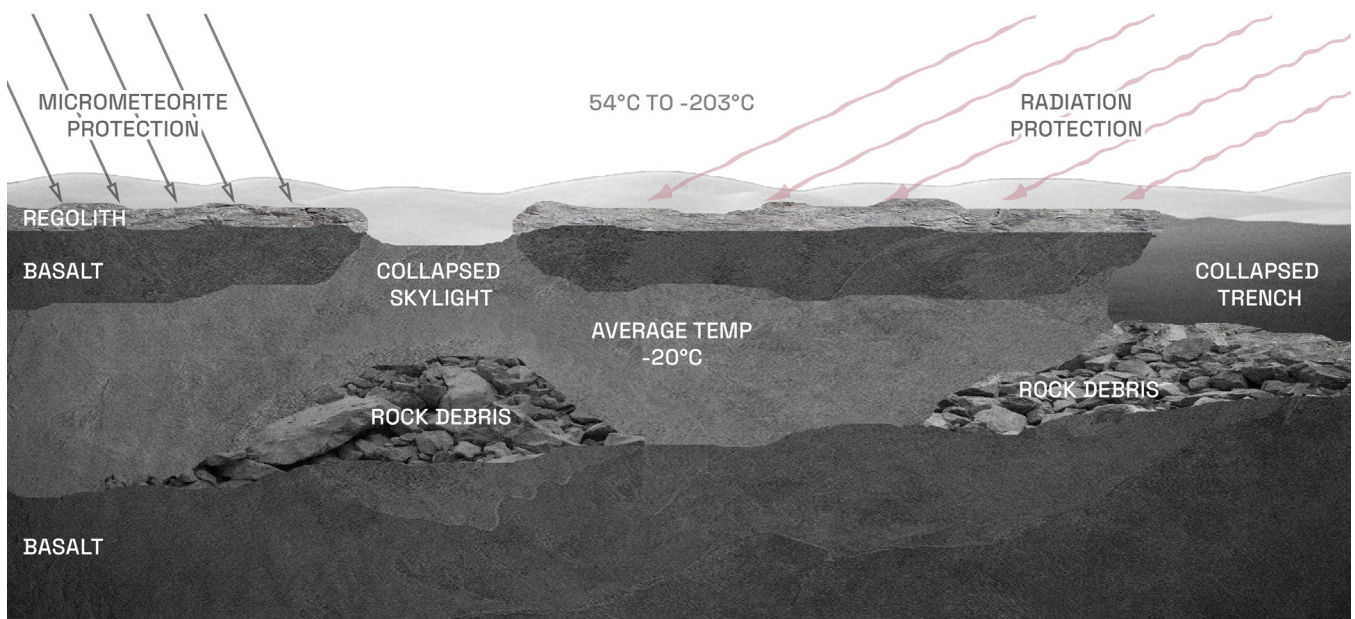


Figure x (Below): Diagram showing the sheltering properties of Lunar lava tubes against micrometeorites, radiation and temperature fluctuations (own work)



# LUNAR MOVEMENT

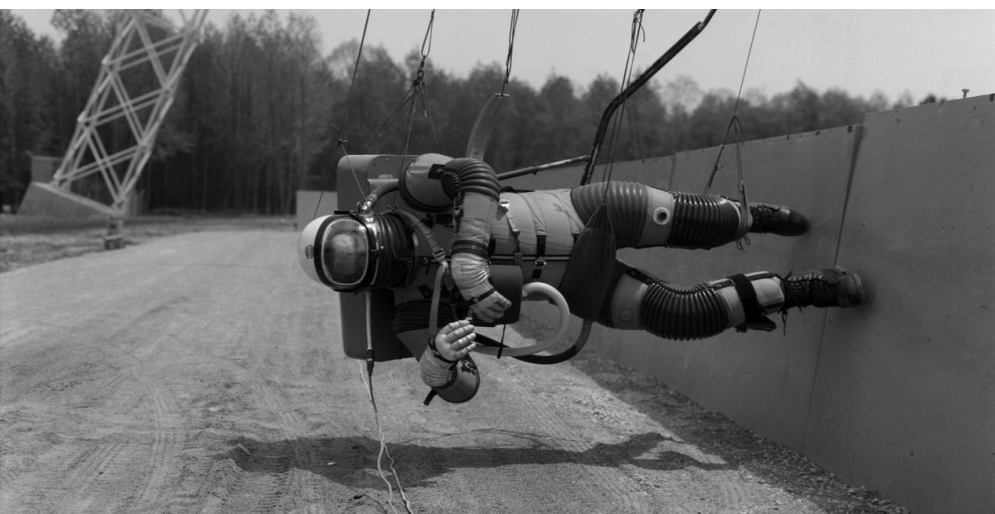
## How does Lunar Movement compare to on the Earth?

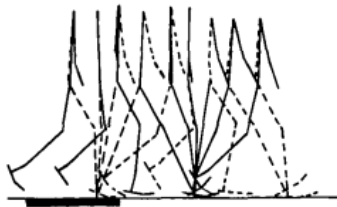
The Moon's gravity is about 1/6th of that on Earth. A study was done by Harris et al. (1966) to compare human movement on earth vs simulated lunar gravity. It made the following conclusions about movement on the Moon:

- Max. walking and running speeds ~60% of that on earth
- Lunar stride is greater and has a lower step rate than on earth
- Most comfortable loping gait was about 3 m/s compared to 1.2 m/s on earth
- Subjects tended to walk more stiff-legged with less flexing in the knees
- Subjects leaned forward more and swung their legs further forward

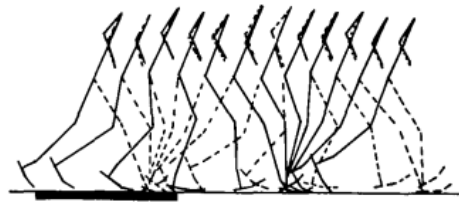
## How might this affect the design?

- Higher ceilings to accommodate bounding gait
- Higher step on stairs as gravity is lower
- Ramps might be preferable
- Railings to prevent falling forwards
- Texturised floor for extra friction and grip to compensate for the lower gravity



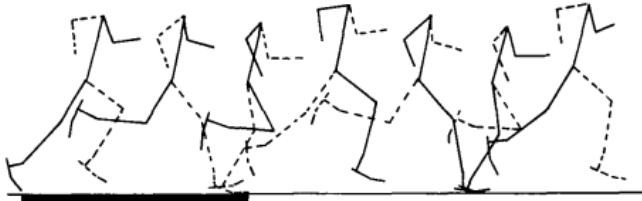


Earth gravity, 4.0 ft/sec (1.22 m/sec)

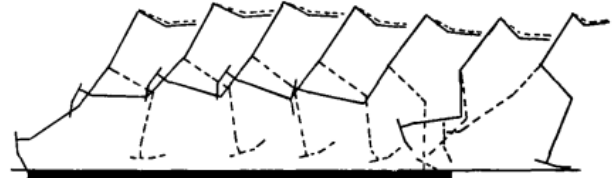


Lunar gravity, 4.1 ft/sec (1.25 m/sec)

(a) Walk.

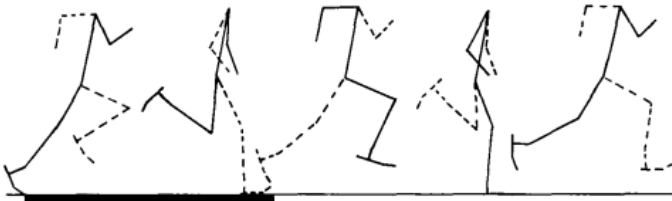


Earth gravity, 10.0 ft/sec (3.01 m/sec)

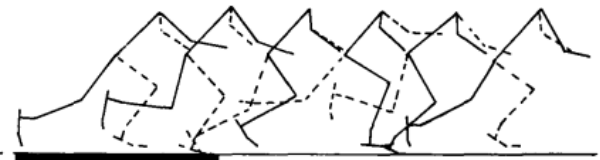


Lunar gravity, 10.5 ft/sec (3.20 m/sec)

(b) Lope.



Earth gravity, 19.8 ft/sec (6.04 m/sec)



Lunar gravity, 13.1 ft/sec (3.99 m/sec)



Figure x (Top): Stickman representation of typical walk, lope, and sprint in earth and lunar gravity (SOURCE)

Figure x (Far left): Reduced gravity walking simulator (SOURCE)

Figure x (Close left): Astronaut leaps on the lunar surface (SOURCE)

## Soil Composition

In-Situ Resource Utilization (ISRU) is the practice of harvesting, processing, leveraging and storing materials found on-site. The Moon's surface contains the fundamental building blocks necessary to support long-term missions through ISRU (Zhang et al., 2023). Water and oxygen for life support, regolith, metals and silica for construction, and hydrogen, oxygen and methane for rocket fuel. Especially the top layer is of interest as it consists of a layer of unconsolidated debris caused by constant bombardment of the lunar surface (Heiken et al, 1991, p. 285). This loose top layer consists of fine dust-like particles that can be easily mined and collected.

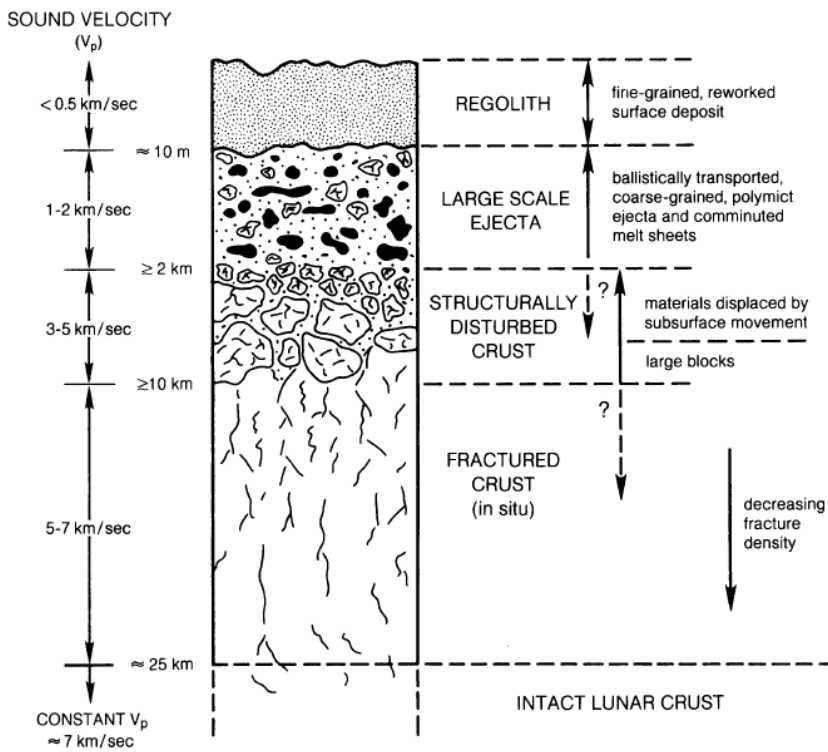


Figure x: Lunar surface layers (Heiken et al., 1991)

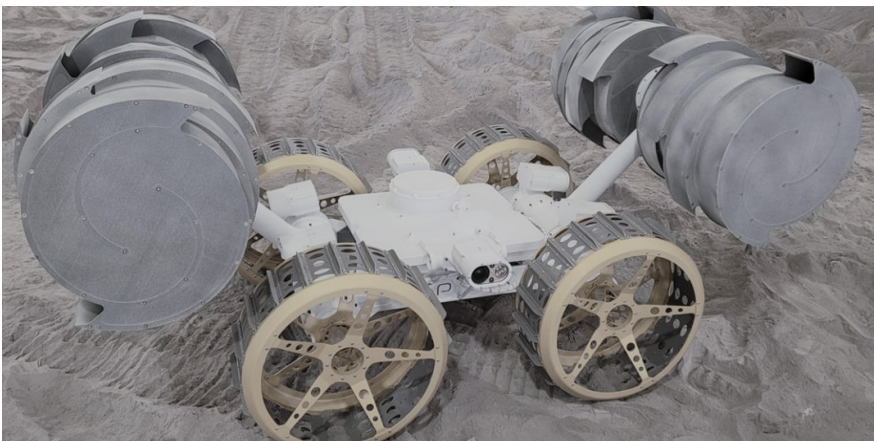


Figure x: Regolith collection robot (SOURCE)

## Regolith Collection

In order to collect the regolith top layer for processing and sintering, NASA has designed a robot with counter-acting bucket drums. This project will also utilise this robot type for its regolith mining.

## 3D Printing Method

Once the regolith is collected it can be used to 3D print structures. However, due to the vacuum conditions and ISRU nature, some additive manufacturing techniques can't be used as they require an external binding agent. Therefore the best methods would be to use Powder Bed Fusion that fuses powdered materials layer-by-layer through lasers (Chen et al., 2019). This would only require the powder (regolith) and a laser that can be powered by solar energy.

There are two types to consider: Selective Laser Sintering (SLS) and Selective Laser Melting (SLM). With SLS the regolith would be heated just below the melting point to fuse its grains through sintering. However, research indicates that this method results in more porous results when done in a vacuum, leading to reduced mechanical properties (Agapkin & Slyuta, 2025)

SLM requires significantly more energy than SLS as it heats the material above its melting point. However, the advantage of this is that it also cools more rapidly and can have multiple passes, reducing porosity. To achieve this dense, glass-like product, the regolith must be completely melted at 1500 °C, giving it a compressive strength of around 125 MPa (Guo et al., 2025).

Figure x: SEM image of lunar simulant powder, (b) Sintered part embedded within a molten zone, (c) Fully melted and resolidified part. (Fateri & Gebhardt, 2014)

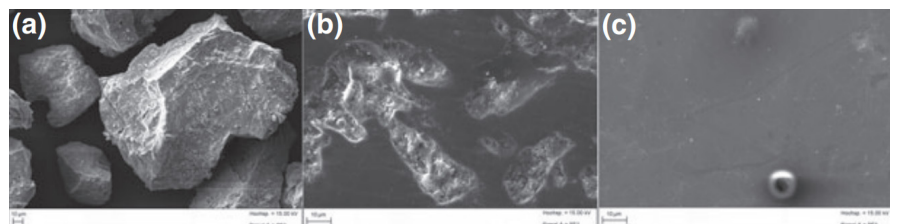
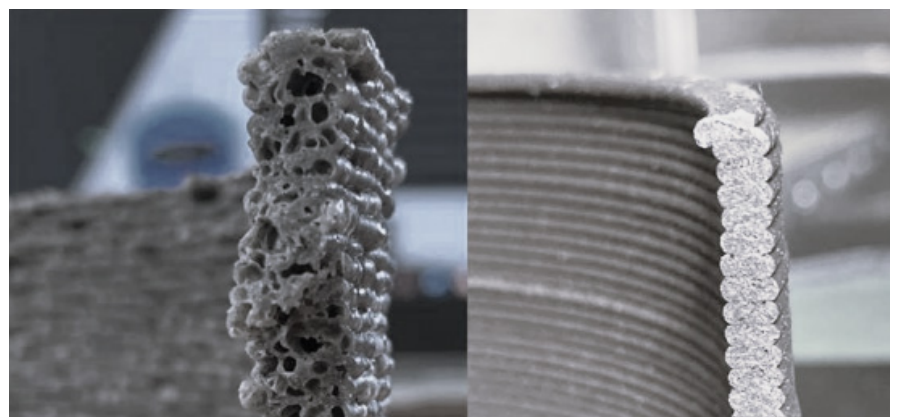


Figure x: Porous vs dense 3D printed regolith simulant under vacuum conditions (SOURCE)



## Case Study - TECLA

This 3D printed structure is an example of what can be achieved. Although TECLA by Mario Cucinella Architects used a different type of AM, it is still relevant. Note how well it achieves organic shapes and is designed to seamlessly integrate lighting.

Moreover, the design of TECLA utilised biophilic principles through its integration of nature, lighting and soft organic shaping. The large openings and indoor tree also connect it to nature. Overall, the design maximises the relationship between AM and biophilic design to give it a calming sense of refuge and rest.



Figure x: TECLA View From Outside



Figure x: TECLA View from the connection point between the volumes

Lastly, the facade was printed with a very unique pattern. Something that could also be applied to other surfaces in the habitat. A study by Vertico showed that surface patterns can be 3D printed to give acoustic benefits.

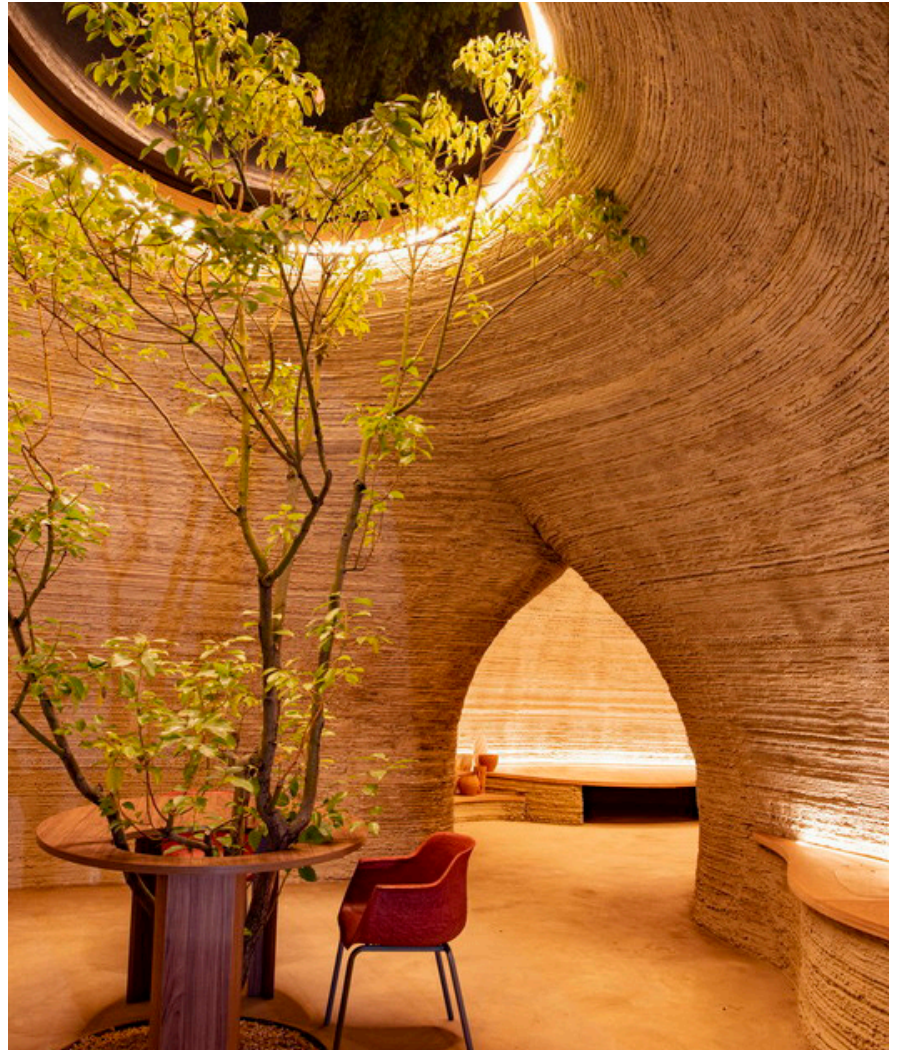


Figure x: TECLA living room with integrated greenery and lighting



Figure x: TECLA bedroom with circular skylight and stepped organic plateau

# BIOPHILIC DESIGN

## Definition

An approach to architecture and interior design that connects people with nature within built environments, using natural elements, forms, and processes to improve human health, well-being, and productivity, stemming from our innate love for nature.

Biophilic Design as a framework can be divided into three clusters: Nature in the Space, Natural Analogues and Nature of the Space (Ryan et al., 2014,).

## Nature in the Space

Nature in Space refers to the direct physical presence of nature within space. This includes elements like plants and water, but also sensory stimuli like sounds, temperature, humidity, light and touch.



Figure x: Prototype for a Lunar/Mars greenhouse

## Nature Analogues

This category focuses on more indirect representations of nature, by mimicking nature in the built environment through the use of shapes, patterns and processes.

## Nature of the Space

The last category refers to how the configuration of a space can mimic the experiences found in nature. This can be boiled down to 4 types of experiences.

Prospect refers to having a view over a large distance, allowing you to survey the area and look at what may lie ahead.

Refuge offers a place to withdraw and feel protected. It is an area that may be partially or fully obscured to give the user a sense of calm.

Mystery comes through partially obscured views, hints of other rooms entices the user to explore a space, making it more dynamic.

Risk/Peril comes through identifiable threats, in architecture this is often through height. This sense of danger is meant to give the user thrill and fascination.

# MENTAL HEALTH & COMFORT

## Astronaut Mental Health

Long term space habitation places crew in isolated, confined and high-stress environments for an extended duration. It is also monotonous living with the same small crew in an unchanging environment. For astronauts this can cause mental health and well-being to deteriorate (Arone et al., 2021)

## Sick Bulding Syndrome

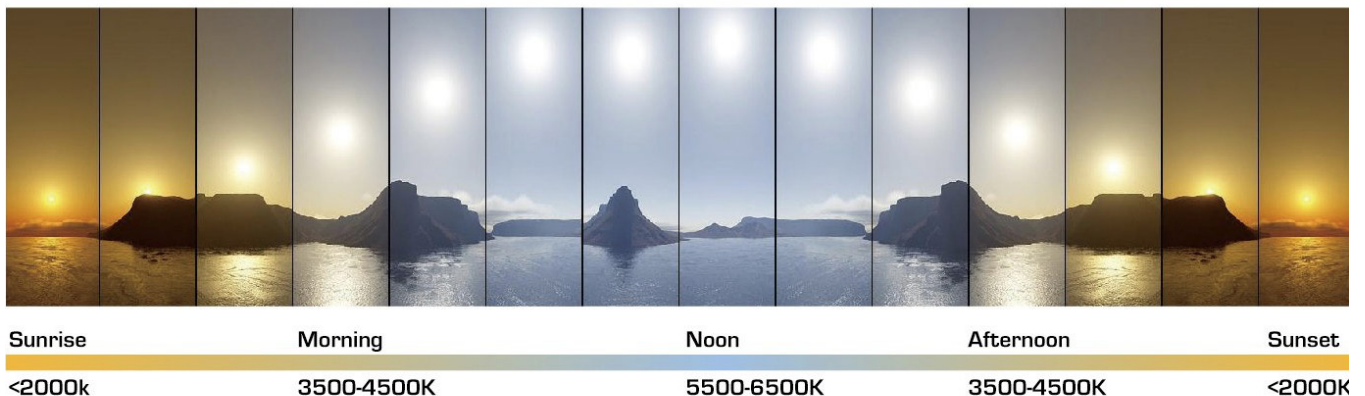
Sick Building Syndrome occurs when the health and comfort of inhabitants are compromised by the time spent in a building, often due to factors like lighting, air quality, temperature and noise (Rostron, 2008). This phenomenon is especially relevant to space architecture as astronauts remain confined within the habitat for the entirety of their mission duration . To prevent the habitat from becoming a source of illness, biophilic design must be integrated to help improve mental health and well-being.

## Indoor Environmental Quality

In order to gauge the health and comfort of the habitat, the Indoor Environmental Quality (IEQ) will be used as a guide for biophilic.interventions. By aligning biophilic strategies with this framework the design will respond directly to the theorised causes of SBS.

Lighting: The Moon does not follow the 24-hour solar cycle, disrupting the crew’s circadian rhythm and subsequently their cognitive performance and sleep. Through the integration of lighting that changes color and intensity throughout the day, the habitat can mimic the feelings of different periods in the day to allow our biological clock, productivity and sleep to be optimised (SOURCE).

Figure x: Different natural lighting colors throughout the day



Air quality: Indoor air quality is another important consideration. Although mechanical scrubbers can filter the air and keep oxygen levels optimal, the NASA Biohome experiment (Johnson, 1990) has also shown that plants can act as natural air filters. This is especially attractive for space habitats as they require less energy, require little maintenance and can double up as food production (Wolverton & Nelson, 2020).

Acoustic comfort: Dense, 3D-printed regolith domes behave similarly to concrete and can cause sound to create harsh echoes that reflect rather than scatter and be absorbed (SOURCE). By implementing an acoustic pattern or plant life into the walls, acoustic fatigue can be reduced.

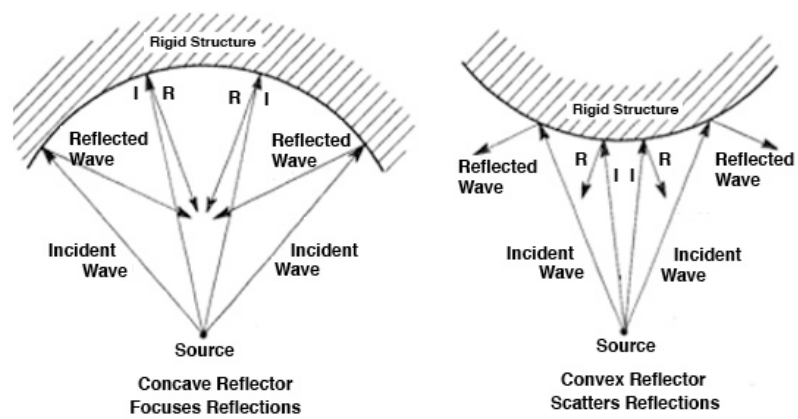


Figure x: Diagram showing how concave dome shapes reflect and focus sound back to the source (<https://www.sfu.ca/sonic-studio-webdav/cmns/Handbook%20Tutorial/Sound-Environment.html>)

Thermal comfort: The Moon's vacuum environment makes it difficult to shed excess heat from electronics and humans. Subsequently, the habitat can utilize thermal mass from the structure and ground as well as indoor plant transpiration to help cool the habitat naturally (SOURCE), reducing the cooling load of the structure.

### Biophilic Integration

To improve mental health & comfort the habitat design should respond to the following properties through biophilic design:

- Non-monotomous, dynamic spaces
- Private & public area separation with the ability to retreat
- Acoustic comfort
- Thermal comfort
- Lighting Quality
- Air quality

# L-SYSTEM

## Definition and Computational Logic

L-systems, or Lindenmayers systems, are a mathematical method to model the growth process of plants (Prusinkiewicz & Lindenmayer, 2012). It defines an initial axiom and set of rules which are applied iteratively to create complex, branching structures. In this project an L-system is used computationally to serve as the primary organisational framework of the habitat.

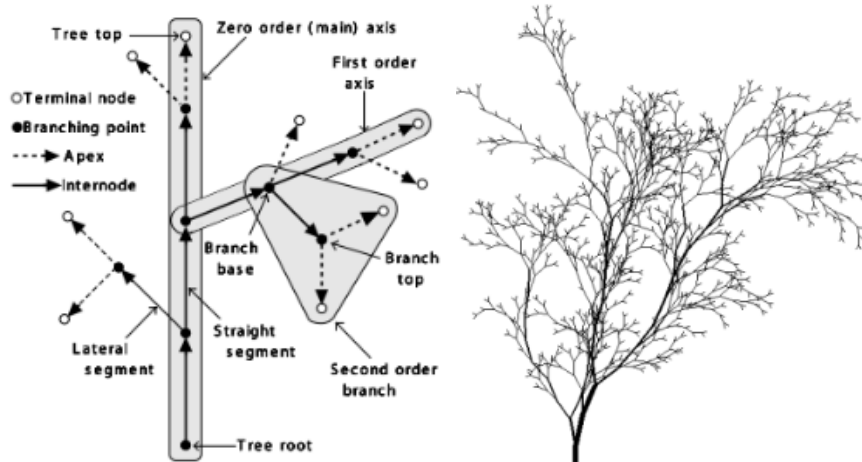


Figure x: L-system branching behaviour and rules

## Biophilic Integration

L-systems apply biomimicry to model plant growth. This is particularly relevant for humanity's long-term goal of living on the Moon. Due to the inherently recursive nature of L-systems, the habitat would be designed for modular expansion. As crew sizes expand, the habitat could generate new branches for additional living areas to form one large interconnected system.

## Organizational Benefit

Organisationally, the L-system offers numerous benefits. The central branching system creates an efficient pathing for both circulation and technical piping and wiring. Moreover, the branching naturally forms sections in the design. The transition nodes between branches provide ideal locations for pressure-sealing doors to compartmentalize the habitat for safety in case of a fire or structural breach.

Lastly, the L-system also creates an intuitive spatial hierarchy as branches subdivide and decrease in scale. This facilitates a natural transition from larger social spaces to smaller private ones.

## Case Study: Greg Lynn – Cardiff Bay Opera House

Greg Lynn's proposal for the Cardiff Bay Opera House serves as a precedent for utilizing L-systems as a generative architectural tool. In the design, recursive branching was applied to a set of ovals to establish the building's rough footprint. This system facilitated a clear spatial hierarchy, where the varying scales give each branch a distinct spatial quality that guide functional distribution. After some architectural refining, the resulting diversity in volume and ceiling height give the building a dynamic interior landscape.

Figure x: L-system branching using ovals

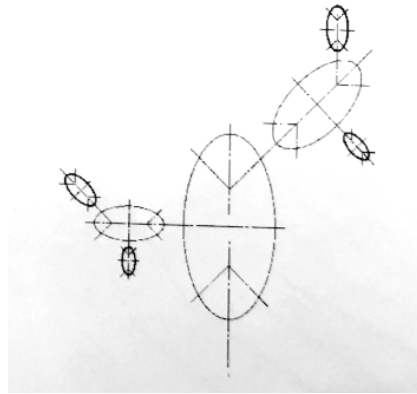


Figure x: Adjusted L-system logic as the building's footprint

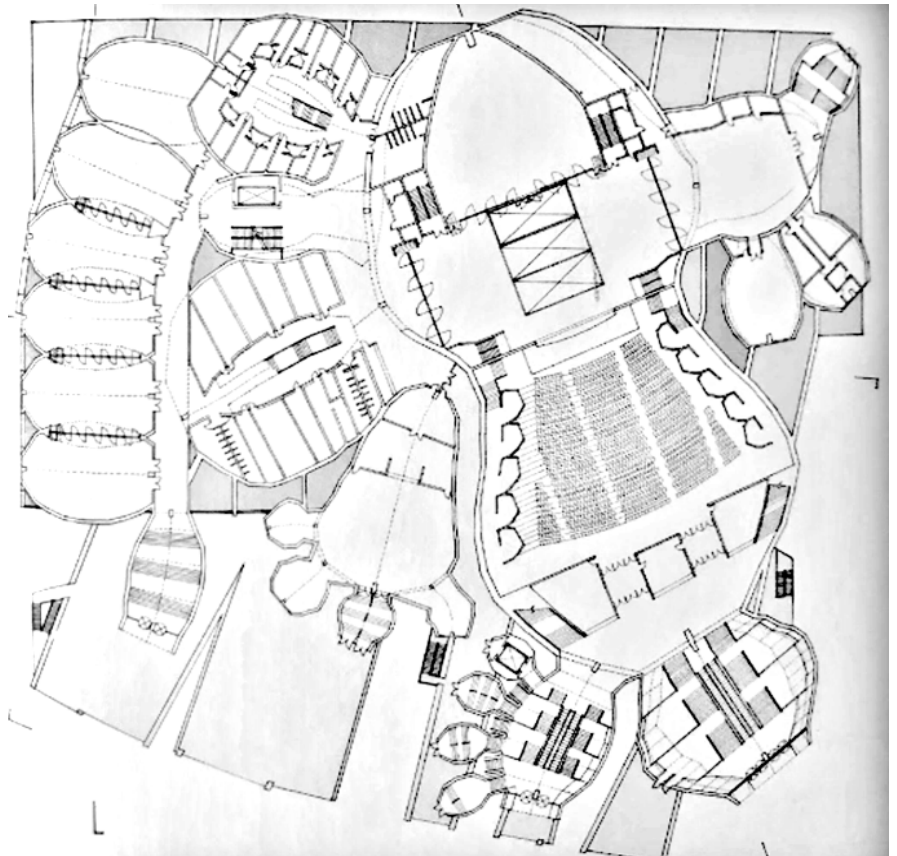
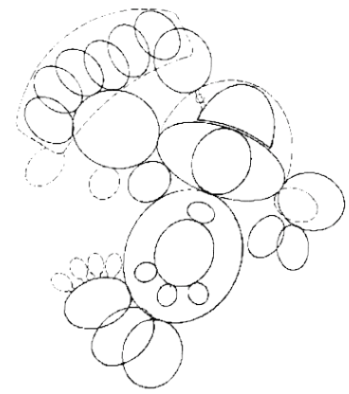


Figure x: Architectural plan drawing of the design proposal

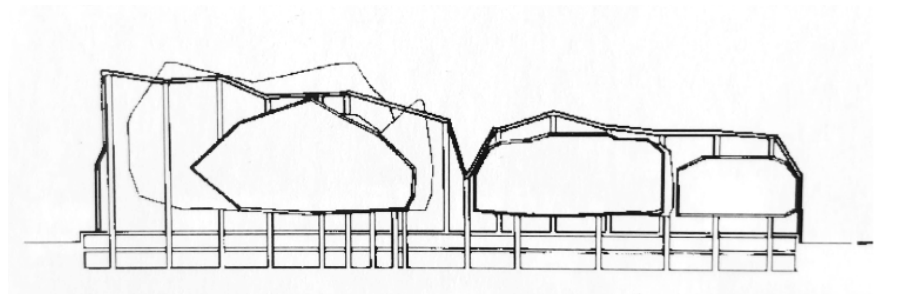


Figure x: Section showing the varying height and room sizes

# METABALLS

## Definition and Computational Logic

While the L-system defines the pathing of the building, metaballs provide the computational system that generates the building's volume. Metaballs are defined as n-dimensional iso-surfaces that are defined by a scalar field. The center points, called seed points, will be defined using nodes derived from the L-system branches. When these points are in close proximity, their fields of influence overlap, causing the volumes to merge into a continuous fluid morphology. By adjusting the strength of their influence and the proximity between seeds, the degree of merging can be controlled.

## Biophilic Integration

The choice of metaballs is rooted in the principle of Natural Analogues, the concept of mimicking nature. This specific morphology is inspired by water droplets and how they behave in microgravity. Without gravity, the droplet's surface tension is the dominant force, pulling it into a perfect sphere that seamlessly fuses it with any surrounding droplets. This organic fluidity results in curving, dynamic volumes that will intentionally move the habitat away from rectilinear geometries found in more traditional architecture.



Figure x: Behaviour of water in microgravity aboard the ISS

## Structural Optimization

Beyond aesthetics, the metaball morphology also has performance benefits. 3D printed structures are built up in layers; the horizontal seams between layers are inherently weaker in tension. Consequently, the design should prioritise compression-based forms. The metaball system employs catenary-like arches that distribute their weight downwards through compression.

Furthermore, in the vacuum of the lunar surface, the habitat must withstand 1 atmosphere of internal pressure pushing the habitat walls outwards. Spherical and organic 'blob' shapes are more efficient at distributing stress evenly across the envelope, minimizing the risk of localised failure due to tension hotspots.

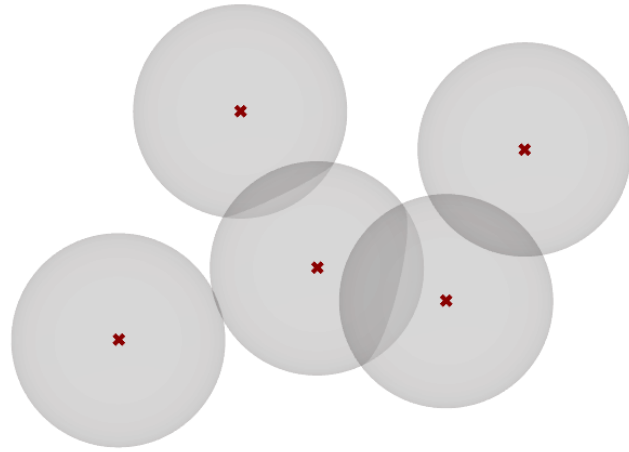


Figure x: Visualisation of seed points and spheres of influence



Figure x: Visualisation of the subsequent metaball morphology

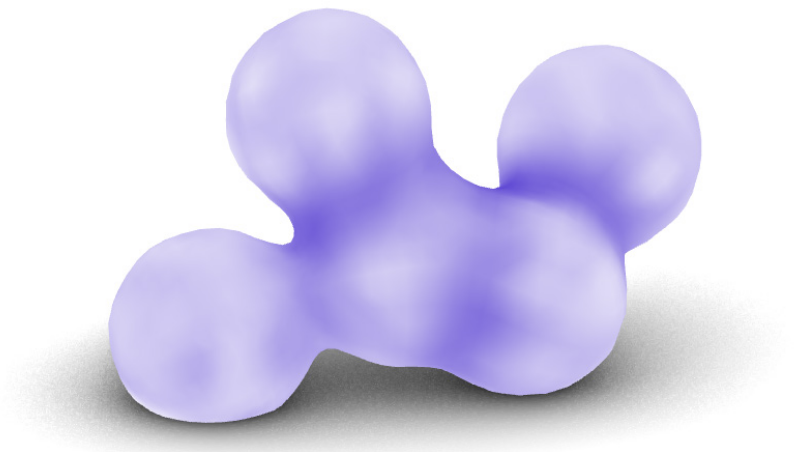
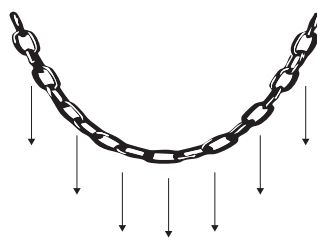
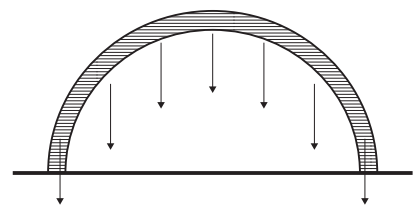


Figure x: Karamba analysis of the effects of internal pressure and gravity, showing relatively equal stress distribution with some peaks in the 'necks' between shapes.



Catenary Chain  
Tension



Dome  
Compression

Figure x: Visualisation of a catenary chain and compression dome

# PART 3

# RESULTS





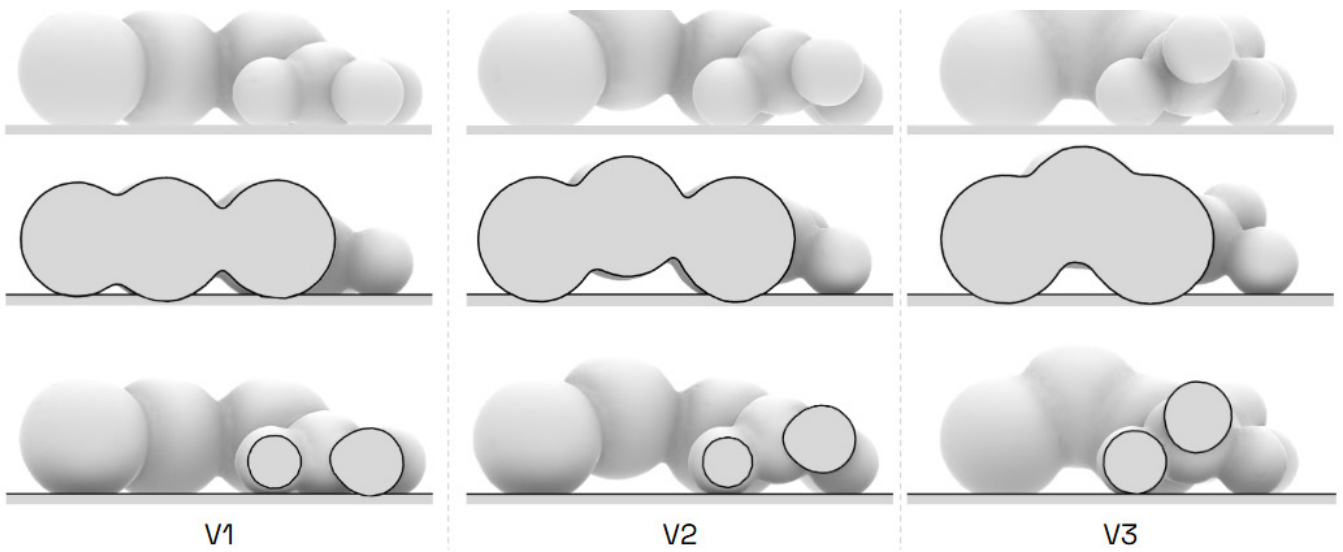
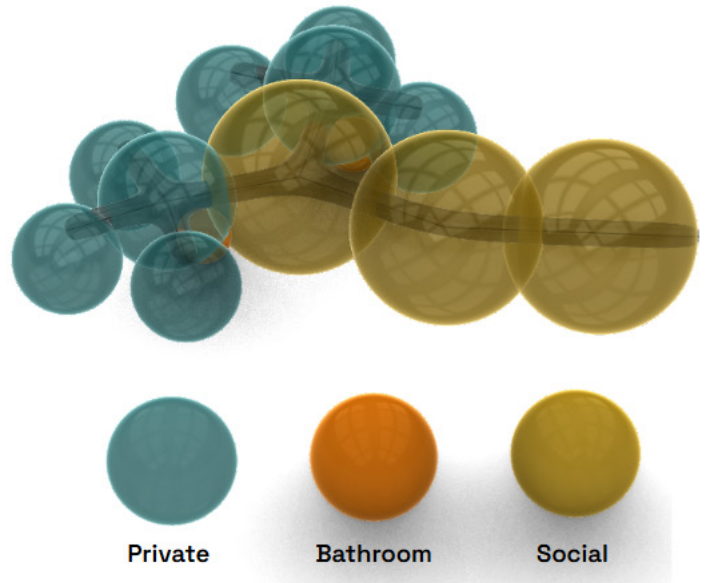
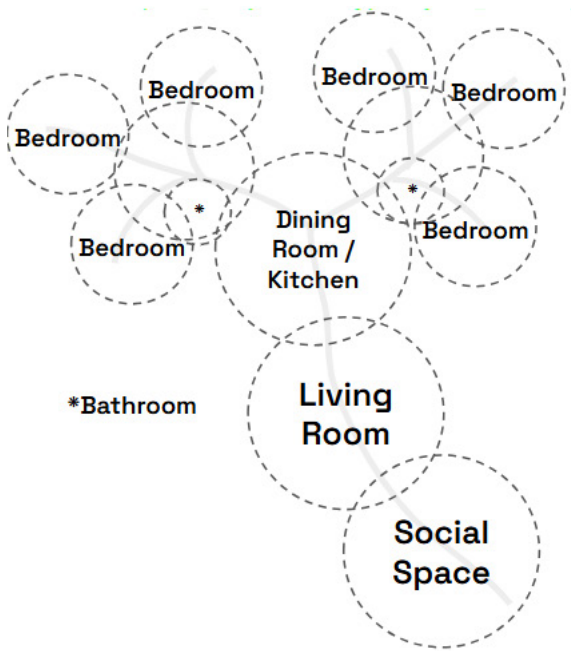
National Aeronautics and Space Administration. (1972, December 13). Apollo XVII extravehicular activity (EVA) - scientist-astronaut Harrison H. Schmitt - Moon [Photograph]. <https://images.nasa.gov/details/S73-22871>

# PROGRAMME

TYPOLOGY		SIZE						
PROGRAMME	ROOM	AREA 1 Person (m <sup>2</sup> )	Max. Capacity	MIN. AREA (m <sup>2</sup> )	Number of rooms	Total floor area (m <sup>2</sup> )	% OF HABITAT	MIN. HEIGHT (m)
Dirty Zone	Airlock (EVA Prep)	8	3	24	2	48	9.14%	3
	Lunar Soil Lab	12	2	24	1	24	4.57%	3
	Geology Lab	12	2	24	1	24	4.57%	3
	System Maintenance	8	1	8	1	8	1.52%	3
	Storage (outdoor equipment)	4	3	12	1	12	2.29%	3
Core Utility Zone	Life Support Systems	8	1	8	1	8	1.52%	3
	Systems Maintenance	8	1	8	1	8	1.52%	3
	Storage (food, water, oxygen)	8	3	24	1	24	4.57%	3
	Bathrooms	5	1	5	3	15	2.86%	3
Personal/Quite Zone	Private quarters	8	1	8	6	48	9.14%	3
	Meditation Room	8	1	8	1	8	1.52%	3
	Medical Bay	10	2	20	1	20	3.81%	3
Social Zone	Kitchen	2	6	12	1	12	2.29%	6
	Dining Room	3	6	18	1	18	3.43%	6
	Living Room	4	6	24	1	24	4.57%	6
	Social Space	4	6	24	1	24	4.57%	6
	Gym	8	6	48	1	48	9.14%	6

TYPE	ACTIVITY			PRIVACY			EXTERIOR	
	PROGRAMME	CATEGORY	CROSS-FUNCTION Details	CAPACITY	VISIBILITY	ACOUSTICS	ACCESS	VIEW
Dirty Zone	Support	/		Small groups (2-3)	Enclos...	Neutral	Yes	No
	Work	/		Large groups (4-6)	Enclos...	Neutral	No	No
	Work	/		Large groups (4-6)	Enclos...	Neutral	No	No
	Support	/		Small groups (2-3)	Enclos...	Neutral	No	No
	Support	/		Storage	Enclos...	Neutral	Yes	No
Core Utility Zone	Support	/		Small groups (2-3)	Enclos...	Sound ...	No	No
	Support	/		Small groups (2-3)	Enclos...	Sound ...	No	No
	Support	/		Storage	Enclos...	Neutral	No	No
	Support	/		Individual	Enclos...	Sound ...	No	No
Personal/Quite Zone	Personal	/		Individual	Enclos...	Sound ...	No	No
	Personal	/		Individual	Enclos...	Sound ...	No	Yes
	Personal	Support		Small groups (2-3)	Enclos...	Sound ...	No	No
Social Zone	Social	/		Small groups (2-3)	Open	Neutral	No	No
	Social	/		Large groups (4-6)	Open	Neutral	No	Yes
	Social	/		Large groups (4-6)	Open	Neutral	No	Yes
	Social	/		Large groups (4-6)	Open	Neutral	No	Yes
	Social	/		Large groups (4-6)	Open	Neutral	No	No

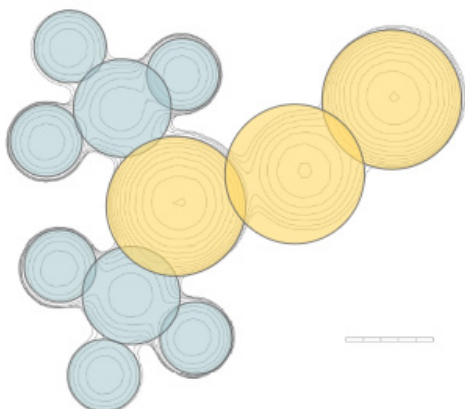
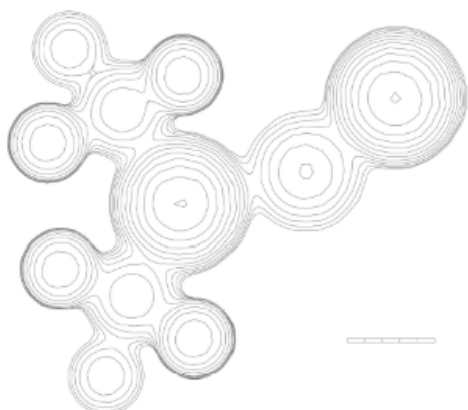
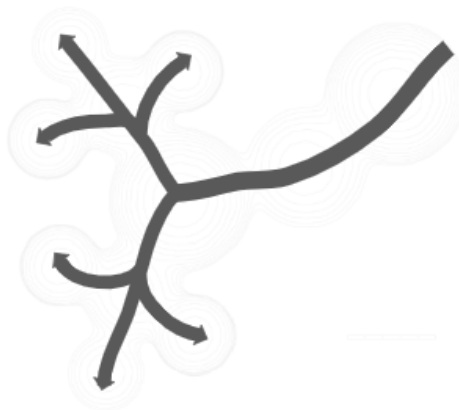
# BUBBLE DIAGRAMS

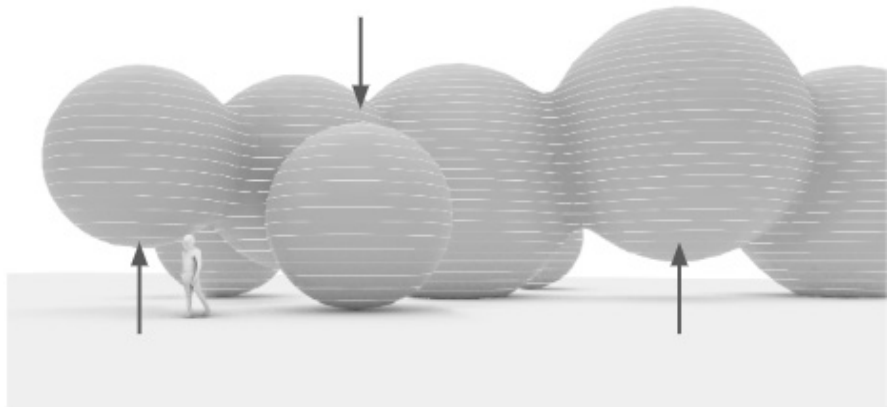
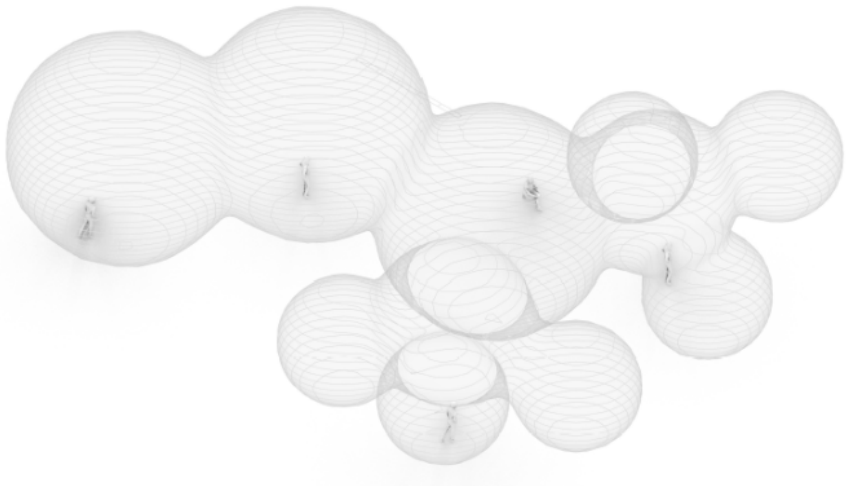


# FRAGMENT

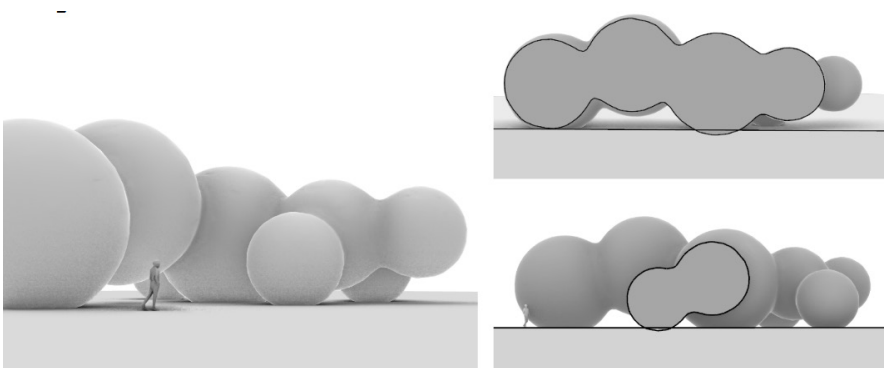
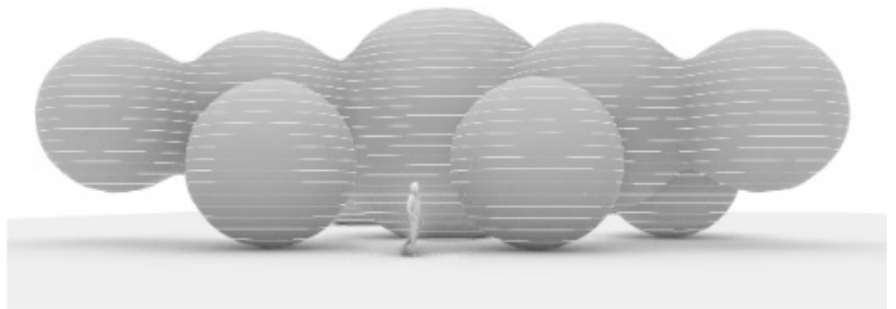
L-system & Metaball integration

text





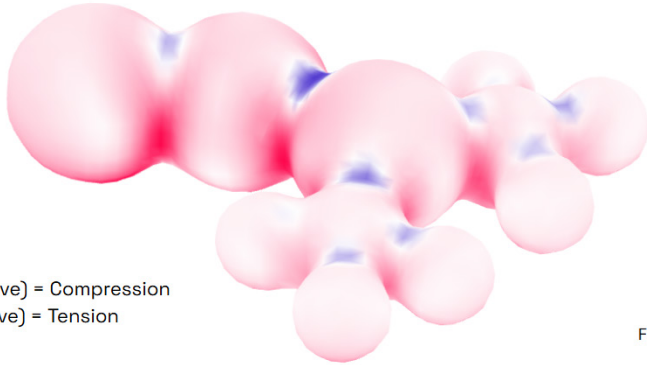
**Height Differences**



# FORM FINDING

## Kramaba Metaball Analysis

### Design V1 - Compression



Red (negative) = Compression  
Blue (positive) = Tension

Forces: Gravity

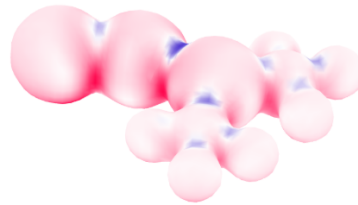
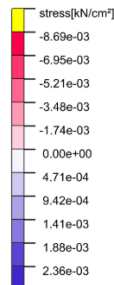
### Design V1 - Force of Gravity

Max Compression  
 $0.00869 < 9.250 \text{ kN/cm}^2$

Max Tension  
 $0.00236 < 0.925$

Structure performs well in low gravity

**Overengineered** thanks to the thickness required for radiation protection



Forces: Gravity + Pressure

[https://www.researchgate.net/publication/390602870\\_Melting\\_and\\_solidifying\\_behavior\\_of\\_lunar\\_regolith\\_simulant\\_under\\_a\\_vacuum\\_environment](https://www.researchgate.net/publication/390602870_Melting_and_solidifying_behavior_of_lunar_regolith_simulant_under_a_vacuum_environment)

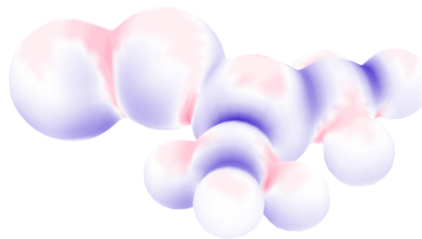
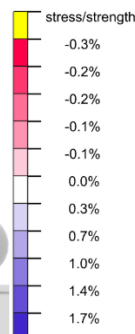
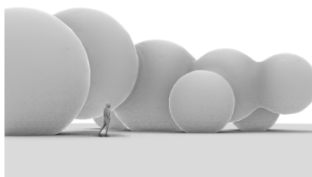
TABLE 4 Compression strength of samples solidified at different target temperatures.

Target temperature (°C)	1300	1400	1500
Compressive strength (MPa)	27.4 ± 2.6	18.2 ± 2.9	12.1 ± 18.4
Initial failure strength (MPa)	15.6 ± 7.0	6.5 ± 2.1	9.2.5 ± 16.3

### Design V2 - Cantilevers

Raising the metaballs

→ More dynamic interior facilitating jumpy lunar movement



Forces: Gravity

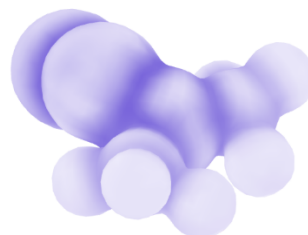
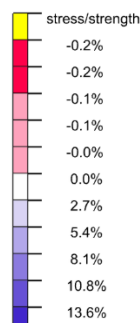
### Design V3 - Metaball smoothing

Metaballs are moved closer together and blended

→ More efficient load path to the ground

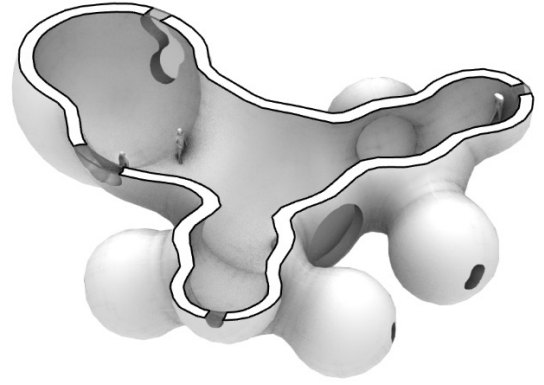
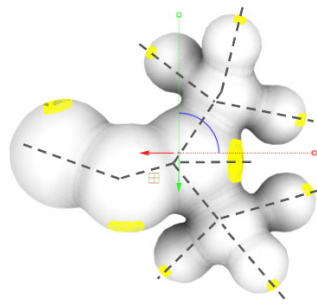
→ 'necks' are reduced

→ Reduce peak stress in the hotspots

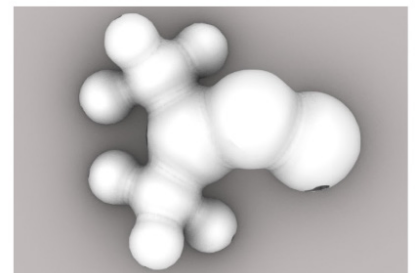


Forces: Gravity + Pressure

## Window / Porosity



Windows generally follow L-system axis

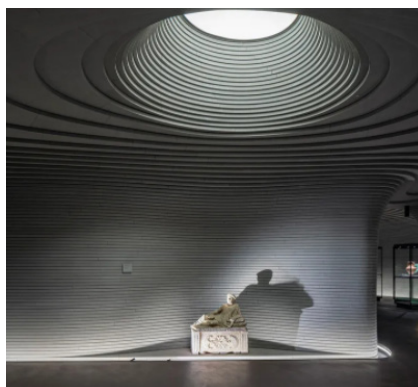
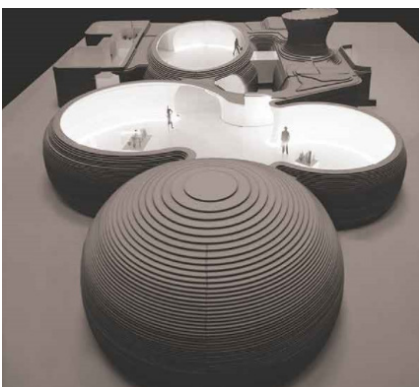
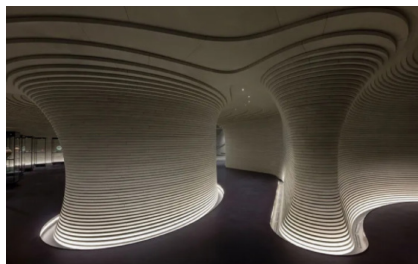


# INTERIOR CASE STUDIES

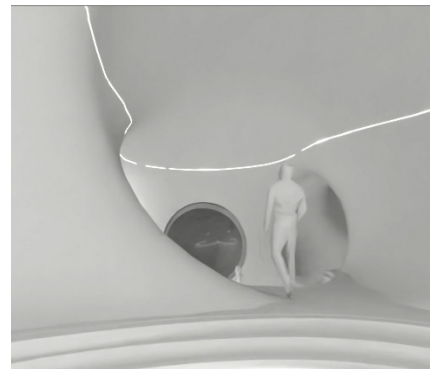
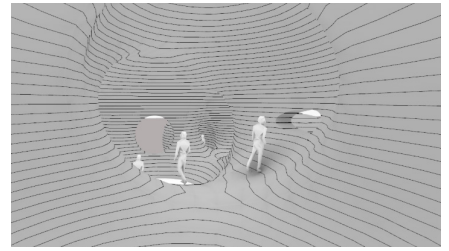
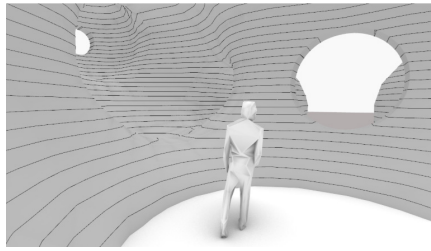
## Chapel of Sound - OPEN Architecture



## Fondazione Luigi Rovati - Mario Cucinella Architects

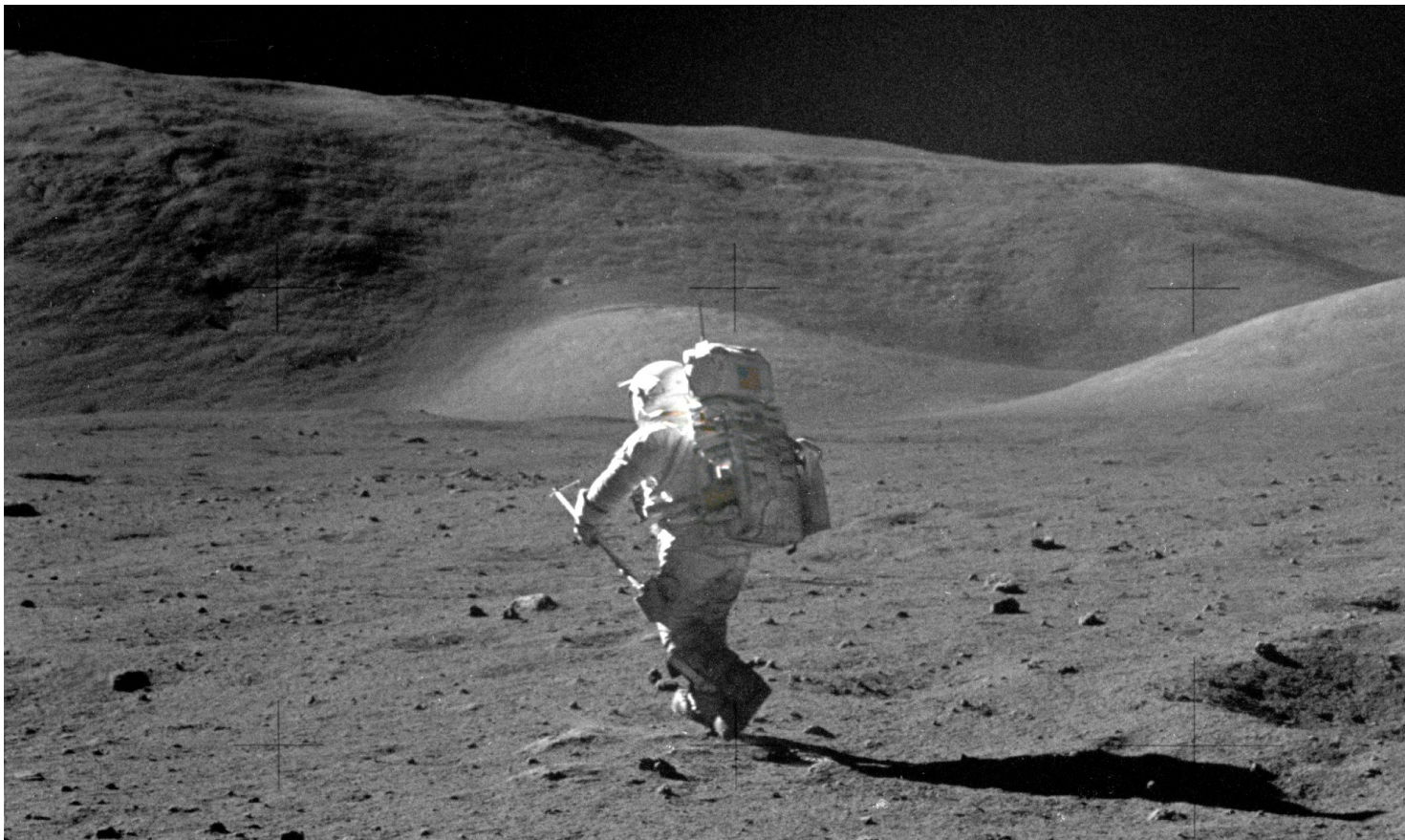


# INTERIOR STUDIES

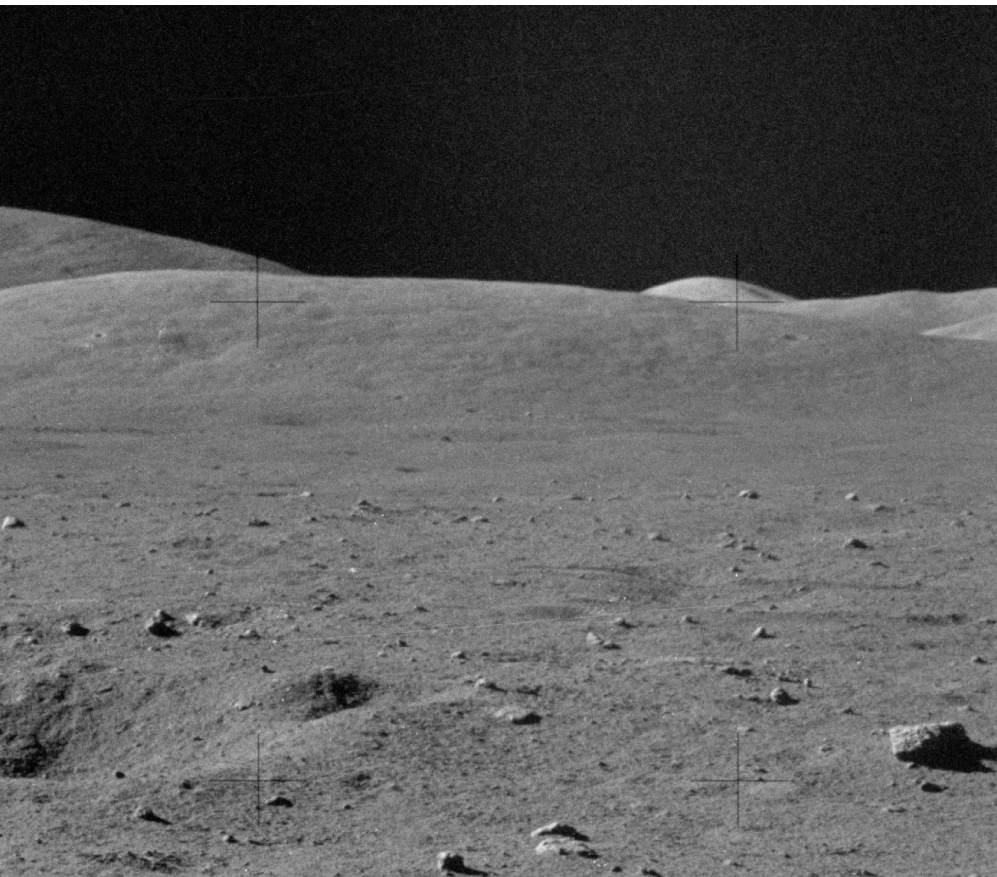


PART 4

# CONCLUSION & DISCO



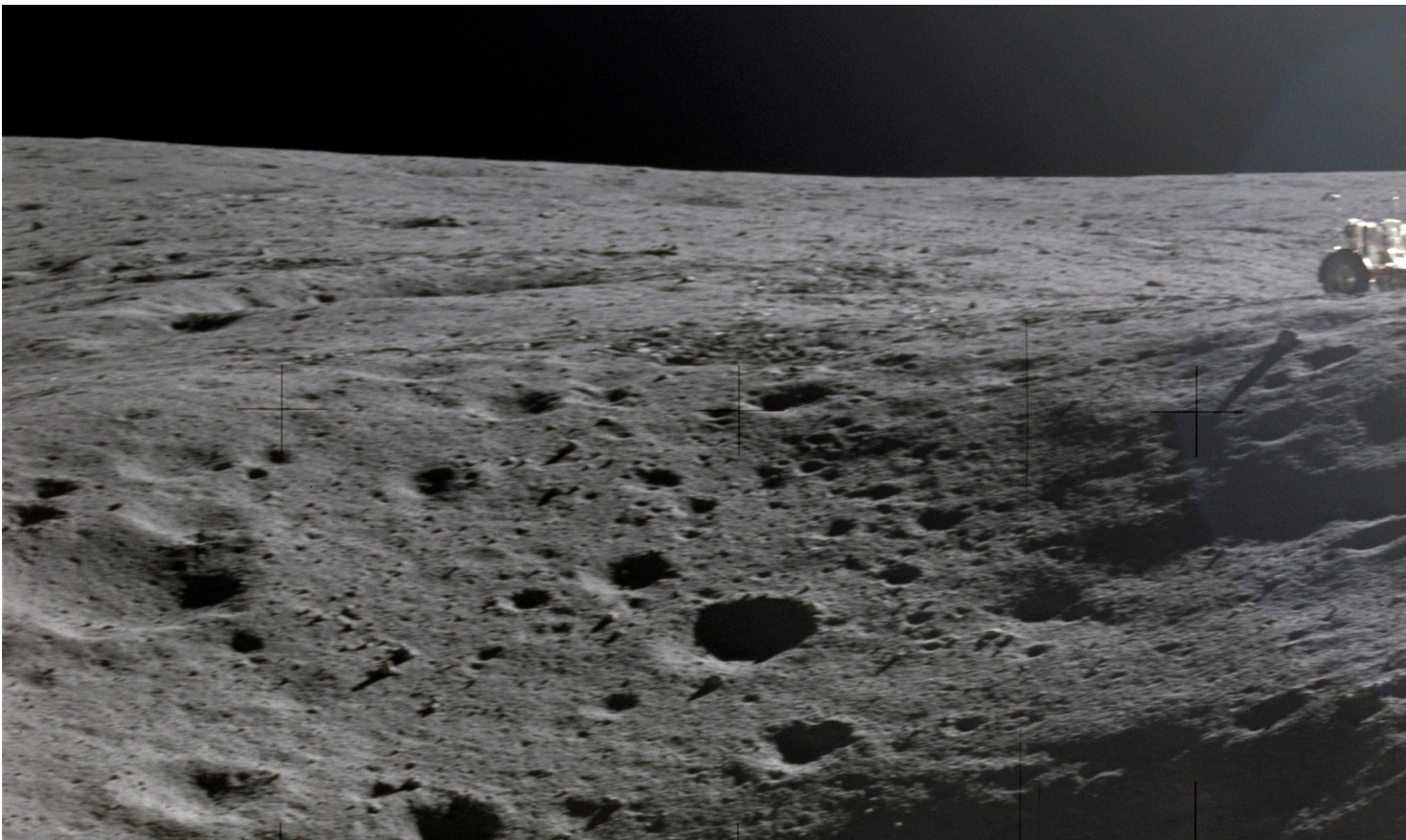
# CUSSION



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## PART 5

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