E.D.E.N.

Extended Duration Extraterrestrial Nest

Designing a lunar lava tube habitat
rooted in biophilic design

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SECTION

BACKGROUND

Problem Statement

What stands in our way of living on the moon?

- In-Situ Resource Utilization
- Environment unlike anything on Earth
- Long periods of isolation and indoor living

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

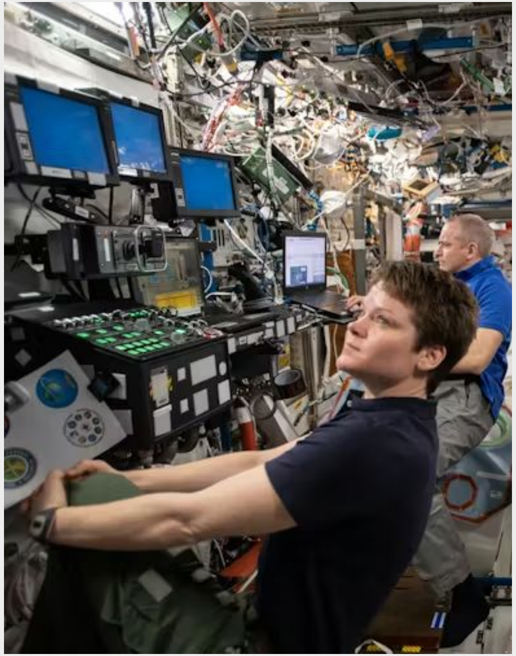
poses a solution by creating a protective cover from the environment in combination with the shelter provided by the habitat

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



Biophilia

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

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

Relevance

Why is this topic urgent/important?

THE MOON

- Artemis missions I → IV are taking us to the moon in the coming years
- The project is a stepping stone in the larger journey to eventually colonise Mars

EARTH

- Space as a driver for innovation
- Transfer of technology

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

Motivation

Personal

- Exciting challenge
- Novel and relevant
- Biophilic design makes it more tangible for terrestrial applications

Study

- ISRU sustainability potential
- Advancing robotic manufacturing methods
- Innovating 3D printing to help solve the housing crisis

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 and topology optimization be applied to the structure to get a more biomorphic design?

Scope

TEAM SIZE	6 person team, rotate 3 at a time for knowledge transfer	**LOCATION**	South pole → Shackleton
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	Different aspects: human-centric, biophilic, circular, computational, advanced manufacturing, life support systems, etc.		

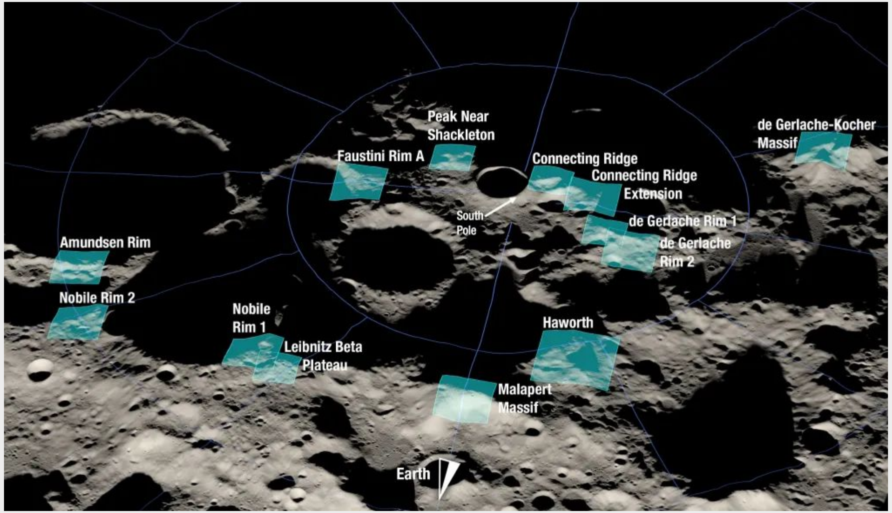
SECTION

ANALYSIS & CONCEPT

Site

ARTEMIS MISSION SITES

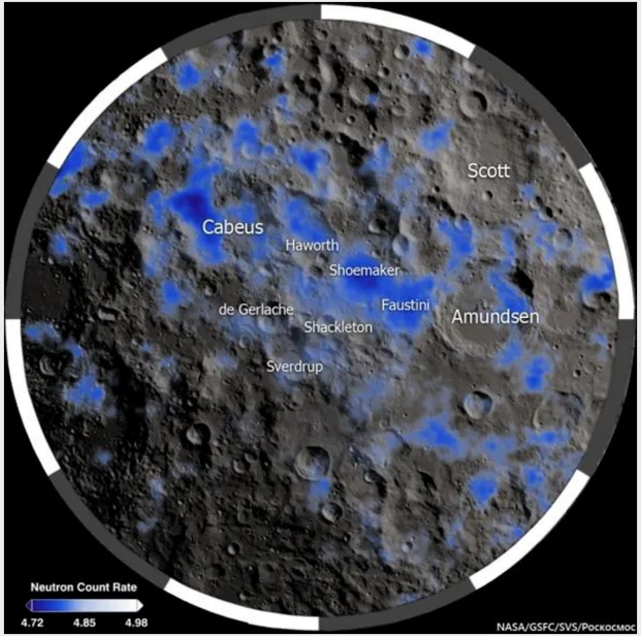
- Going to the South Pole
- First established missions and habitat will be here



Site

Resources

- Water is a critical resource
- Dark pits in the moon under constant shade can have ice deposits
- Lower temperatures stop water sublimation compared to sunlit ridges

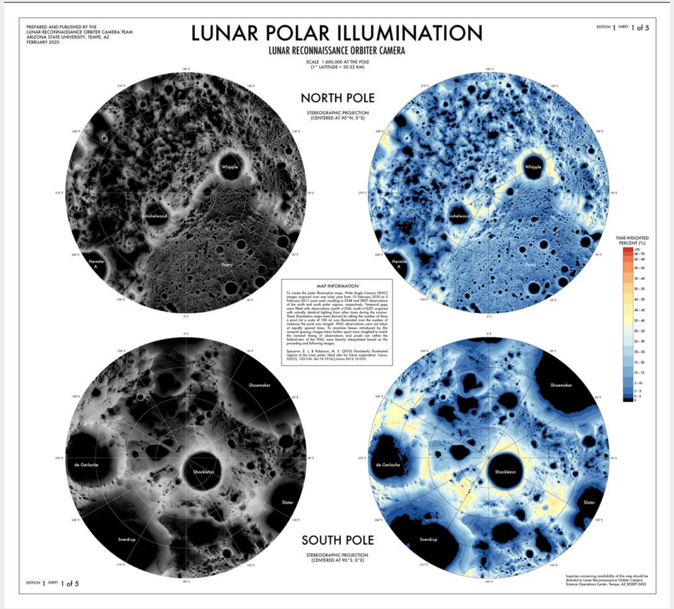


https://science.nasa.gov/image-detail/svs-lend-20130601-580-2/

Site

Sunlight

- Critical for energy production through solar panels
- Long 14 day lunar night cycles
- Only the rim of craters catches the low sun



https://lroc.im-ldi.com/images/downloads?utm_source=chatgpt.com#cat-3

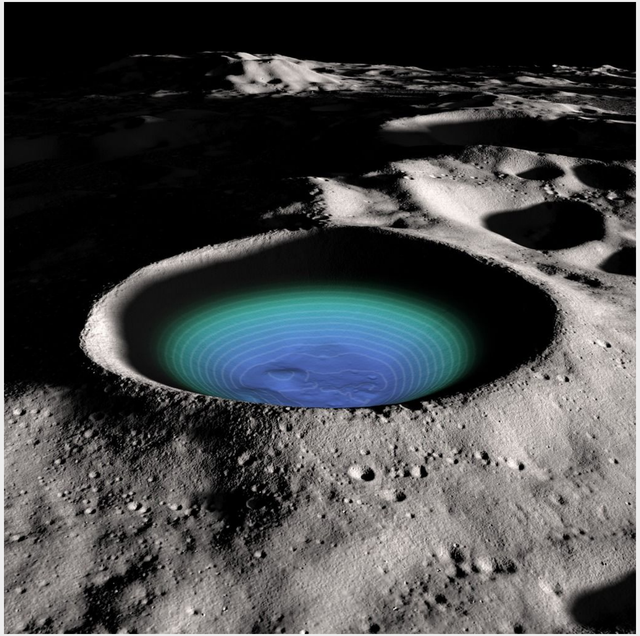
Site

Shackleton

- Shackleton crater has a rim that is almost constantly illuminated.

- Near proposed Artemis landing sites

- Possible ice deposits

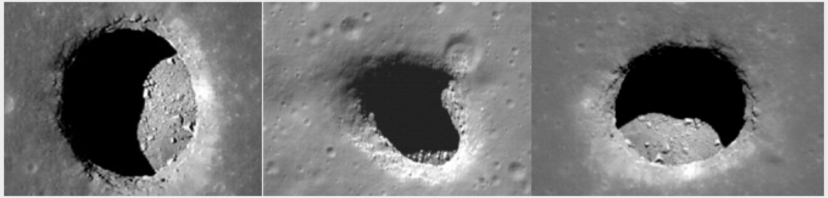


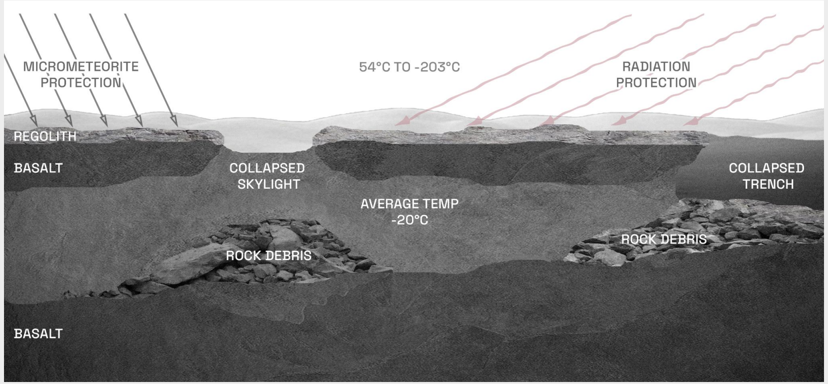
https://svs.gsfc.nasa.gov/4716/

Site

Lunar Lava Tubes

- Possible ice deposits
- Shielding from radiation
- Protection from micrometeorites
- More constant temperature than on the surface
- Much larger than on earth → huge caverns



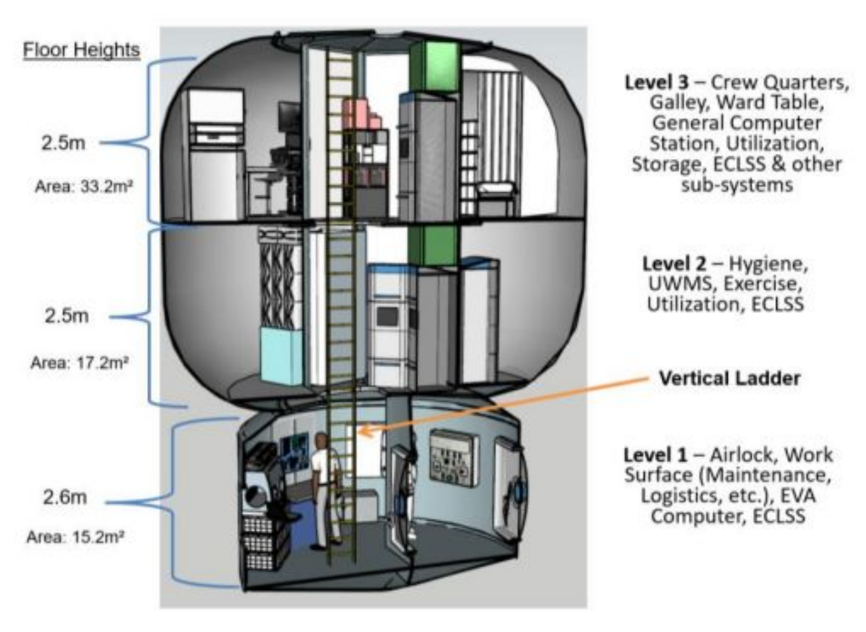


https://phys.org/news/2020-07-lava-tubes-exploration-priority-worlds.html

Programme

Proposed Artemis Habitat

- Cramped / Dense
- Utilitarian
- Relatively low ceiling height



https://ntrs.nasa.gov/api/citations/20220013669/downloads/Internal%20Layout%20of%20a%20Lunar%20Surface%20Habitat.pdf

Programme

Schematic Design

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												

Programme

Zoning

- 5 main zones based on activity type
- Square footage based on a team of 6

ZONE	AREA	Percentage
Dirty	116	22.10%
Core Utility	55	10.48%
Personal/Quite	76	14.48%
Social	126	24.00%
Work	152	28.95%
TOTAL	525 m^2	100.00%

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**

source

Organic Shapes

Case Study

Casa Organica by Javier Senosiain Arquitectos

- Organic shapes
- Cozy interior
- Integrated lighting
- Integrated furniture

https://www.archdaily.cl/cl/907098/casa-organica-javier-senosiain

Organic Shapes

Biophilic Design

https://www.archdaily.cl/cl/907098/casa-organica-javier-senosiain

Contact with Nature

Case Study
Singapore Airport

- Use of water and plants
- Indoor environment with an outdoor quality
- Large atrium space helps achieve the effect of forgetting you're inside

L-System

Method

- Lindenmayer systems
- The mathematical theory of how plants develop
- Geometric modeling of plant growth with branches moving outwards

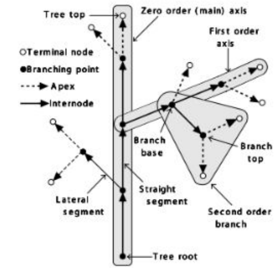
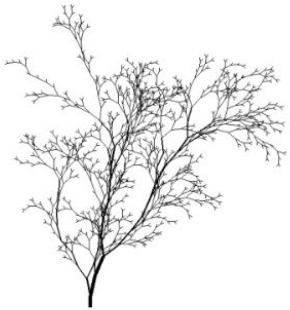


Figure 1.20: An axial tree



Effect on Design

- Can be used to inform designs
- Spatial L-system that allows the habitat to be modularly expanded and ‘grow’
- Columns can follow the system to look like trees and evoke biophilia

Prusinkiewicz, P., & Lindenmayer, A. (2012). *The algorithmic beauty of plants*. Springer Science & Business Media.
https://drive.google.com/file/d/1que6baMY2ARKjPUPH36M0zoywumJKhKp/view

L-System

Case Study

Sagrada Familia by Antoni Gaudi

- Inspired by nature
- Tree-like columns
- Lots of natural lighting

Inverted Catenary

Case Study
Sagrada Familia by Antoni Gaudi

- Exact opposite of tension is compression

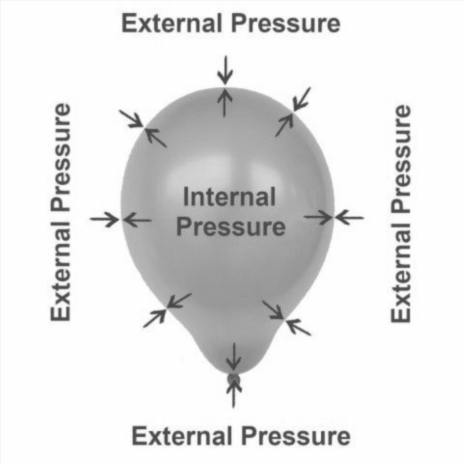
Inverted Catenary

- Perfect tension
  → Perfect Compression

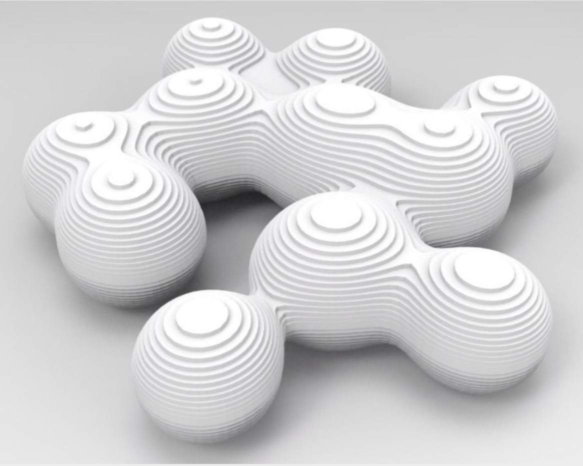
- 3D printing is stronger in compression than tension

Metaballs

1. Easy way to achieve an organic look
2. Spheres are ideal shapes when dealing with pressure
3. In a vacuum there is no external pressure pushing in, so the air expands and pops the balloon



Force from pressurised cabin in a vacuum puts stress on the structure



Modular collection of spherical pods

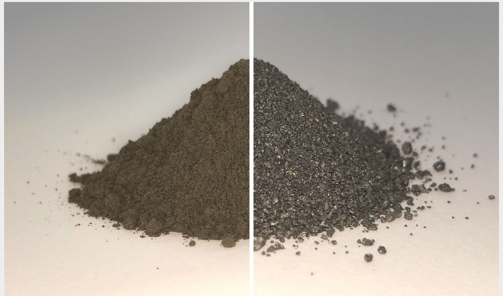
Source

SECTION

CONSTRUCTION & MATERIALISATION

ISRU

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

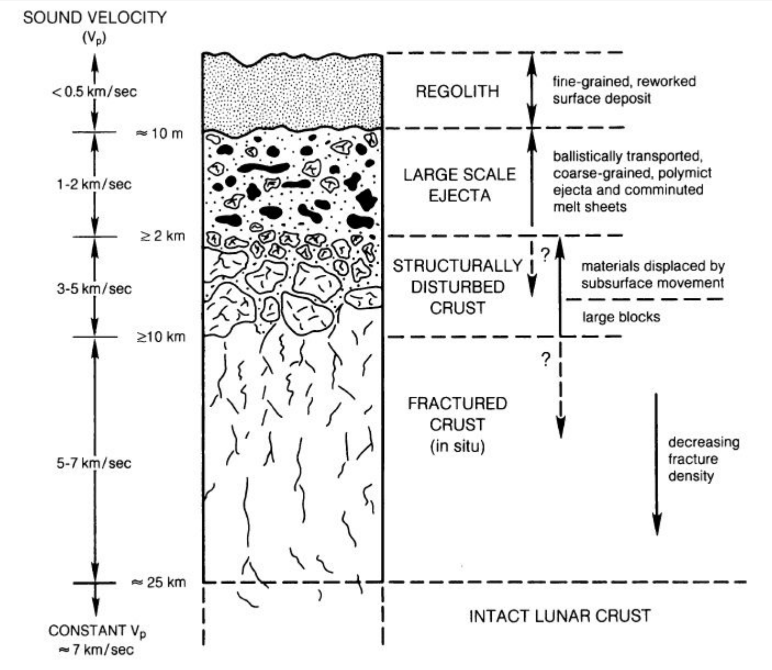
https://www.researchgate.net/figure/Assumed-Composition-of-the-Lunar-Regolith-and-Variation-Across-Soil-Types-a_tbl1_258661774

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

ISRU

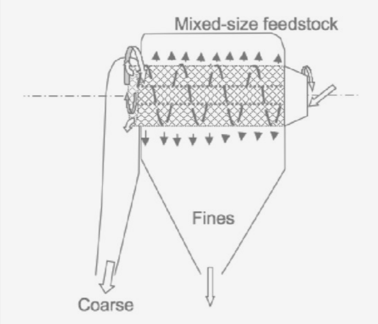
3D Printing

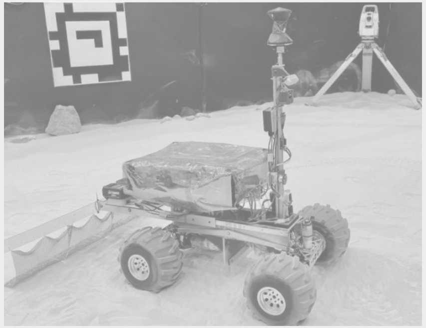
- Using the top layer of regolith
- Easy to mine with robots
- Need a way to 'print' the dust without additives

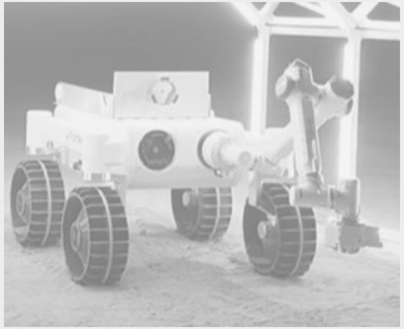


https://www.researchgate.net/figure/The-vertical-structure-of-the-Lunar-regolith-and-crust_fig7_264340952

Robotic Process





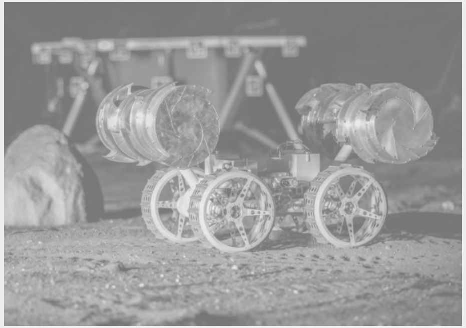


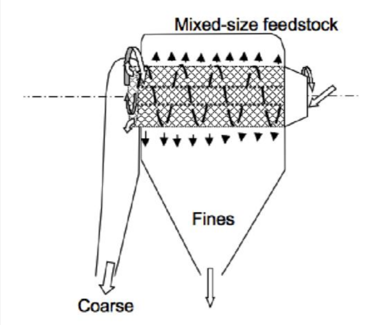
COLLECTING PROCESSING FLATTENING MELTING

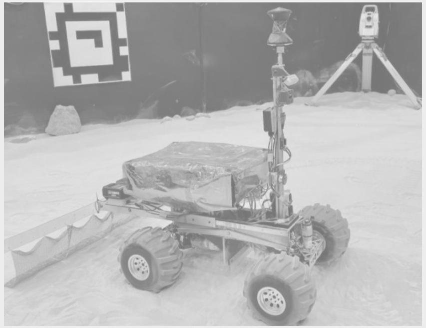
https://moonshotplus.tudelft.nl/images/7/7f/1.13.1_Space%26Robotics_FinalPresentation_JIP2025.pdf

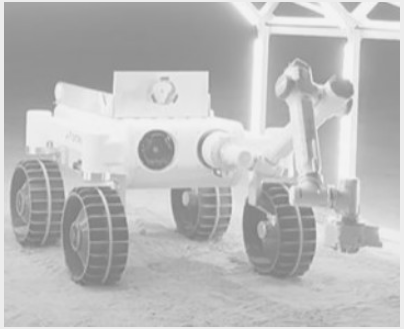
ISRU

Robotic Process









COLLECTING | **PROCESSING** | FLATTENING | MELTING

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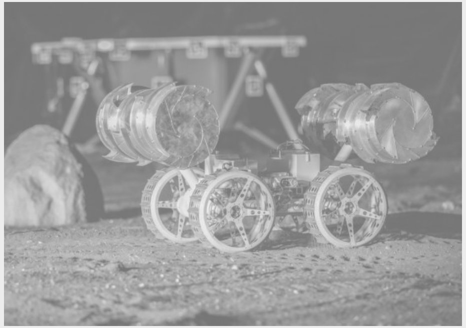

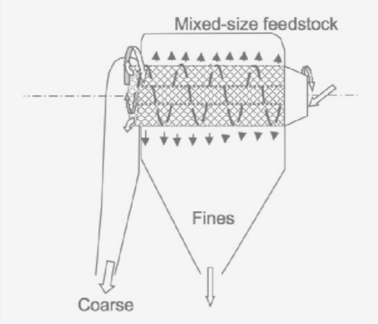

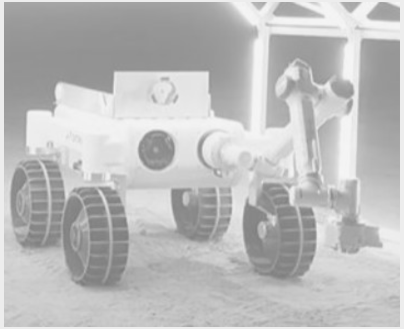

COLLECTING PROCESSING **FLATTENING** MELTING

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ISRU

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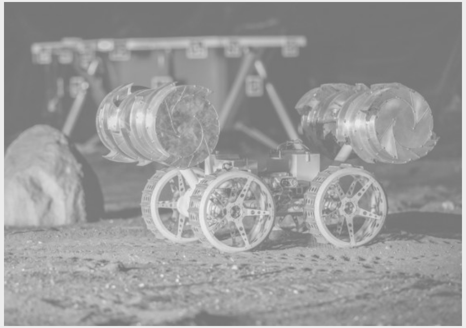
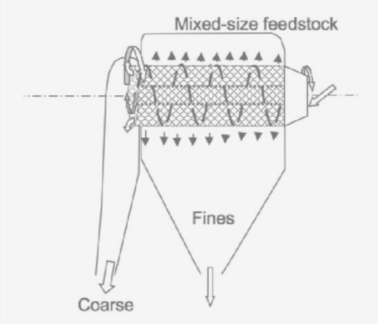
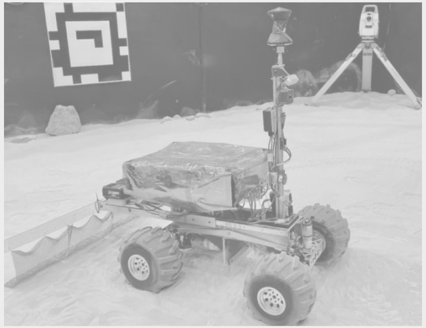
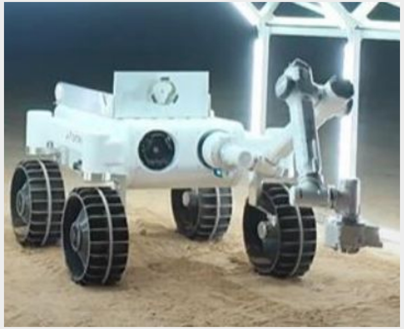








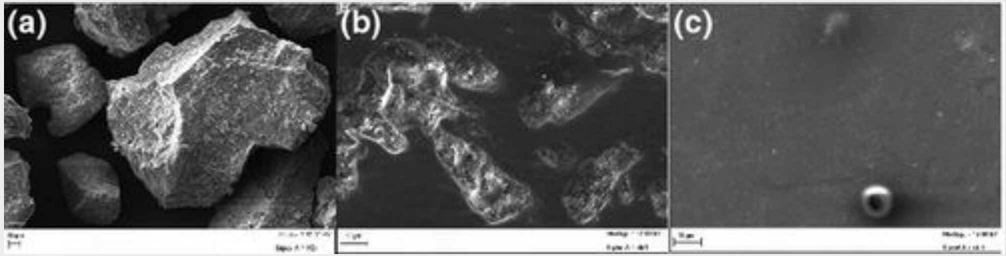
COLLECTING PROCESSING FLATTENING **MELTING**

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

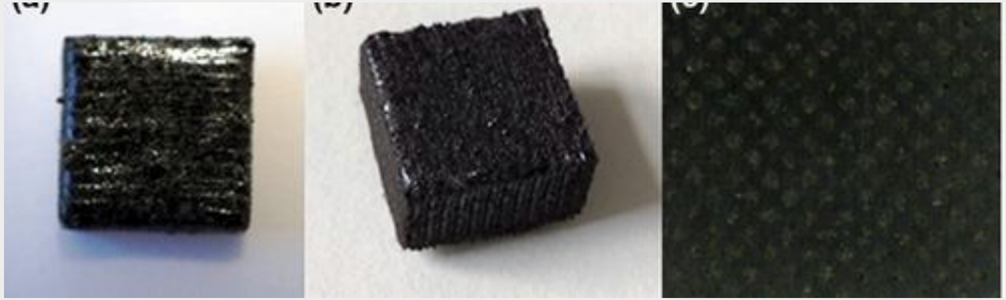
3D Printing

Selective Laser Melting (SLM)

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



Powder | Sintered | Melted



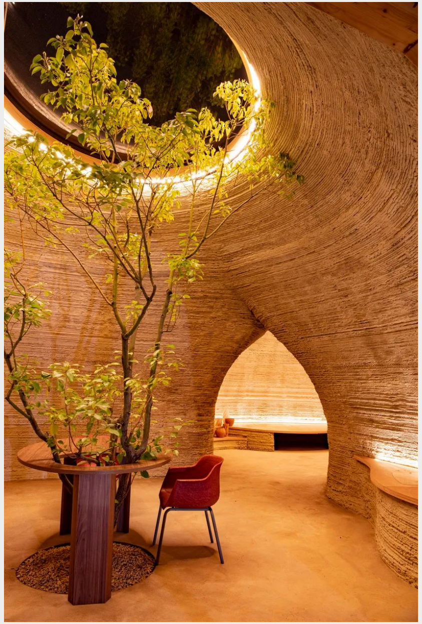
Fateri, M., & Gebhardt, A. (2015). Process parameters development of selective laser melting of lunar regolith for on-site manufacturing applications. International Journal of Applied Ceramic Technology, 12(1), 46-52.

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

SCHEMATIC DESIGN

Why L-systems

1. Modelled after a natural growth process
   → Biophilia

2. Modular design
   a. Building can grow
   b. As lunar presence expands, the habitat can extend to meet new spacial demands

3. Easy/efficient pathing
   a. Central corridor line that connects all branches
   b. Central veins can carry life support resources (oxygen, electricity, water)

L-system generated by me using Francesco's grasshopper script

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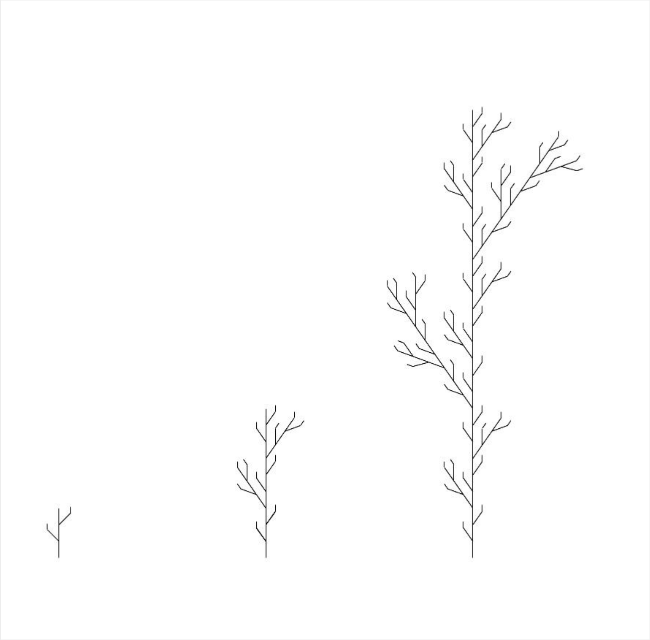

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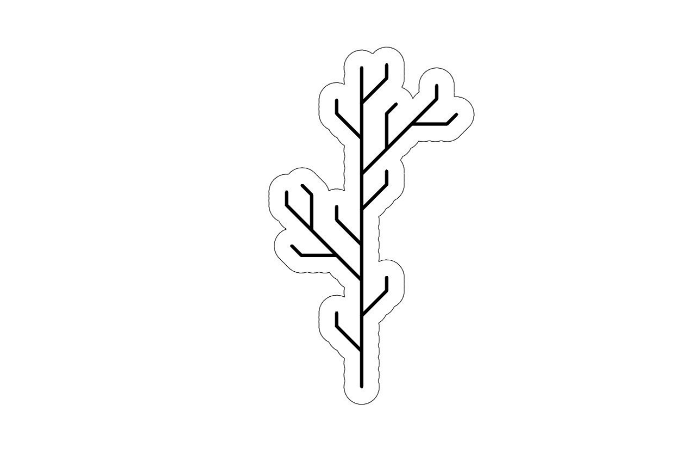
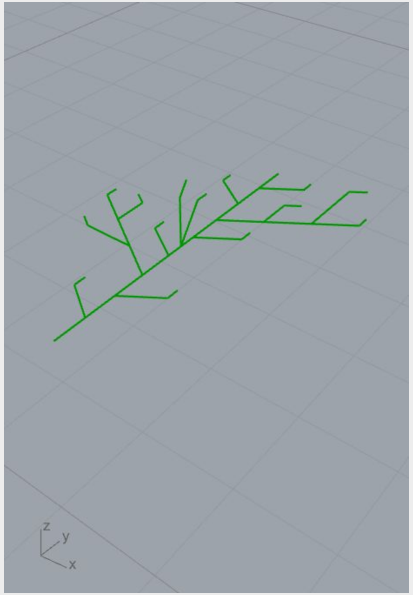
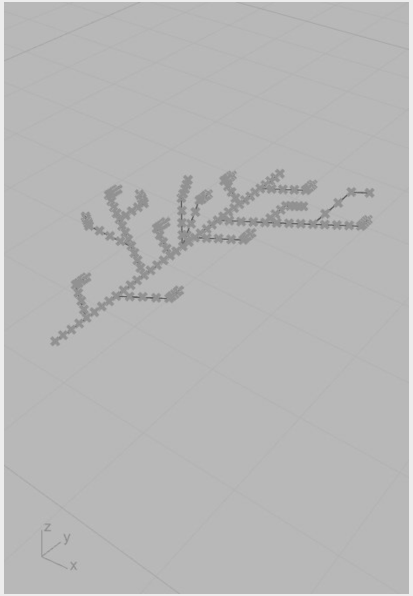


L-system generated by me using Francesco's grasshopper script

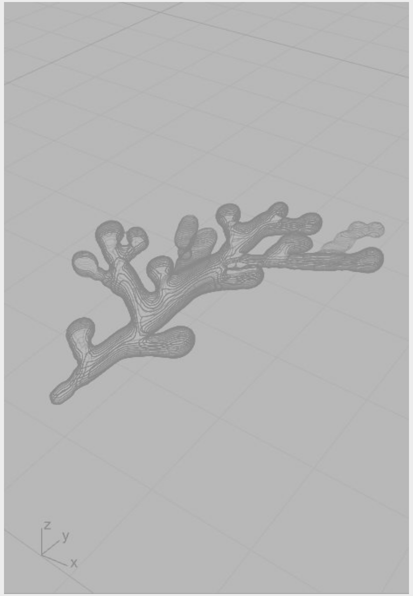
Computational Steps 3D



L-system



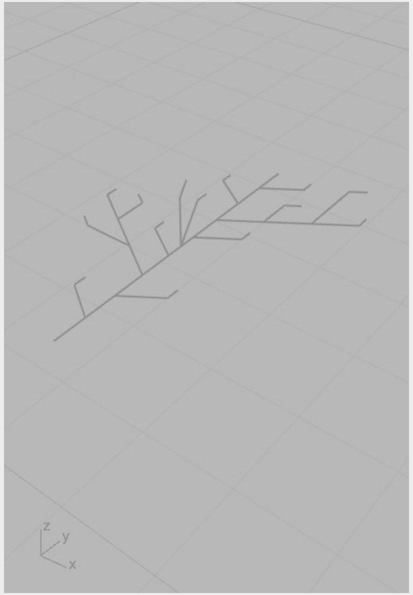
Points



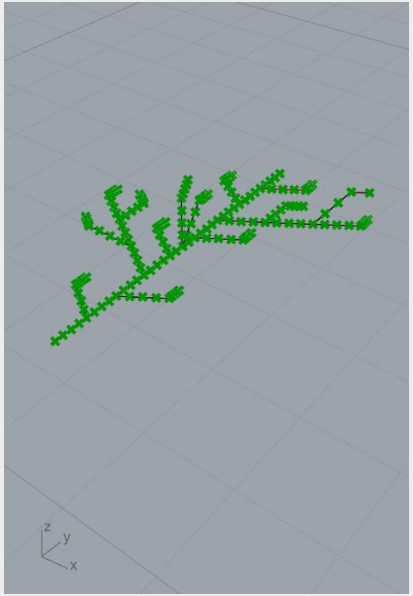
Metaballs

Source

Computational Steps 3D



L-system



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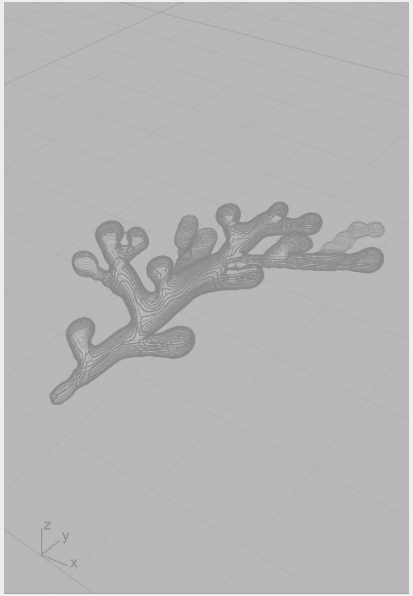
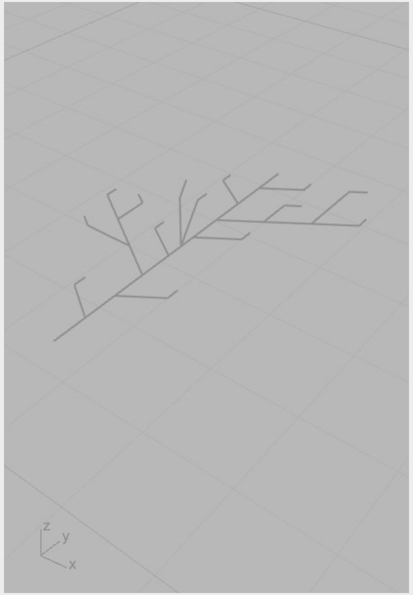


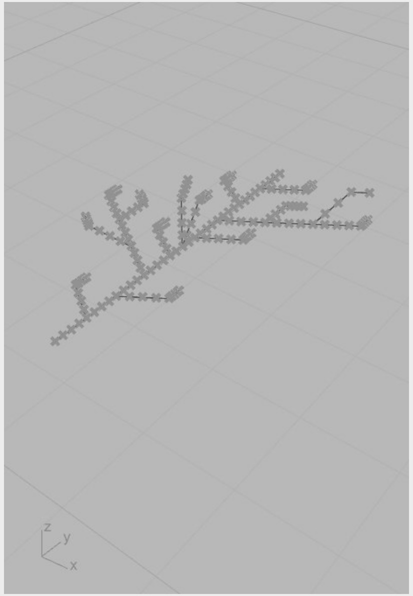
Metaballls

Source

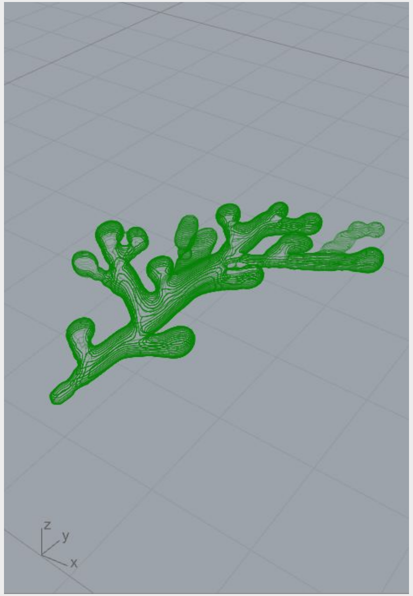
Computational Steps 3D



L-system



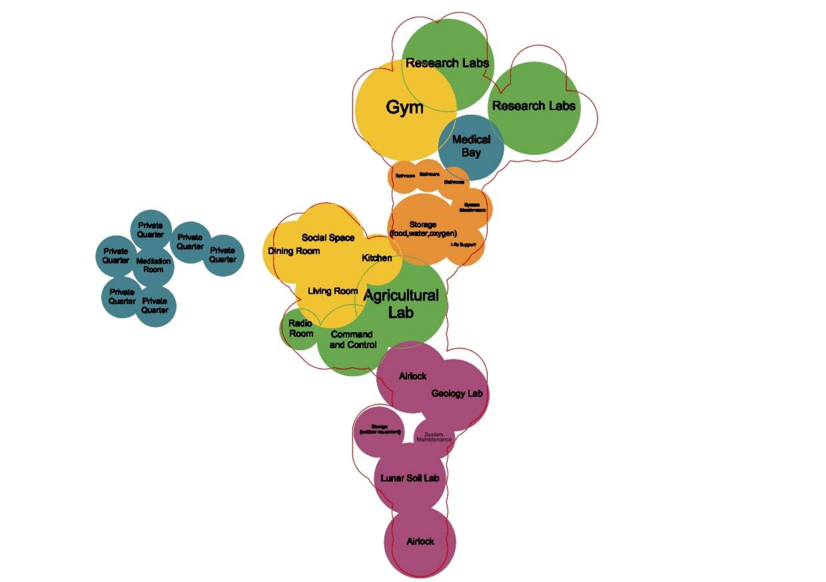
Points



Metaballs

Source

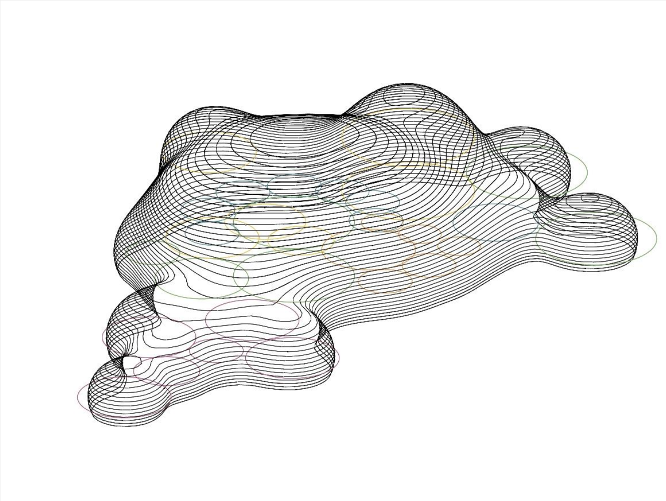
Integrating bubble diagrams



Bubble Diagram Iterations

1

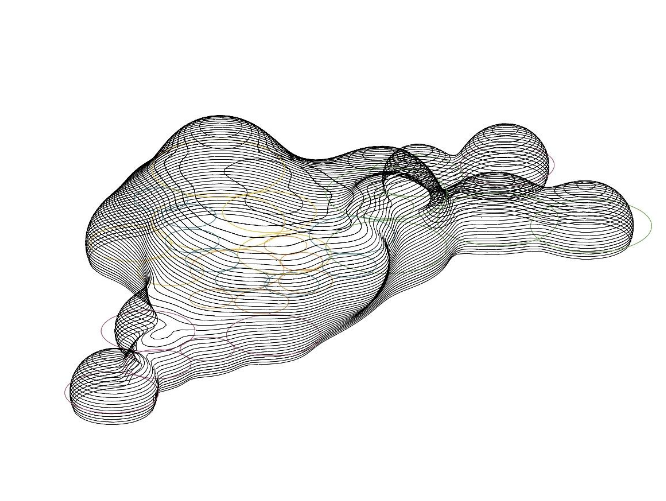
- Too dense
- Too high
- No clear hierarchy and metaballs are lost



Bubble Diagram Iterations

2

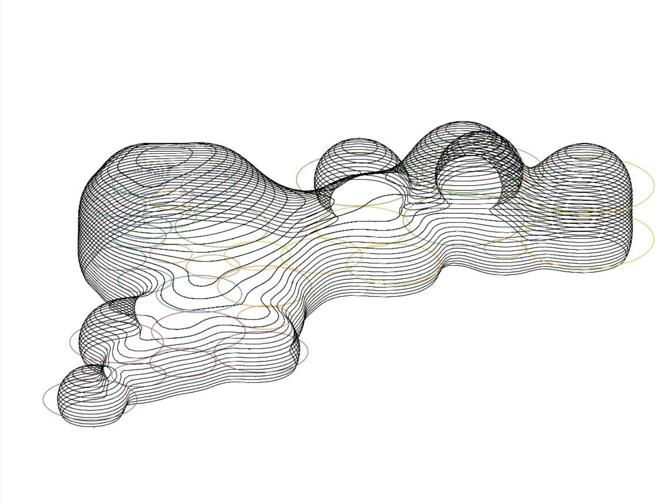
- Clear zoning
- Exit on either end
- Still quite bulky



Bubble Diagram Iterations

3

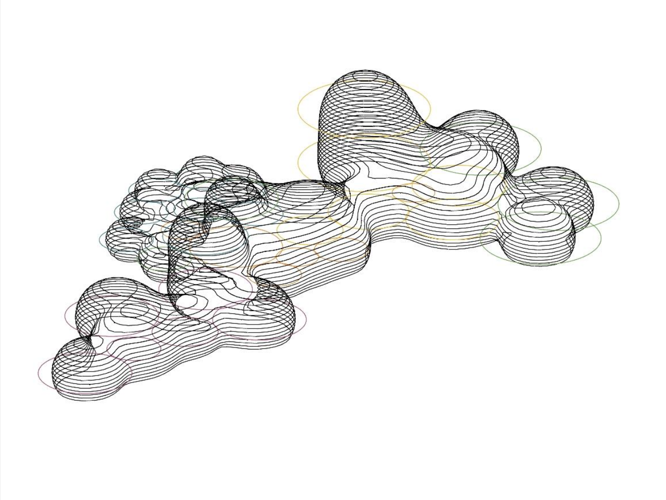
- Clear zoning
- More visible distinction from outside
- Sleeping zone feels large... not intimate



Bubble Diagram Iterations

4

- Clear zoning
- Different volumes
- Sleeping pods
- Tall gym & command



SECTION

NEXT STEPS

Reflection

Next steps

- Refine floor plans
- Expand use of metaballs and L-systems
- Differentiate the different volumes
- Incorporate lunar movement in the design