Biomorphed

Lunar Habitat Design

Computationally based Biophilic
Design for Astronaut Well-being

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Extra-/Terrestrial Architecture Graduation Studio

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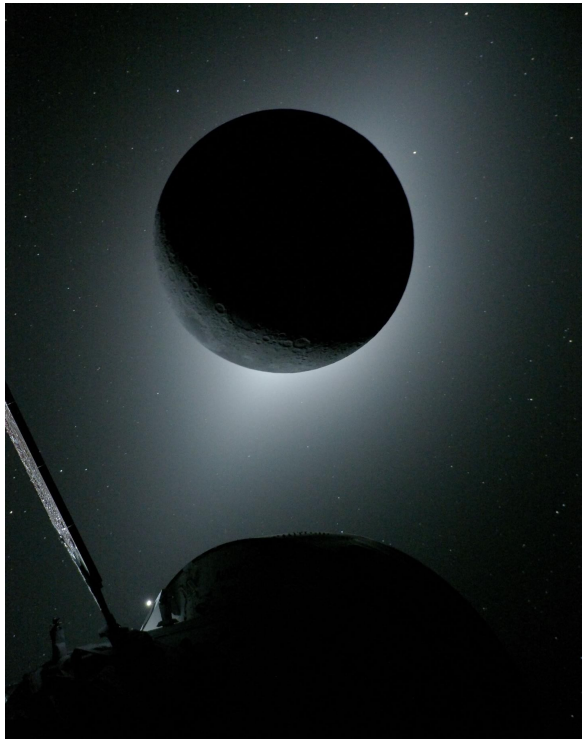
INTRODUCTION / BACKGROUND

Return to the Moon

Return to the Moon

Why is this topic relevant?

- A second space race to put humans on the Moon again
- Involving many space agencies like NASA, ESA, ROSCOSMOS, CNSA, etc.
- Aim for longer term Moon missions
- Eventually leading to colonising of the Moon and beyond



https://www.nasa.gov/news-release/nasas-artemis-ii-crew-beams-official-moon-flyby-photos-to-earth/

Problem Statement

Lunar habitation faces 3 main challenges

Transportation Costs

Hostile Environment

Mental Health

Problem Statement

Transportation Costs

- Expensive to launch rockets
- Price/kg has decreased with reusable rockets
- Building materials are heavy

In-Situ Resource Utilization (ISRU)

poses a solution by reducing the need for transporting materials from earth

https://www.nasa.gov/overview-in-situ-resource-utilization/

Problem Statement

Hostile Environment

- Abrasive lunar dust
- Moonquakes
- Micro meteorites
- Radiation
- Solar wind
- Long lunar nights
- No atmosphere
- Extreme temperature fluctuations

Lava Tubes

poses a solution by creating a protective cover from the environment in combination with the shelter provided by the habitat

https://bsmedia.business-standard.com/_media/bs/img/article/2019-07/18/full/1563434814-8966.jpg

Problem Statement

Mental Health

- Stuck with the same people
- High stress environment
- Away from family and home
- Little privacy
- Confined indoors

Biophilia

poses a solution by adding more greenery and reminding people of earth. Biophilic design can improve mental health & well-being.

https://www.nasa.gov/image-article/expedition-59-crew-members-inside-u-s-destiny-laboratory/

Terrestrial Relevance

UN Sustainable Development Goals

- **Health & well-being** → Biophilic (human-centric design)
- **Innovation** → Design-To-Robotic-Production and 3D printing advancements
- **Sustainable cities and responsible consumption** → ISRU to reduce pollution from transport

Objective

Goals

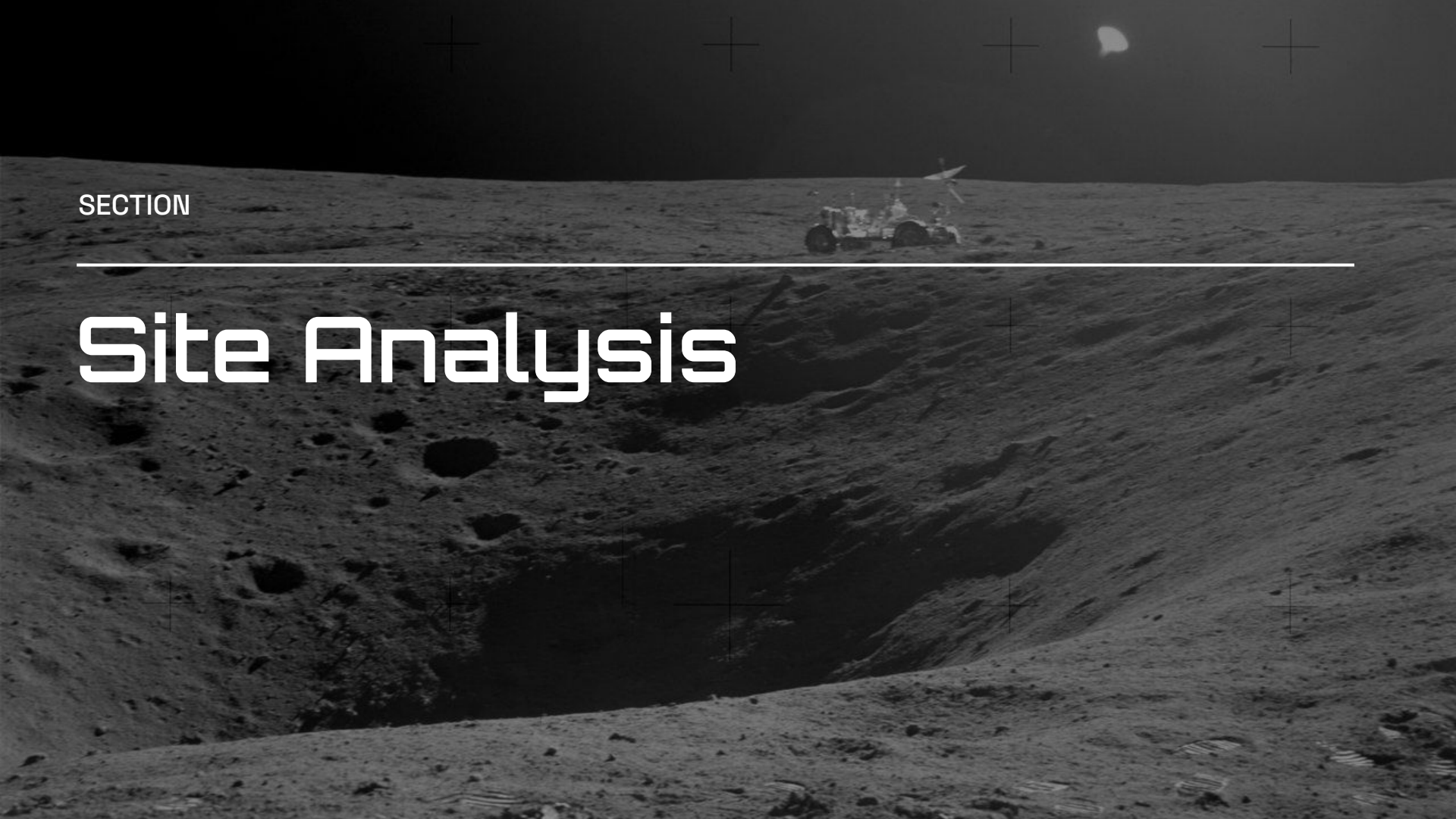
- To design a functional, safe and effective ISRU Lunar habitat
- To explore the relationship between biophilic design and 3D printing
- To create a habitat with a healthy indoor environment for mental wellbeing
- To contribute to the study of future habitats designs on and off Earth

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**?”

Scope

TEAM SIZE	6 person team, rotate 3 at a time for knowledge transfer	**LOCATION**	South pole → Lava tube
MISSION TYPE	Longer term research missions on the south pole of the moon	**MATERIAL**	3D printed lunar regolith
TIMELINE	First lunar base already established. Now in the longer term stay phase.	**BUILD**	ISRU 3D printing Selective Laser Melting
DESIGN	Human-centric, biophilic, circular, computational.		

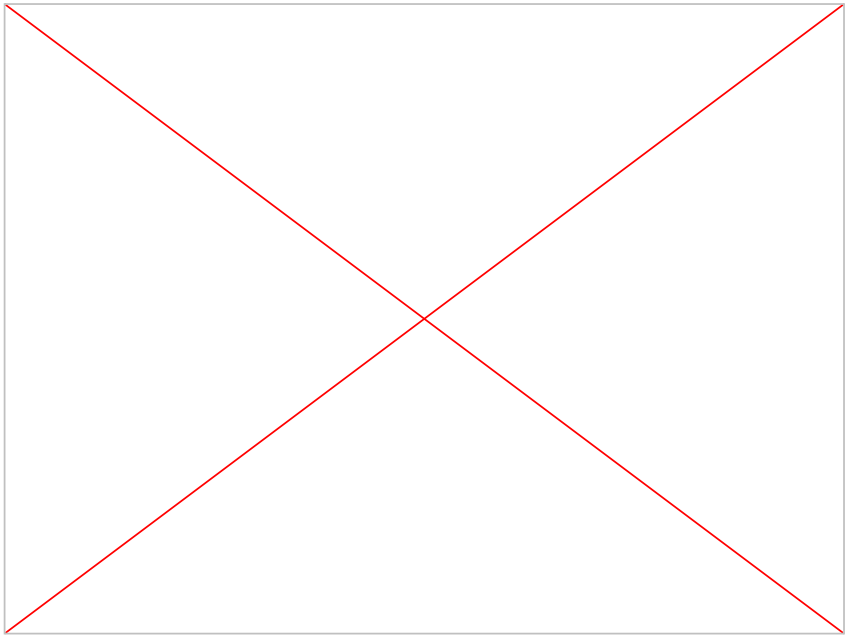


SECTION

Site Analysis

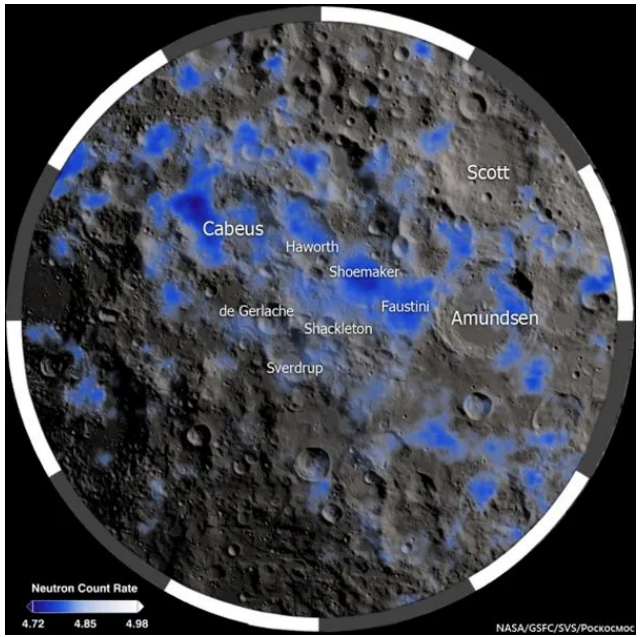
Lunar South Pole

Sunlight



https://svs.gsfc.nasa.gov/4930/

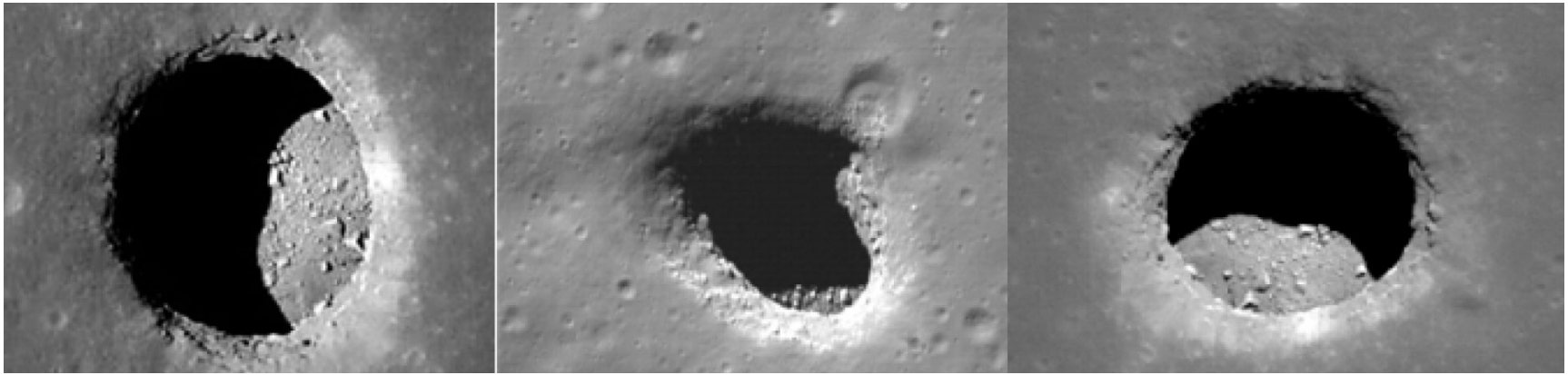
Water Ice deposits



https://science.nasa.gov/image-detail/svs-lend-20130601-580-2/

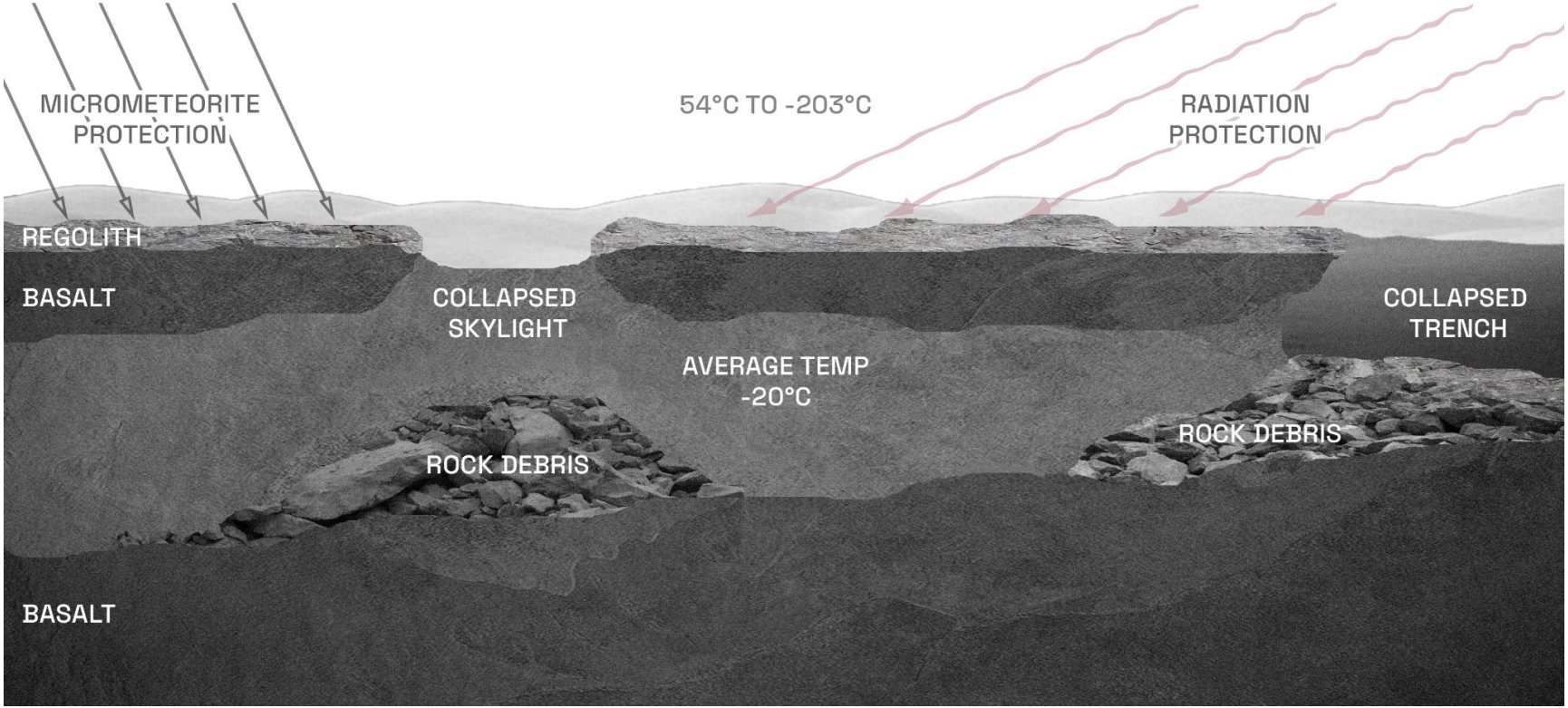
Lunar Lava Tubes

Skylights of theorised lava tubes



https://phys.org/news/2020-07-lava-tubes-exploration-priority-worlds.html

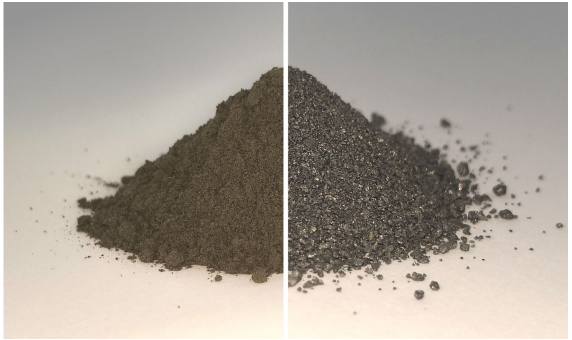
Lunar Lava Tubes



Section

Construction & Materialisation

Extracting Materials



- Water (life support)
- Oxygen (life support)
- Silica (for glass)
- Metal (construction)

Lunar Regolith Composition

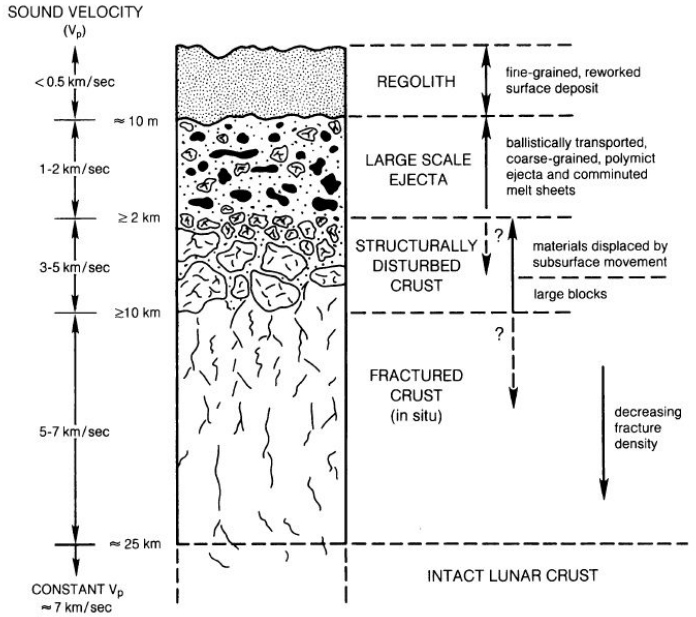
Element	Low-Ti Mare Soils	High-Ti Mare Soils	Highland Soils	KREEP Soils
O	60.26	60.30	60.82	60.47
Si	17.30	15.86	16.31	17.35
Al	5.56	5.70	10.66	6.48
Mg	5.53	5.70	3.84	5.39
Ca	4.44	4.60	5.92	4.43
Fe	5.85	5.29	1.90	4.47
Ti	0.66	2.01	0.17	0.62
Na	0.26	0.31	0.29	0.44
K	0.06	0.05	0.05	0.19
Mn	0.08	0.07	0.03	0.06

https://www.researchgate.net/figure/Assumed-Composition-of-the-Lunar-Regolith-and-Variation-Across-Soil-Types-a_tbl1_258661774

https://ntrs.nasa.gov/api/citations/20250003730/downloads/Progress%20Review%20NASA%20Lunar%20ISRU_Sanders.pdf

3D Printing

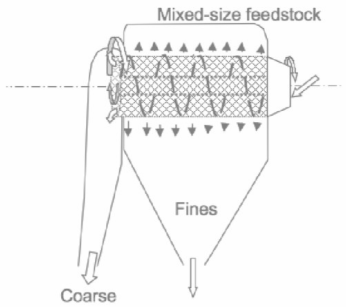
- Using the top layer of regolith
- Easy to mine with robots
- Need a way to ‘print’ the dust without additives



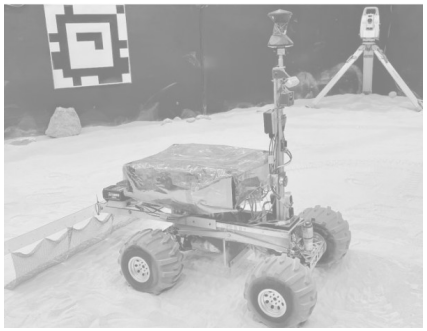
https://www.researchgate.net/figure/The-vertical-structure-of-the-Lunar-regolith-and-crust_fig7_264340952

Robotic Process

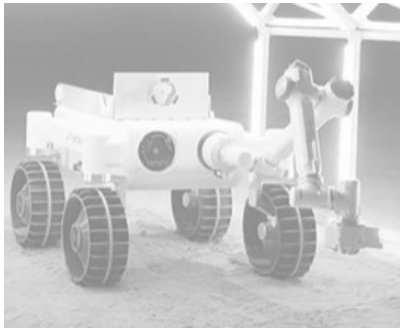
COLLECTING



PROCESSING



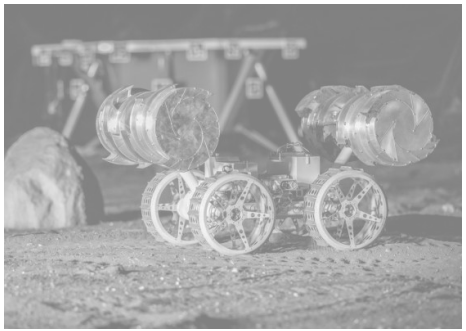
FLATTENING

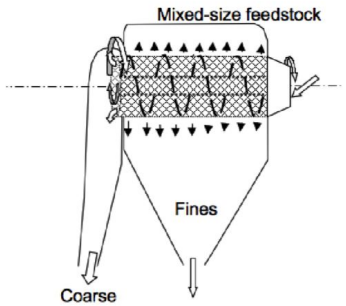


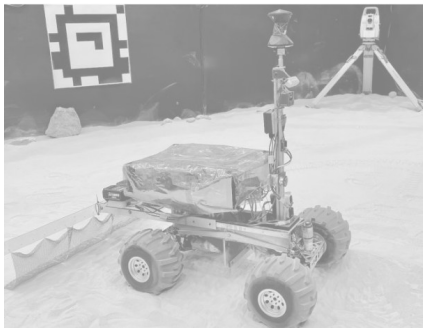
MELTING

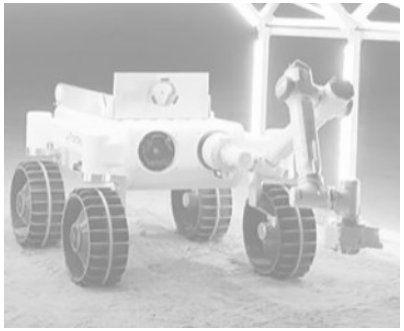
https://moonshotplus.tudelft.nl/images/7/7f/1.13.1_Space%26Robotics_FinalPresentation_JIP2025.pdf

Robotic Process









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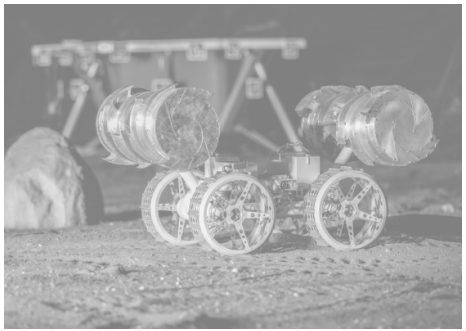

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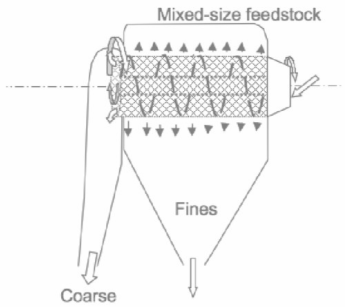

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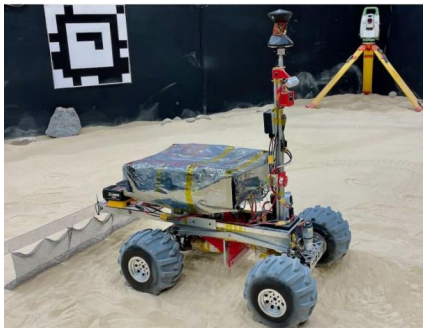

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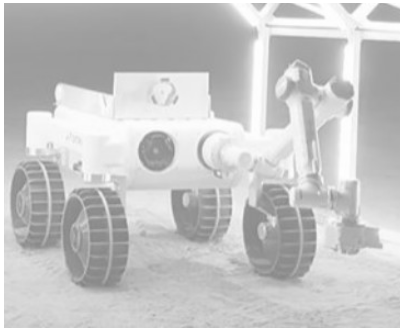

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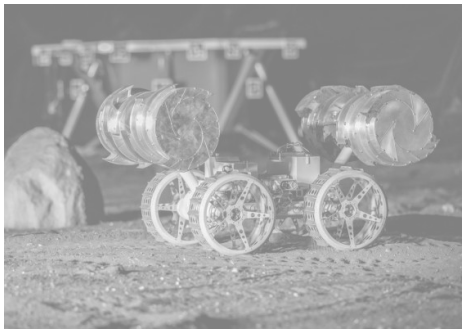

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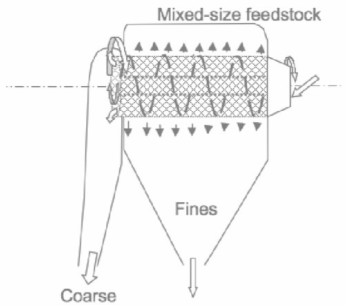

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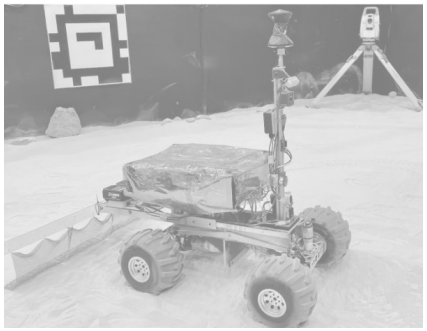

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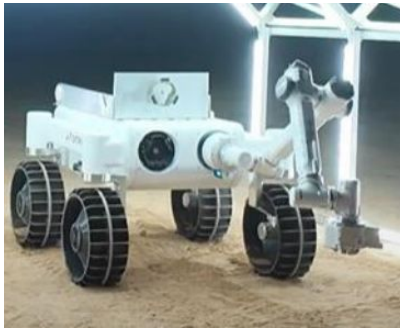

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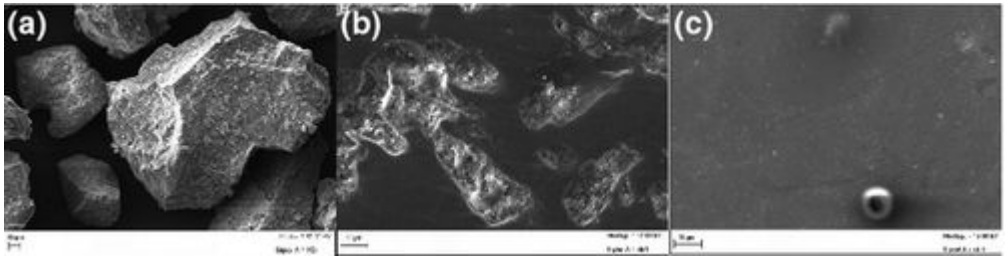
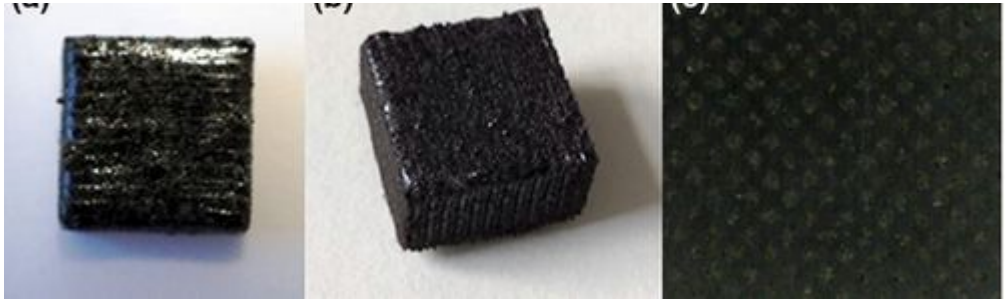
3D Printing

Selective Laser Melting (SLM)

- Melts regolith into a glass-like solid
- No additives required
- Energy-intensive
  - 1500 degrees celcius
- Less porous than SLS so better structural integrity



Powder **Sintered** **Melted**



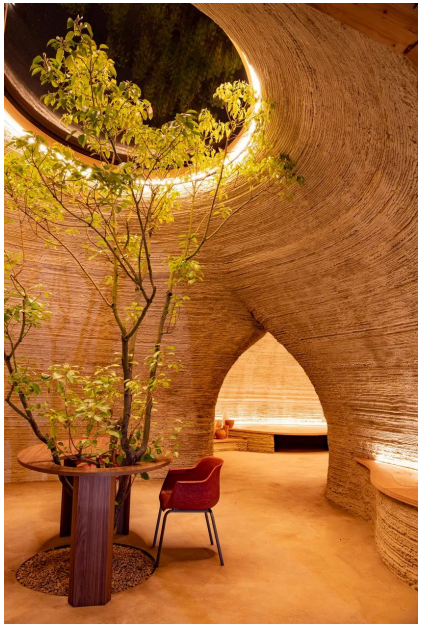
Fateri, M., & Gebhardt, A. (2015). Process parameters development of selective laser melting of lunar regolith for on-site manufacturing applications. International Journal of Applied Ceramic Technology, 12(1), 46-52.

3D Printing

Case Study

TECLA by Mario Cucinella Architects

- Used material extrusion not SLM
- Organic shapes
- Custom unique texture on the exterior
- Integrated strip lighting
- Compressive dome shape



Mario Cucinella Architects. (2020). *TECLA: The first eco-sustainable housing prototype 3D printed from raw earth.* https://www.mcarchitects.it/en/projects/tecla-technology-and-clay

Section

Mental Health & Well-being

Missions in Space

- Stuck with the same people
- High stress environment
- Away from family and home
- Little privacy
- Monotonous environment

Sick Building Syndrome

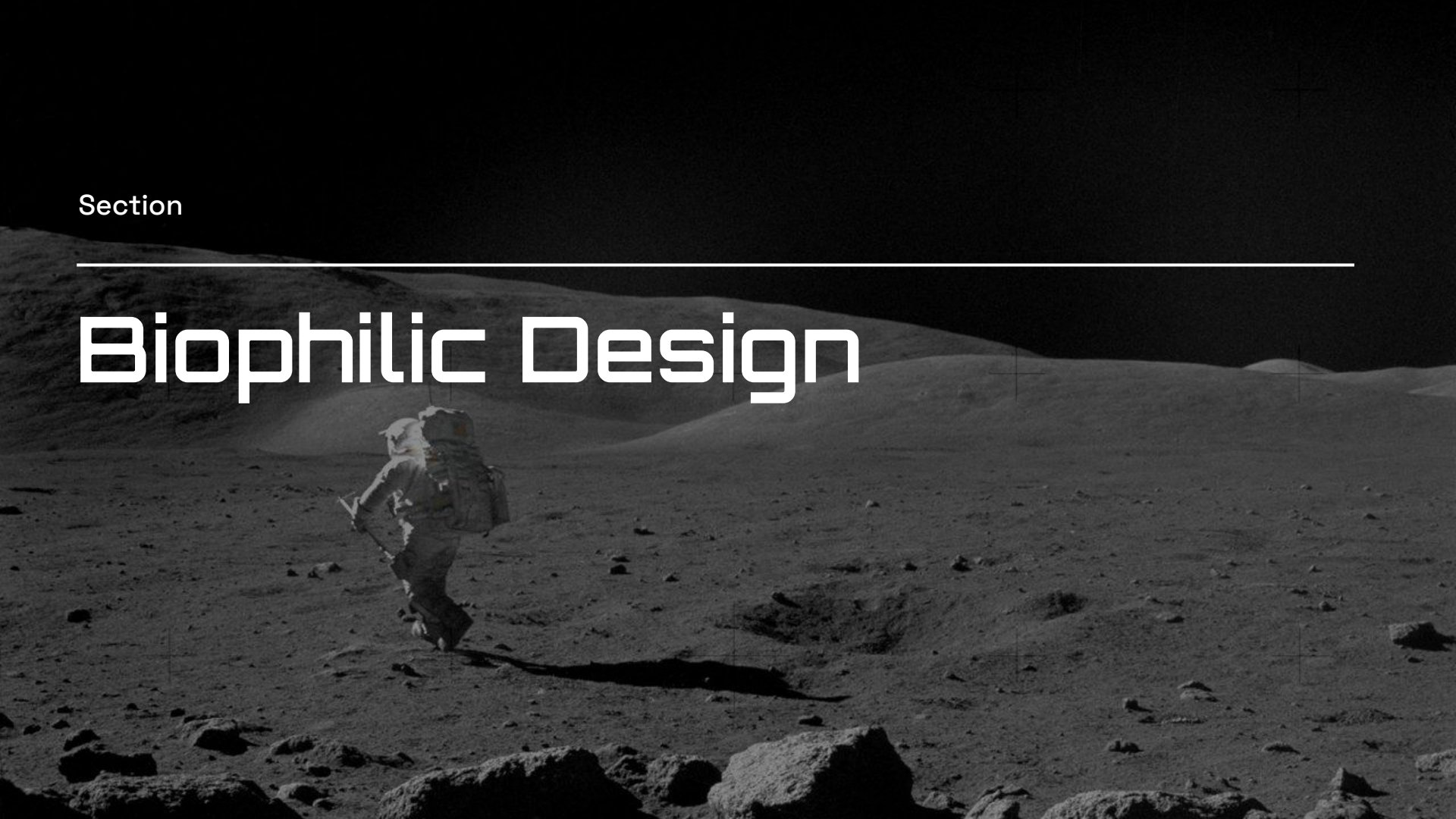
- Improper, harsh lighting
- Thermal/humidity discomfort
- Bad acoustic quality → noise
- Bad air quality

Biophilic Design Interventions Should Respond through:

- Non-monotonous, dynamic spaces
- Seperation between public & private spaces → ability to retreat
- Lighting comfort
- Acoustic comfort
- Thermal comfort
- Air quality

Section

Biophilic Design



Biophilic Design

Definition

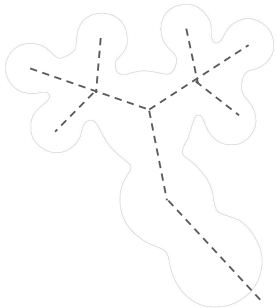
An approach to architecture and interior design that **connects people with nature** within built environments, using **natural elements, forms, and processes** to **improve human health**, well-being, and productivity, stemming from our innate **love for nature**

Computational Systems

At the building level **biophilic design** comes through **2 main design systems**

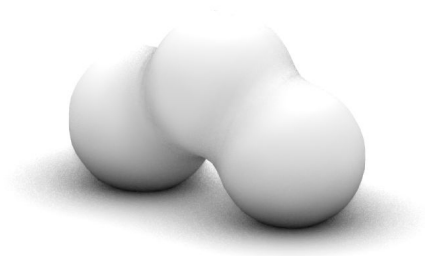
Lindemayers L-System

A mathematical system that describes plant growth and allows us to model it.



Metaballs

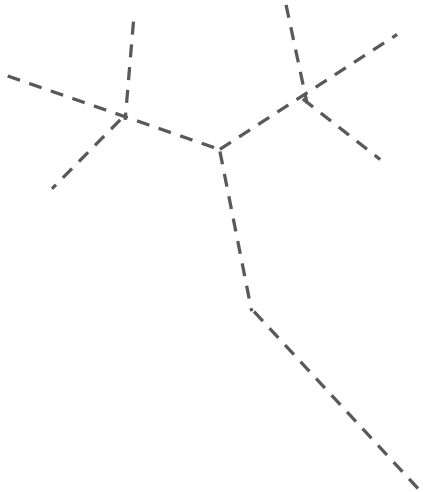
A modelling technique involving spheres to create **organic looking shapes.**



L-System

Why L-System?

1. Biomimicry → mimic plant growth
2. Modular design
    a. Building can grow and branch out in the future
3. Efficient pathing
    a. L-system branches create pathing for humans and LSS
4. Spatial Hierarchy
5. Compartmentalization (safety)



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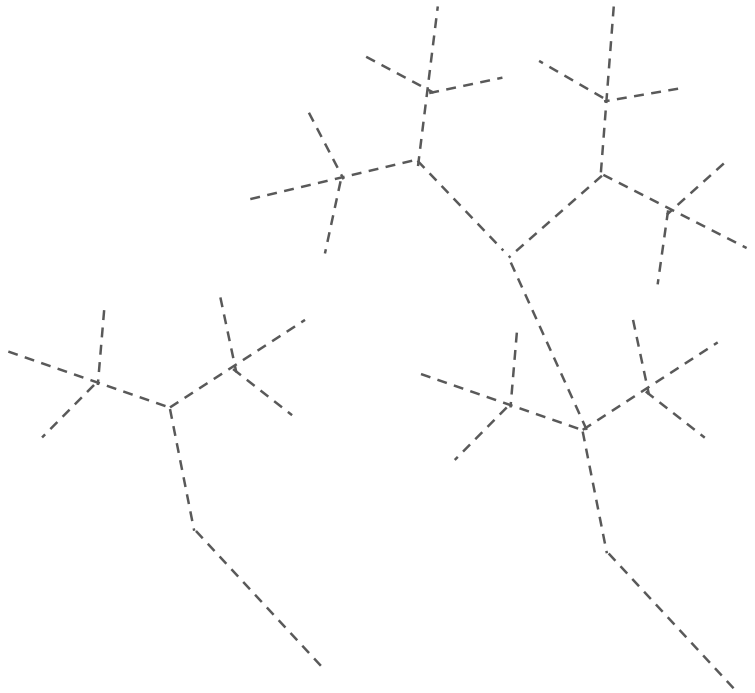

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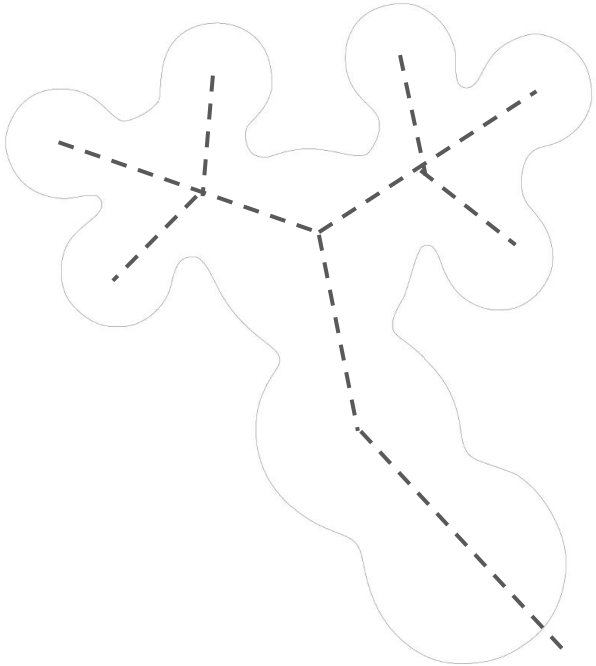

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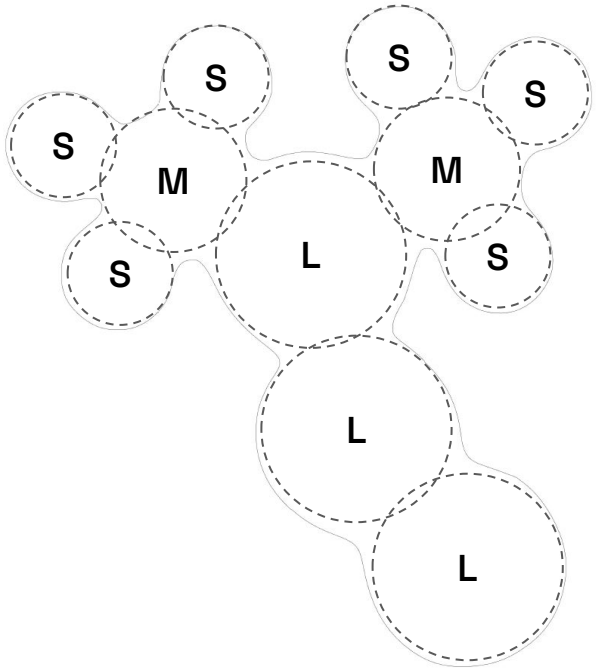

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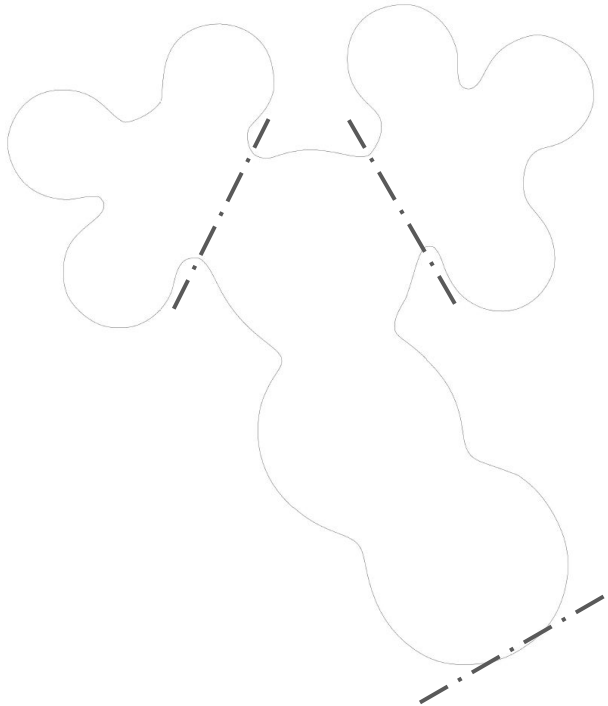
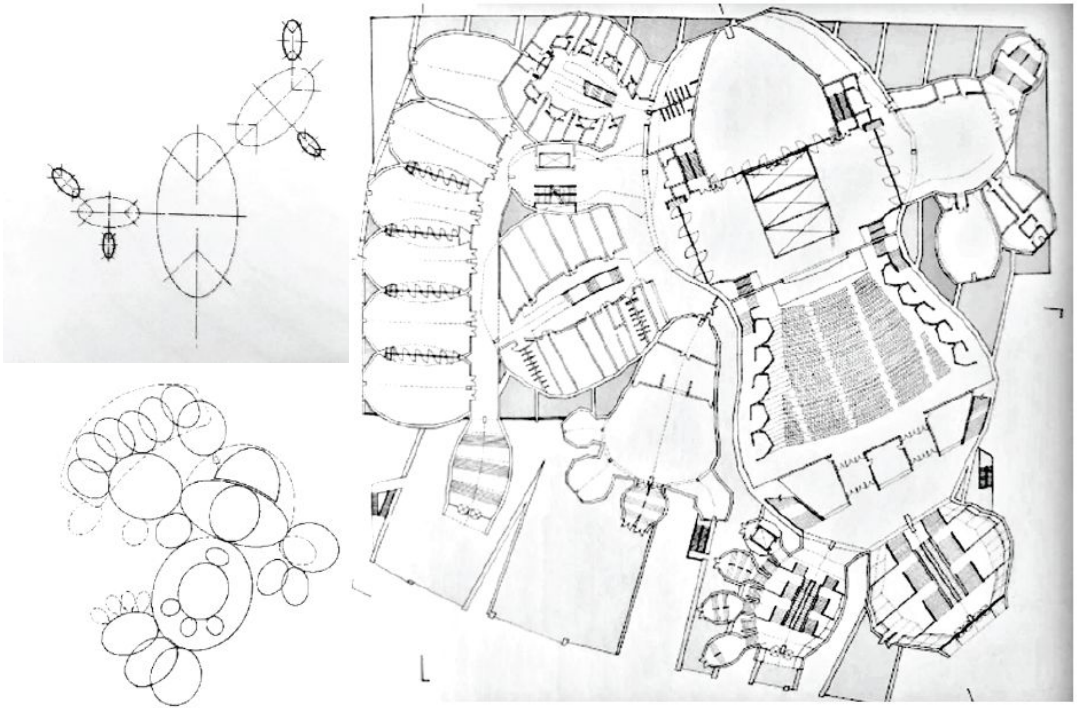


L-System

Case Study

Cardiff Bay Opera House by Greg Lynn

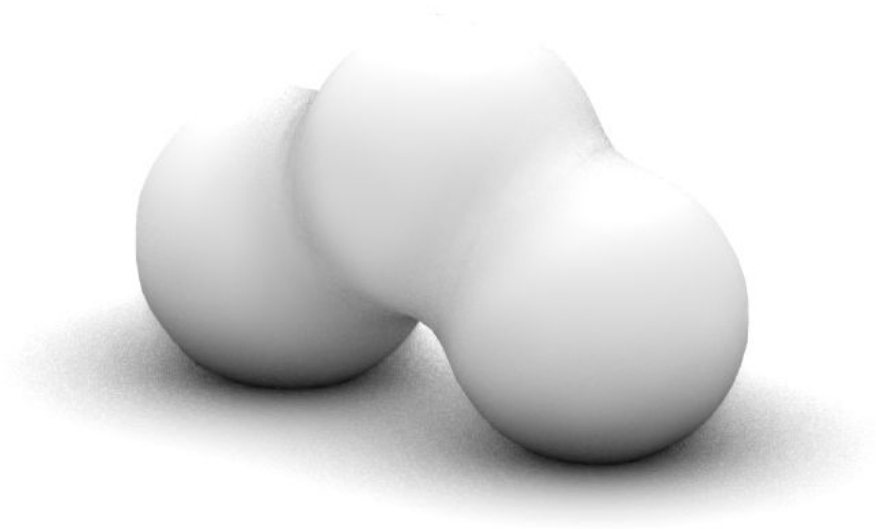
- Precedent for designing with L-systems
- Uses the L-system to define the floorplan
- Clear spatial hierarchy through size differences



Metaballs

Why Metaballs?

1. 3D printing allows us to step away from more typical orthogonal architectural designs
2. Easy way to achieve an organic look
3. Spheres are ideal shapes when dealing with pressure
4. Domes work well in compression, ideal for 3D printing



Metaballs

Why Metaballs?

1. 3D printing allows us to step away from traditional blocky looks you find on Earth at the moment
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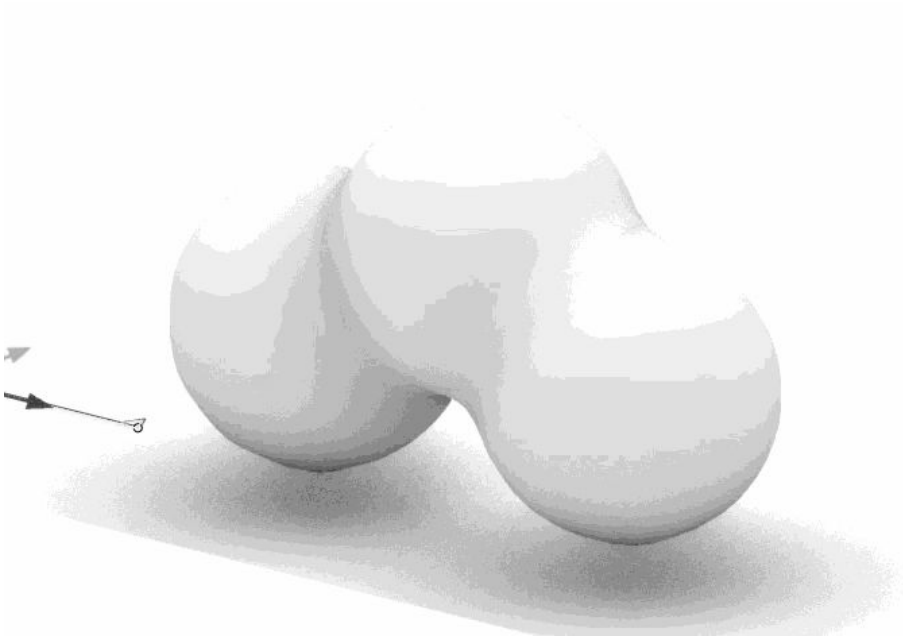

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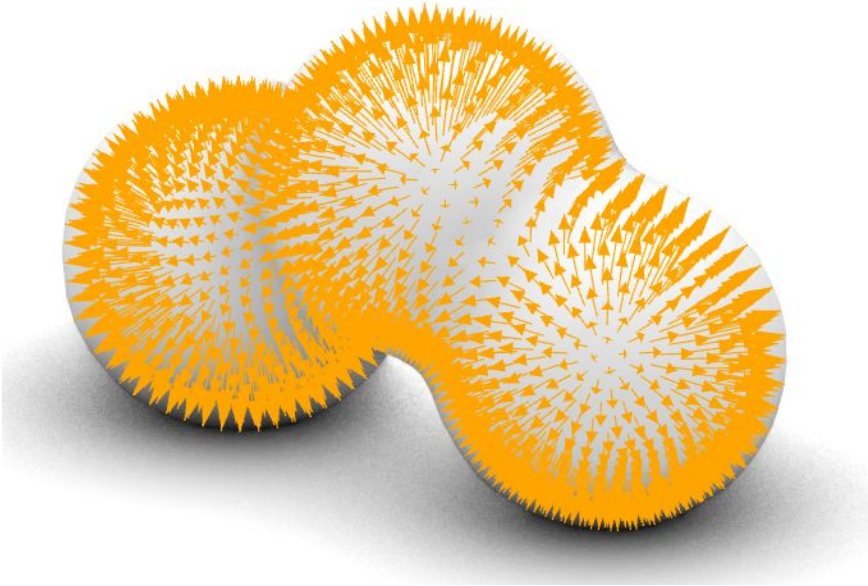

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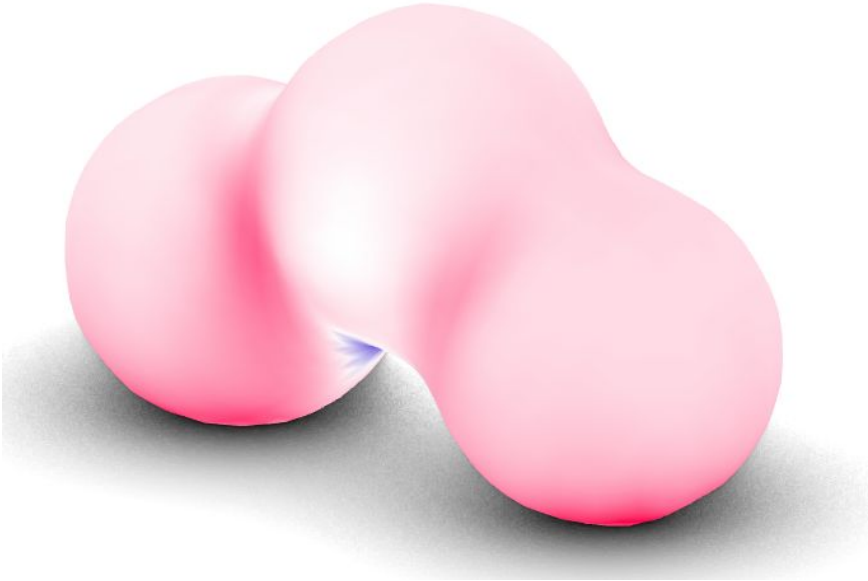


Section

Programme

Long-Term Research Mission For A Crew Of 6

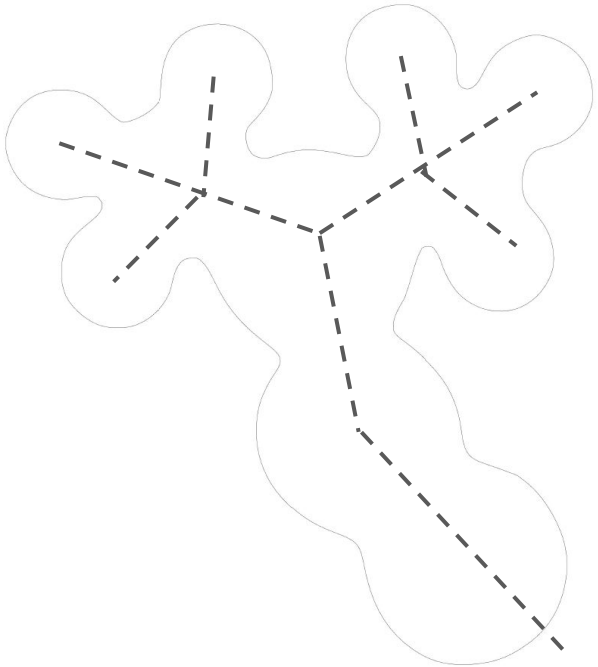
TYPOLOGY		SIZE							ACTIVITY			PRIVACY			EXTERIOR	
PROGRAMME	ROOM	AREA 1 Person (m2)	Max. Capacity	MIN. AREA (m2)	Number of rooms	Total floor area (m2)	% OF HABITAT	MIN. HEIGHT (m)	CATEGORY	CROSS-FUNCTION	Details	CAPACITY	VISIBILITY	ACOUSTICS	ACCESS	VIEW
Dirty Zone	Airlock (EVA Prep)	8	3	24	2	**48**	9.14%	3	Support	/		Small groups (2-3)	Enclos...	Neutral	Yes	No
	Lunar Soil Lab	12	2	24	1	**24**	4.57%	3	Work	/		Large groups (4-6)	Enclos...	Neutral	No	No
	Geology Lab	12	2	24	1	**24**	4.57%	3	Work	/		Large groups (4-6)	Enclos...	Neutral	No	No
	System Mainetenance	8	1	8	1	**8**	1.52%	3	Support	/		Small groups (2-3)	Enclos...	Neutral	No	No
	Storage (outdoor equipement)	4	3	12	1	**12**	2.29%	3	Support	/		Storage	Enclos...	Neutral	Yes	No
Core Utility Zone	Life Support Systems	8	1	8	1	**8**	1.52%	3	Support	/		Small groups (2-3)	Enclos...	Sound ...	No	No
	Systems Maintenance	8	1	8	1	**8**	1.52%	3	Support	/		Small groups (2-3)	Enclos...	Sound ...	No	No
	Storage (food, water, oxygen)	8	3	24	1	**24**	4.57%	3	Support	/		Storage	Enclos...	Neutral	No	No
	Bathrooms	5	1	5	3	**15**	2.86%	3	Support	/		Individual	Enclos...	Sound ...	No	No
Personal/Quite Zone	Private quarters	8	1	8	6	**48**	9.14%	3	Personal	/		Individual	Enclos...	Sound ...	No	No
	Meditation Room	8	1	8	1	**8**	1.52%	3	Personal	/		Individual	Enclos...	Sound ...	No	Yes
	Medical Bay	10	2	20	1	**20**	3.81%	3	Personal	Support		Small groups (2-3)	Enclos...	Sound ...	No	No
Social Zone	Kitchen	2	6	12	1	**12**	2.29%	6	Social	/		Small groups (2-3)	Open	Neutral	No	No
	Dining Room	3	6	18	1	**18**	3.43%	6	Social	/		Large groups (4-6)	Open	Neutral	No	Yes
	Living Room	4	6	24	1	**24**	4.57%	6	Social	/		Large groups (4-6)	Open	Neutral	No	Yes
	Social Space	4	6	24	1	**24**	4.57%	6	Social	/		Large groups (4-6)	Open	Neutral	No	Yes
	Gym	8	6	48	1	**48**	9.14%	6	Social	/		Large groups (4-6)	Open	Neutral	No	No
Work Zone	Research Labs	10	4	40	2	**80**	15.24%	3	Work	/		Large groups (4-6)	Hybrid	Neutral	No	No
	Agricultural Lab	10	4	40	1	**40**	7.62%	3	Work	/		Large groups (4-6)	Hybrid	Neutral	No	No
	Command & Control	4	6	24	1	**24**	4.57%	3	Work	Support		Small groups (2-3)	Hybrid	Sound ...	No	Yes
	Radio Room	4	2	8	1	**8**	1.52%	3	Work	Support		Small groups (2-3)	Hybrid	Sound ...	No	No

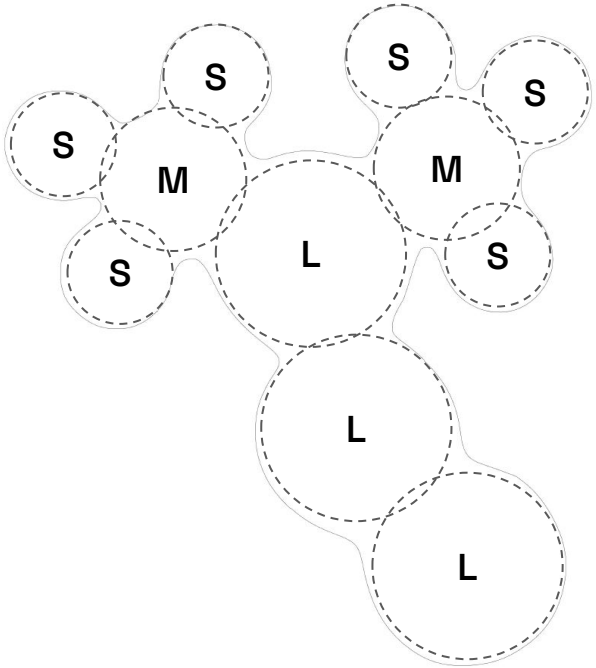
TOTAL AREA	525

Section

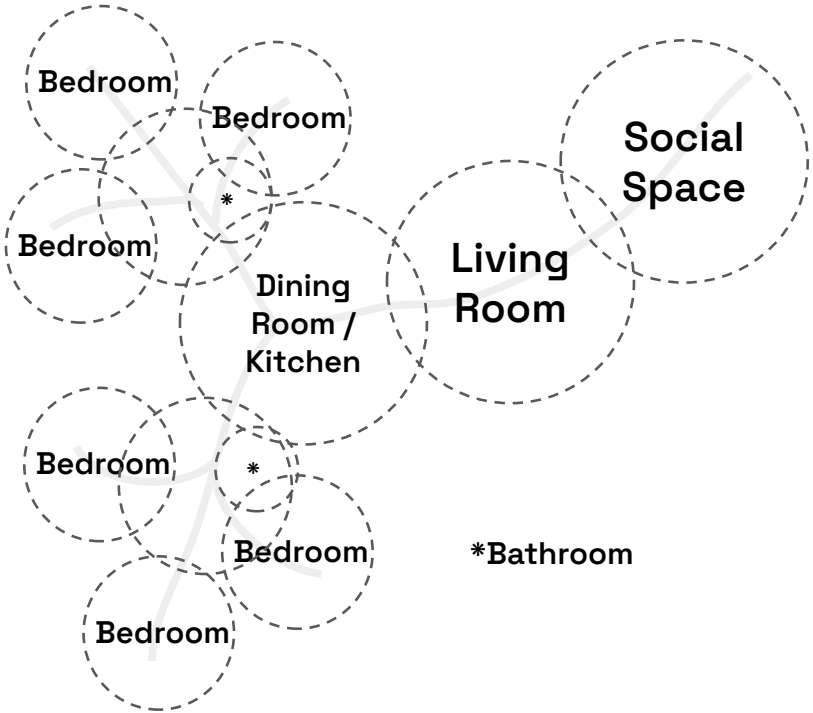
Proof of Concept

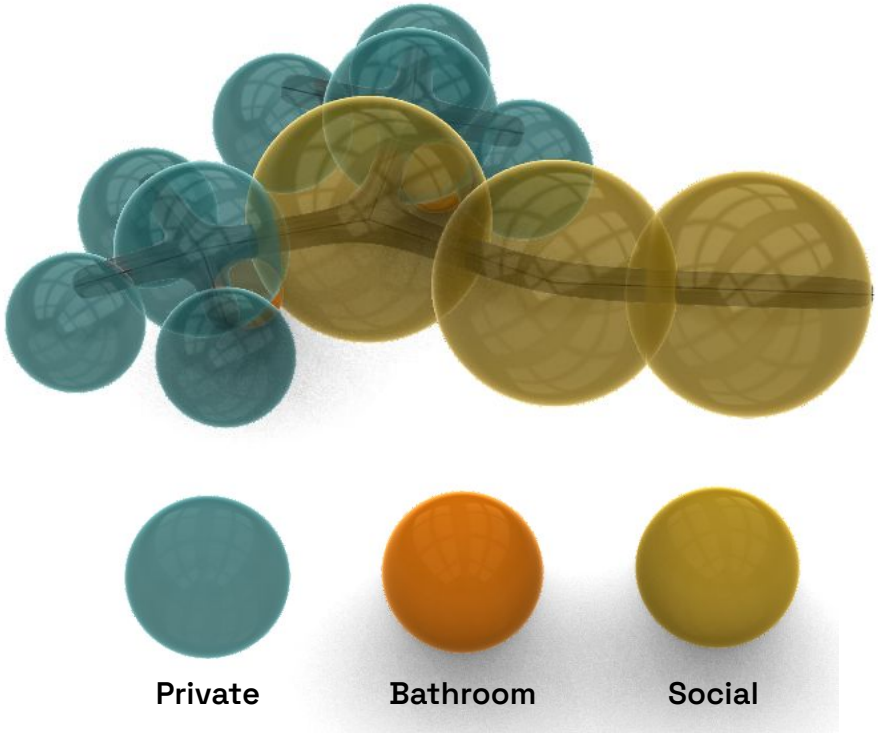
L-System



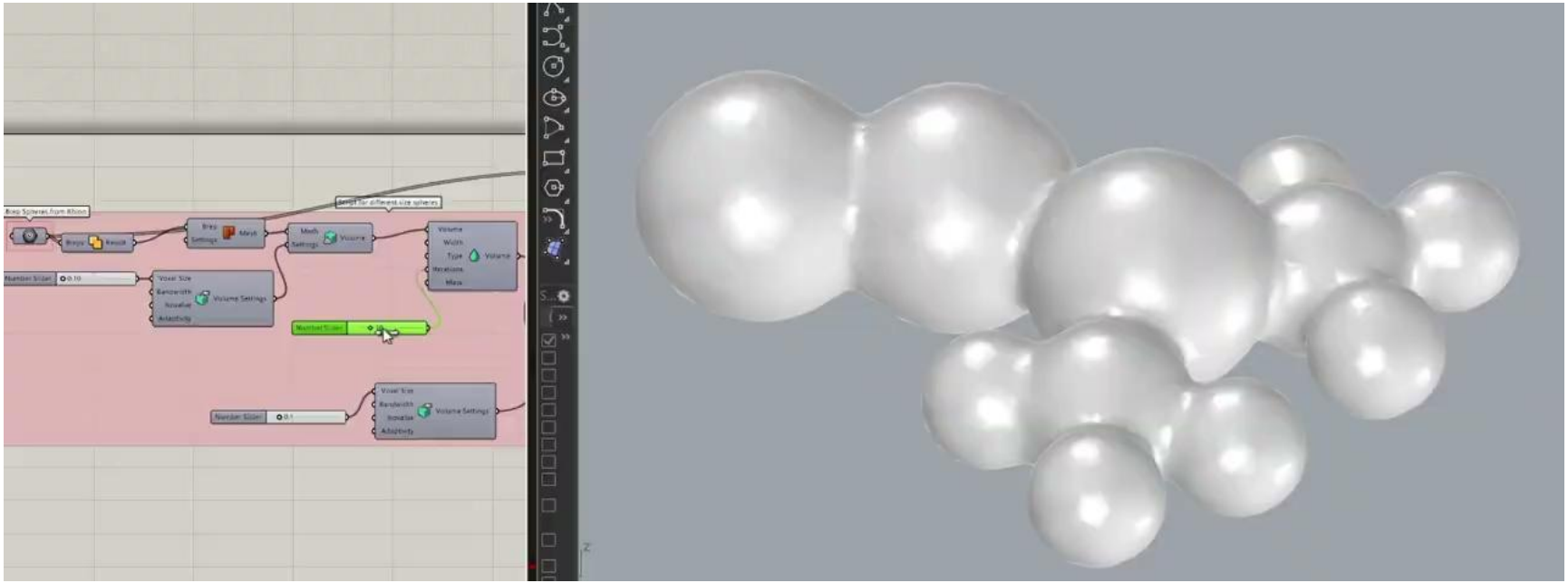


Bubble Diagram

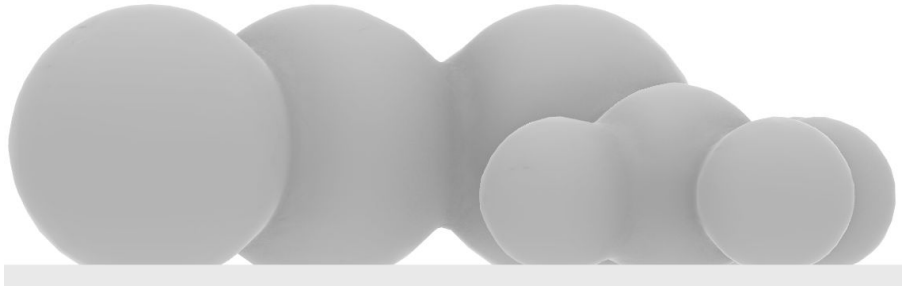


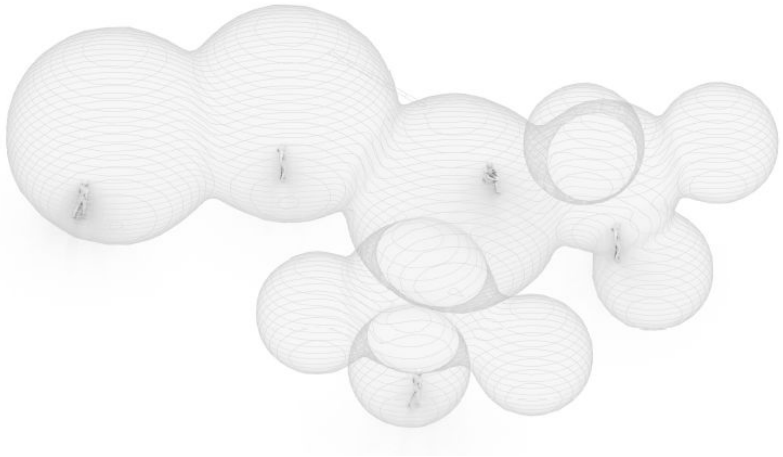


Grasshopper Metaball Script

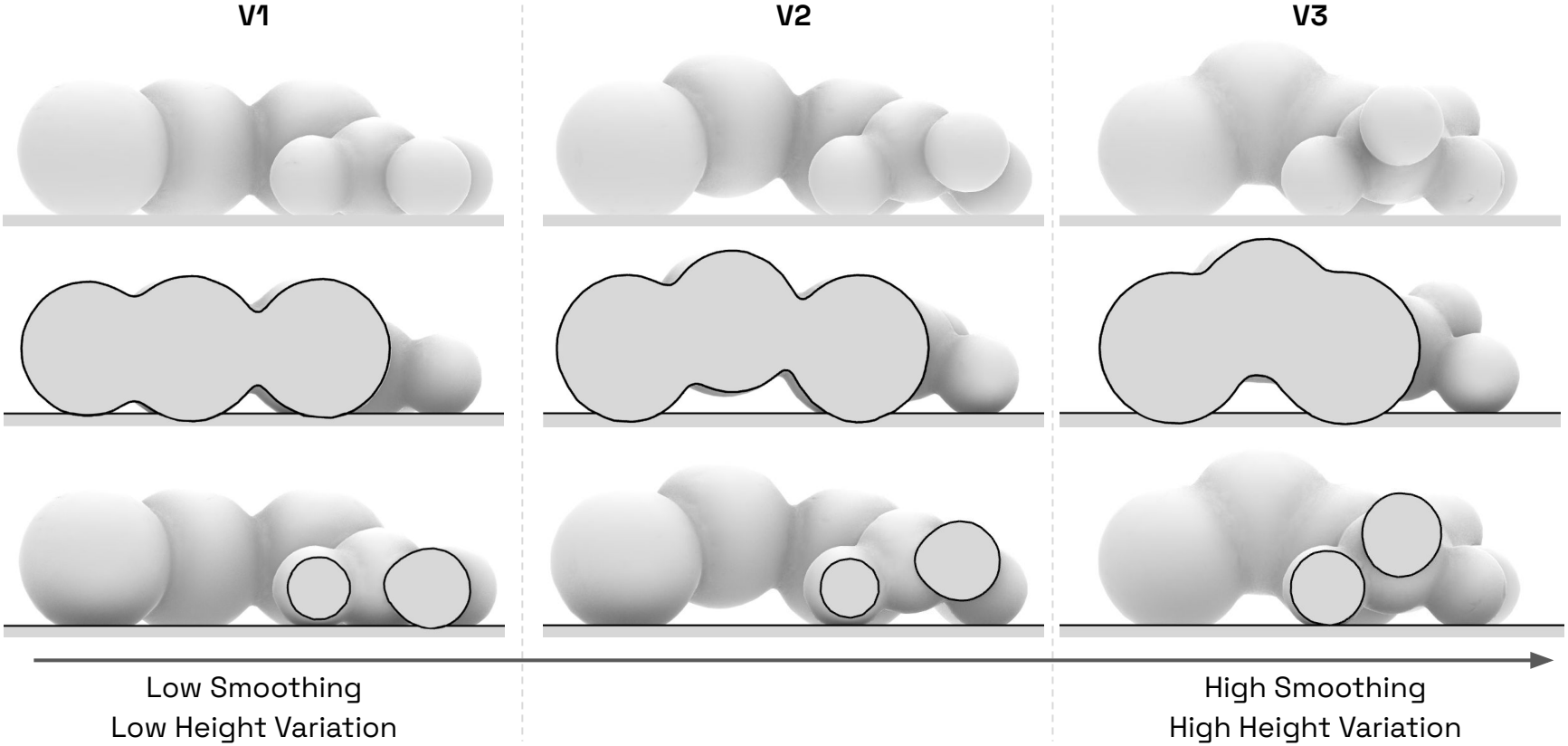


Bubble diagram → metaball volumes



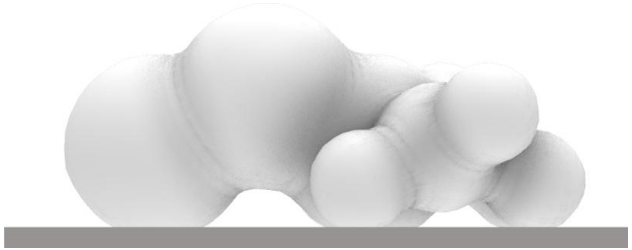


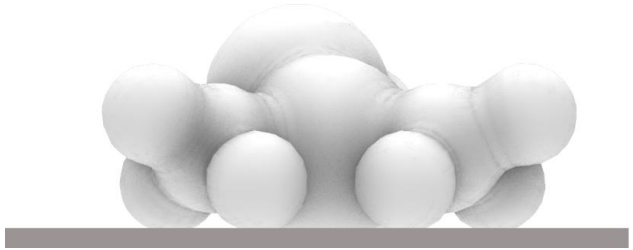
Metaball Adjustments

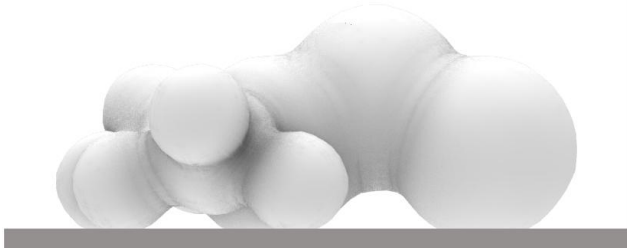


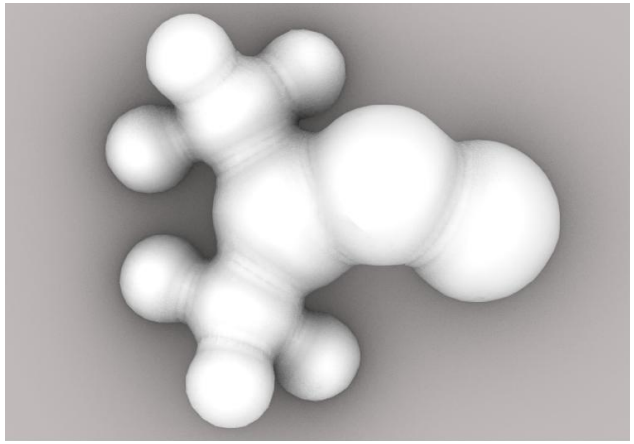
Metaball Adjustments

V3





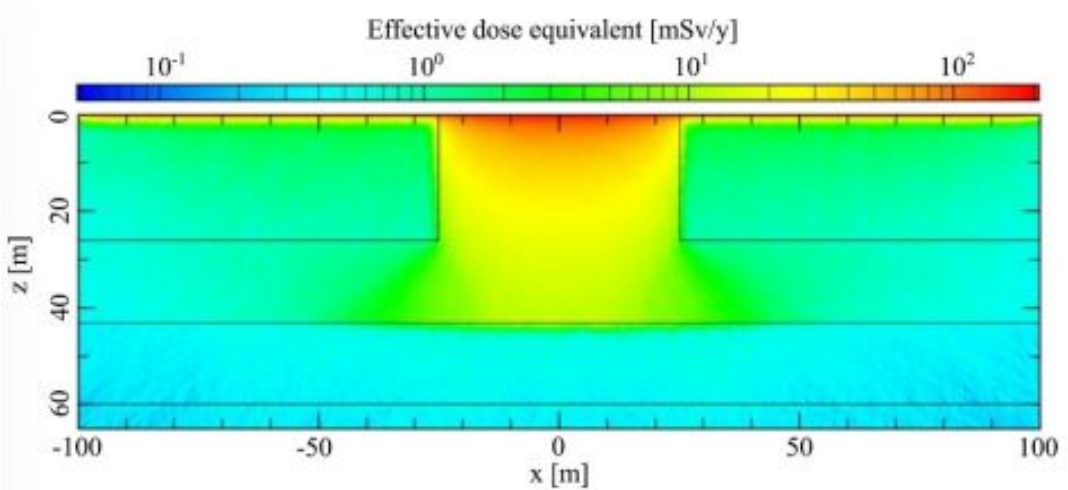




Structural Justification

Radiation protection

- Lava tubes significantly reduce radiation exposure
- **54 cm of regolith** shielding is required for a safe habitat



Simulation of effective radiation dose equivalent inside a lava tube. (from M. Naito et al. She et al., 2025)

https://moonshotplus.tudelft.nl/images/f/f4/1.13.1_RoboticsInstitute_FinalReport_JIP2025.pdf

Structural Justifications

Design V1 - Force of Gravity

Max Compression
0.00869 < 9.250 kN/cm^2

Max Tension
0.00236 < 0.925

Structure performs well in low gravity

Overengineered thanks to the thickness required for radiation protection

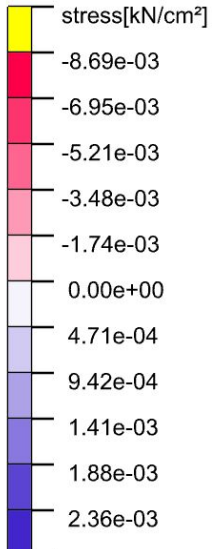
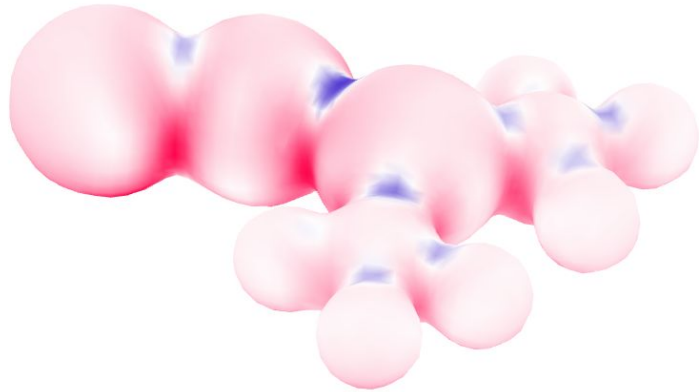


TABLE 4 Compression strength of samples solidified at different target temperatures.

Target temperature (°C)	1300	1400	1500
Compressive strength (MPa)	27.4 ± 2.6	118.2 ± 2.9	125.1 ± 18.4
Initial failure strength (MPa)	15.6 ± 7.0	65.5 ± 2.1	92.5 ± 16.3



Forces: Gravity

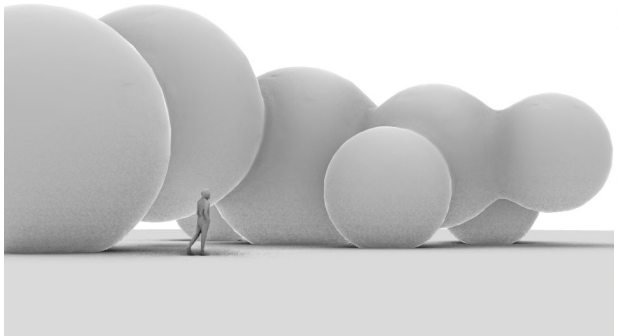
https://www.researchgate.net/publication/390602870_Melting_and_solidifying_behavior_of_lunar_regolith_simulant_under_a_vacuum_environment

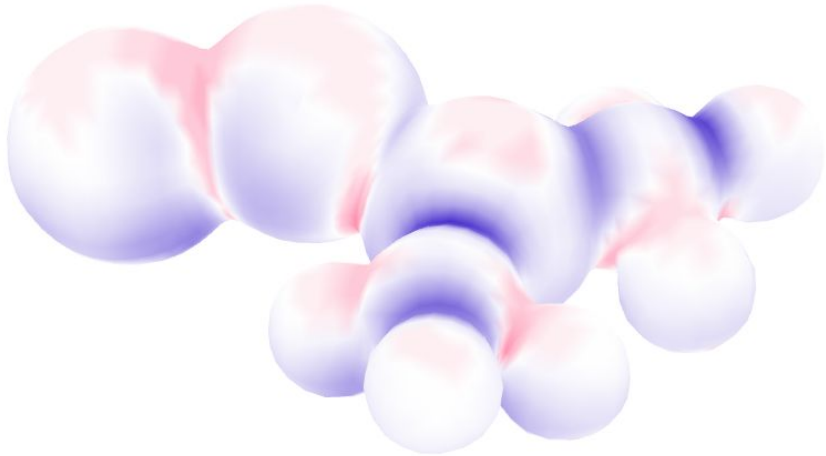
Structural Justification

Design V2 - Cantilevers

Raising the metaballs

→ More variable interior facilitating jumpy lunar movement

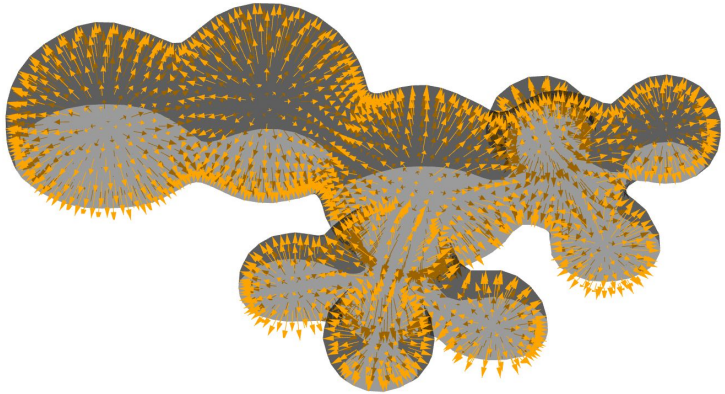


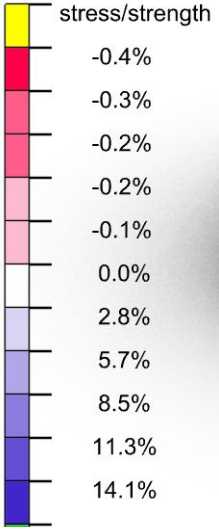


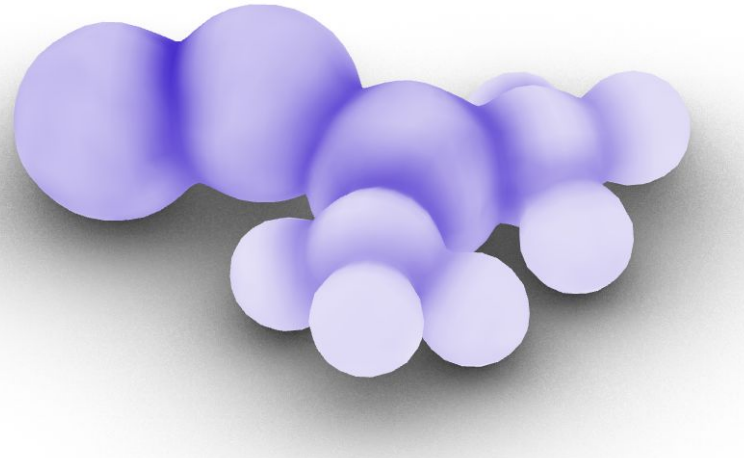
Forces: Gravity

Structural Justification

Design V2 - Pressurised







Air pressure pushes the shell out

Peak tension 1.7% → 14.1%

Forces: Pressure

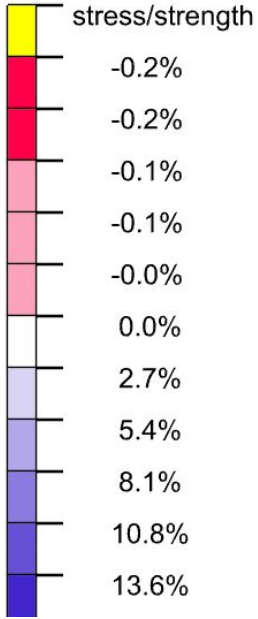
Design V3 - Metaball smoothing

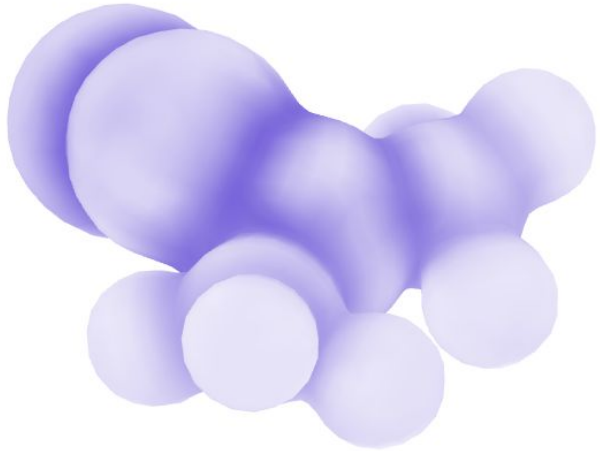
Metaballs are moved closer together and blended

→ More efficient load path to the ground

→ ‘necks’ are reduced

→ Reduce peak stress in the hotspots





Forces: Gravity + Presure

Porosity

Window Type Exploration

Small

Large

Metaball

Window Type Exploration

Round

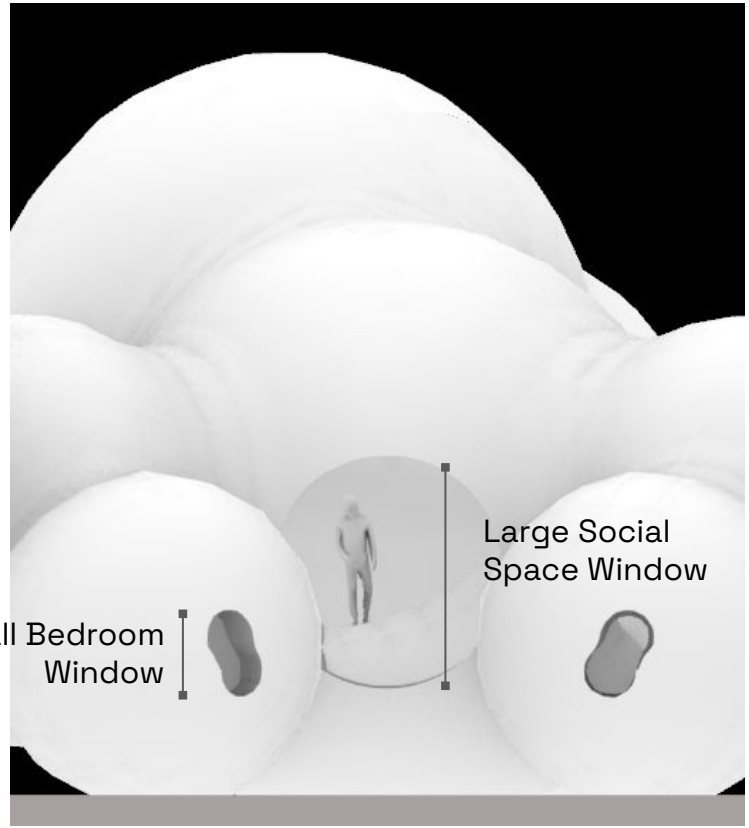
Metaball

Porosity

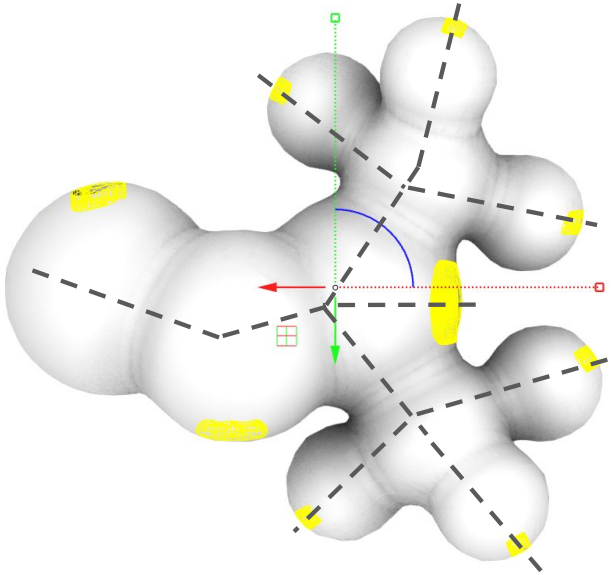
Porosity levels

	Function	Porosity Demand
	Private Quarters	Low-Medium
	Transition Space	No-Low
	Kitchen/dining room	High
	Social Space	Medium
	Living Room	High

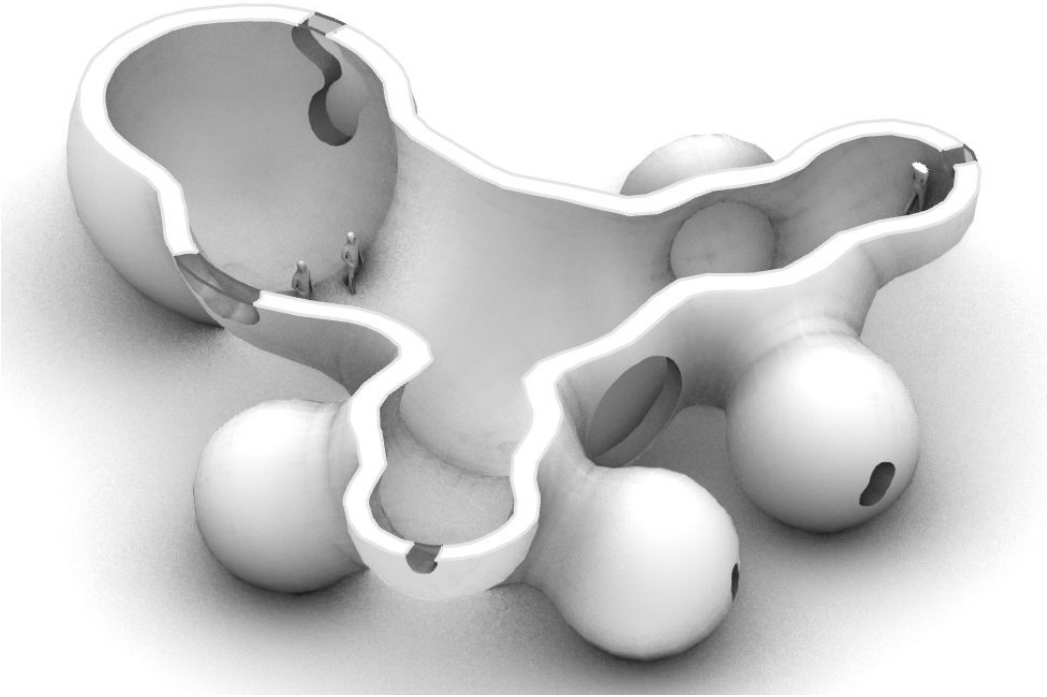
- Dependent on function
- Private vs Public



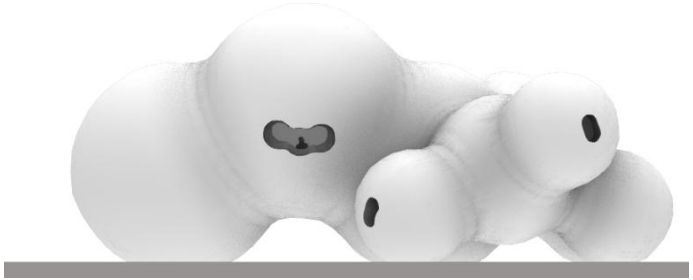
Porosity

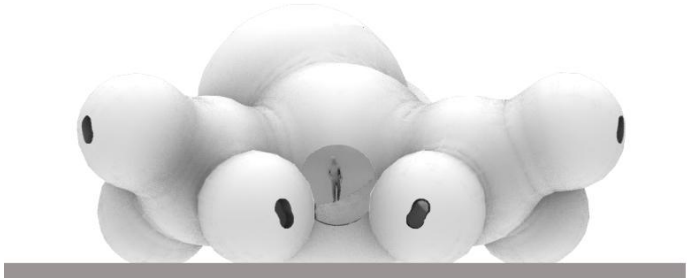


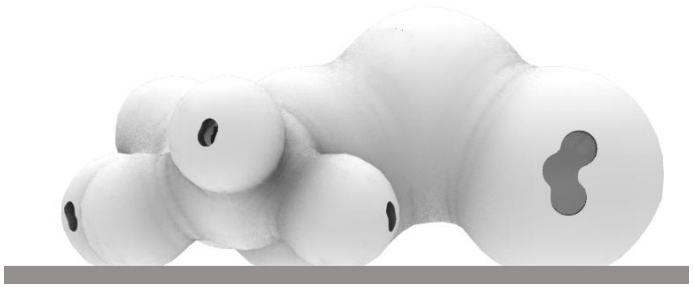
Windows generally
follow L-system axis

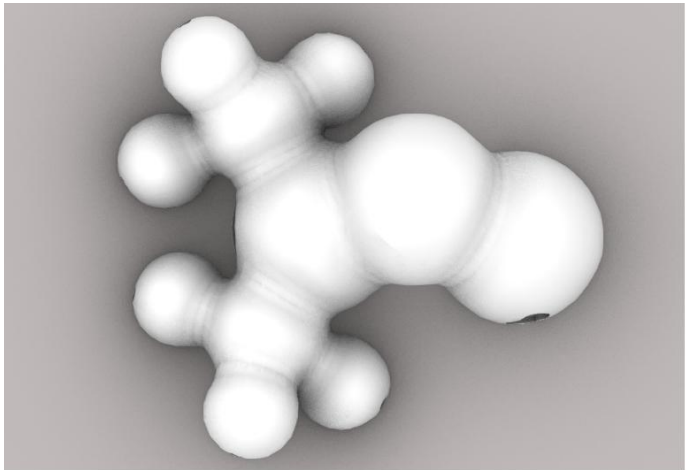


Porosity

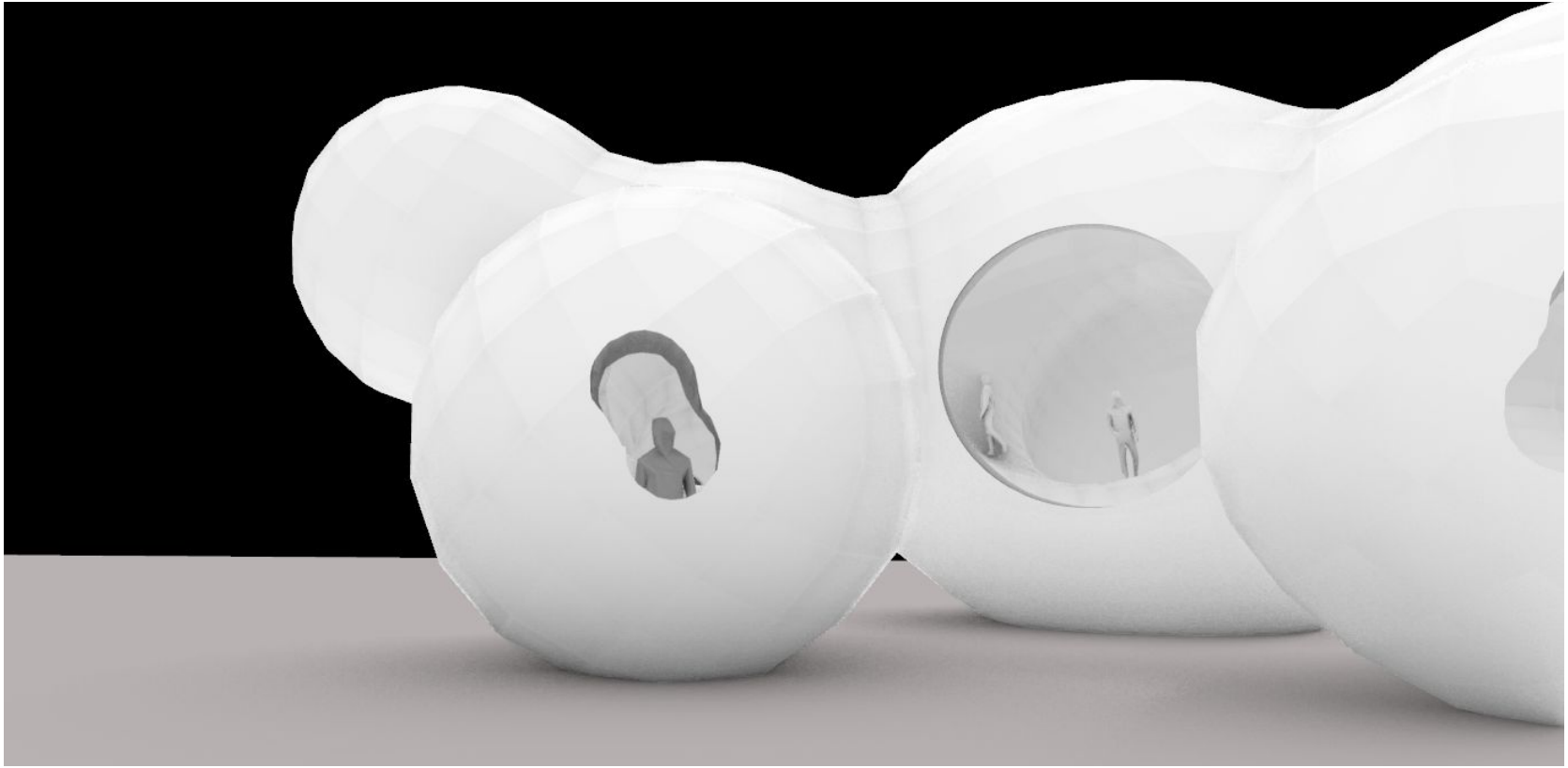




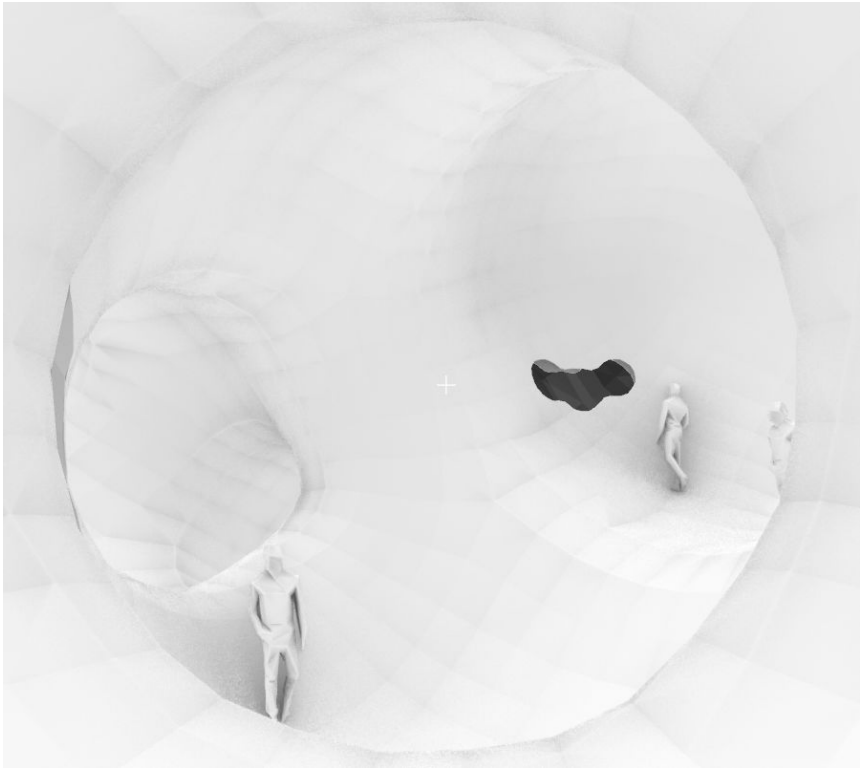




Porosity



Interior - Lunar Playground



Circadian Lighting

SECTION

Conclusion

Concept Summary

Design Steps

1. L-system
2. Bubble diagram
3. Metaballs
4. Metaball structure optimization
5. Porosity
6. Integrated Circadian Lighting

Biophilic Response

Checklist

- ☐ Non-monotonous, dynamic spaces
- ☐ Seperation between public & private spaces → ability to retreat
- ☐ Lighting comfort
- ❑ Acoustic comfort
- ❑ Thermal comfort
- ❑ Air quality

Next Steps

- Integrate plant life into the indoor climate system to help with life support, food production, waste stream management and air quality
- Show thermal massing, heat sinks and plant cooling to increase thermal comfort
- Integrate biophilic inspired acoustic pattern on the interior
- Integrate biophilic pattern for the exterior