Computational Design

Paul Bourke

iVEC @UWA

Outline

- Introduction to iVEC

- (Science) Visualisation

- Serial vs parallel computing

- Examples - Euclidean geometry. Equation vs algorithm
  - Supershape, parametric equations
  - Space filling algorithm
  - dForm surfaces, form determined by simulation
  - constructive solid geometry

- Examples - Fractal geometry, modelling natural forms
  - Diffusion limited aggregation
  - Landscape and planet modelling
  - L-Systems
  - 3D replacement rules
  - Tiling and texture synthesis

- Technologies
  - Rapid prototyping
  - 3D reconstruction

Introduction to iVEC

- A joint venture between the 5 research institution in Western Australia.
- Comprises of the 4 public Universities in WA and CSIRO.
- Provides advanced computing to researchers in the state.
  - Supercomputing
  - Storage
  - Visualisation
  - Collaboration
  - Expertise
- Partners subscribe to be members of iVEC => no end user charges.
- Programs
  - Supercomputing technologies
  - Industry uptake
  - eResearch
  - Education (* See call for interns http://ivec.org)
  - Visualisation

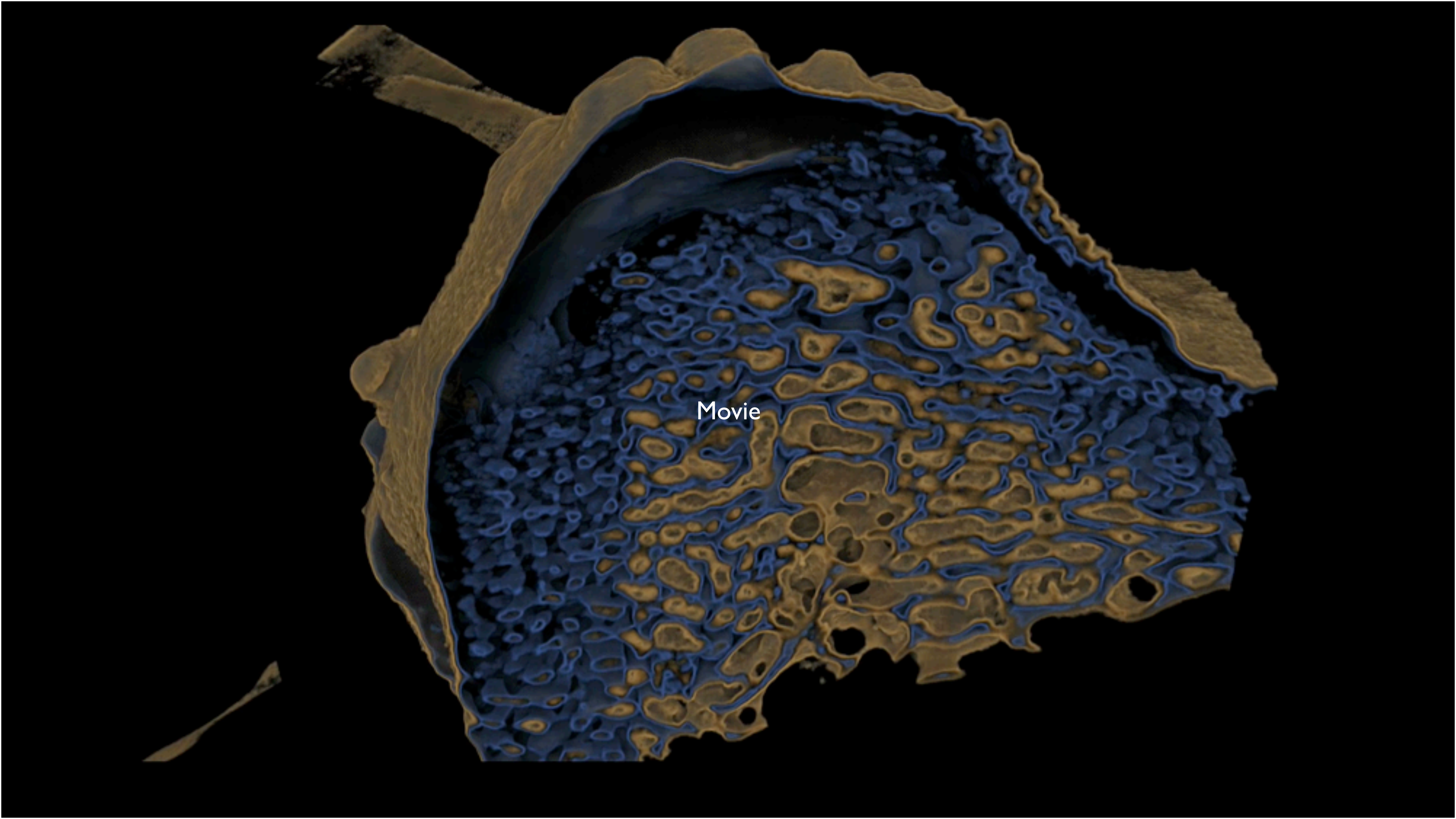
Visualisation

- Term used very broadly across a wide range of disciplines, sometimes meaning different things.
- My definition: Visualisation is the process of applying advanced computing techniques to data in order to provide insight into the underlying structures, relationships and processes.
- "Turning data into images and animations to assist researchers".
- Wide range of sources of data: observational, simulation, theoretical.
- Finds application across a wide range of disciplines.
- Often employs novel capture methodologies, display technologies and user interfaces.
- Frequently requires high performance computing and sophisticated algorithms.
- Outcomes
  - Revealing something new within datasets.
  - Finding errors within datasets.
  - Communicating to peers.
  - Communicating to the general public.
- Technologies
  Display hardware: stereo3D, immersion, fidelity.
  Algorithms: graphics, computer science, mathematics
  Techniques: volume visualisation, stereographics, haptics

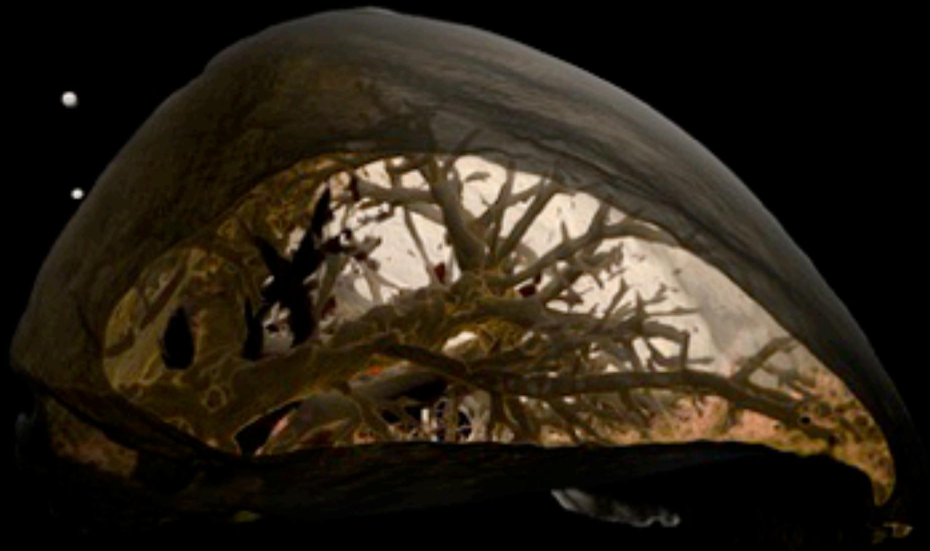
Visualisation laboratory

- By definition visualisation often targets/leverages the characteristics of the human visual system
  - depth perception
  - peripheral vision
  - visual fidelity

Example: Jaw of placoderm fish - CT scan

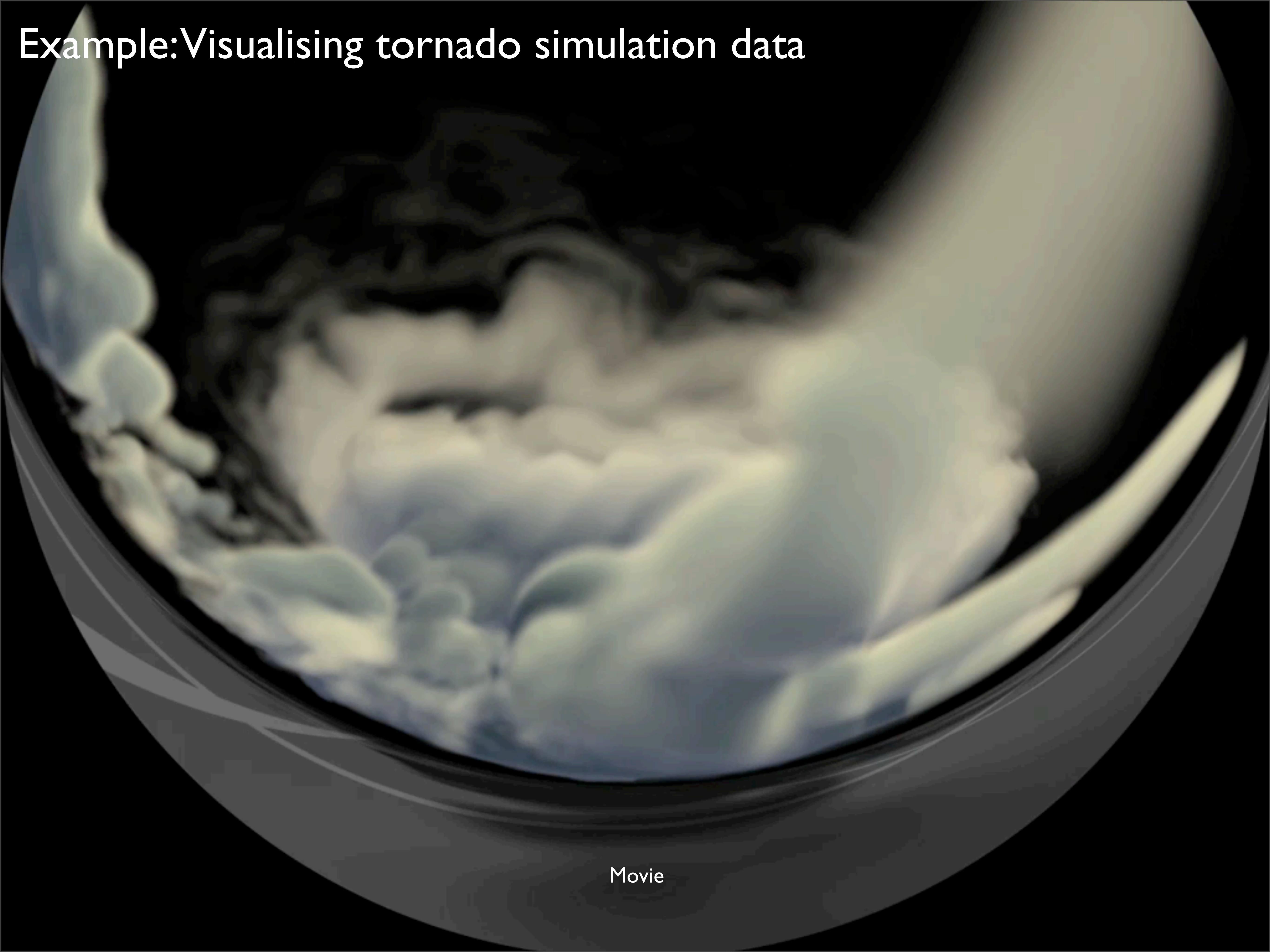


Example: Rabbits liver - Cancer research



Movie

Example: Visualising tornado simulation data

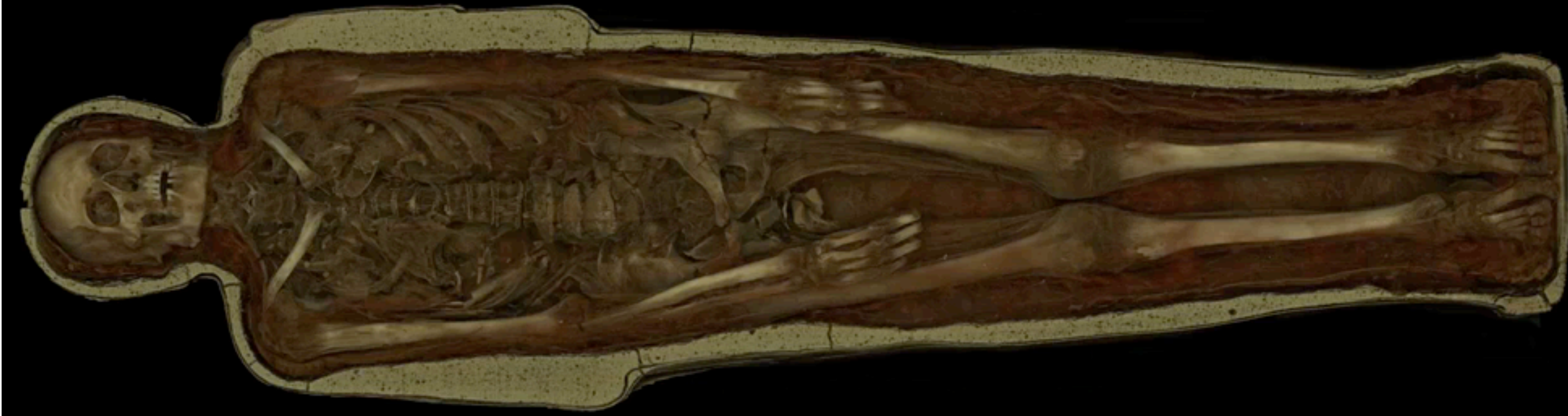


Movie

Example: Molecular motors

Movie

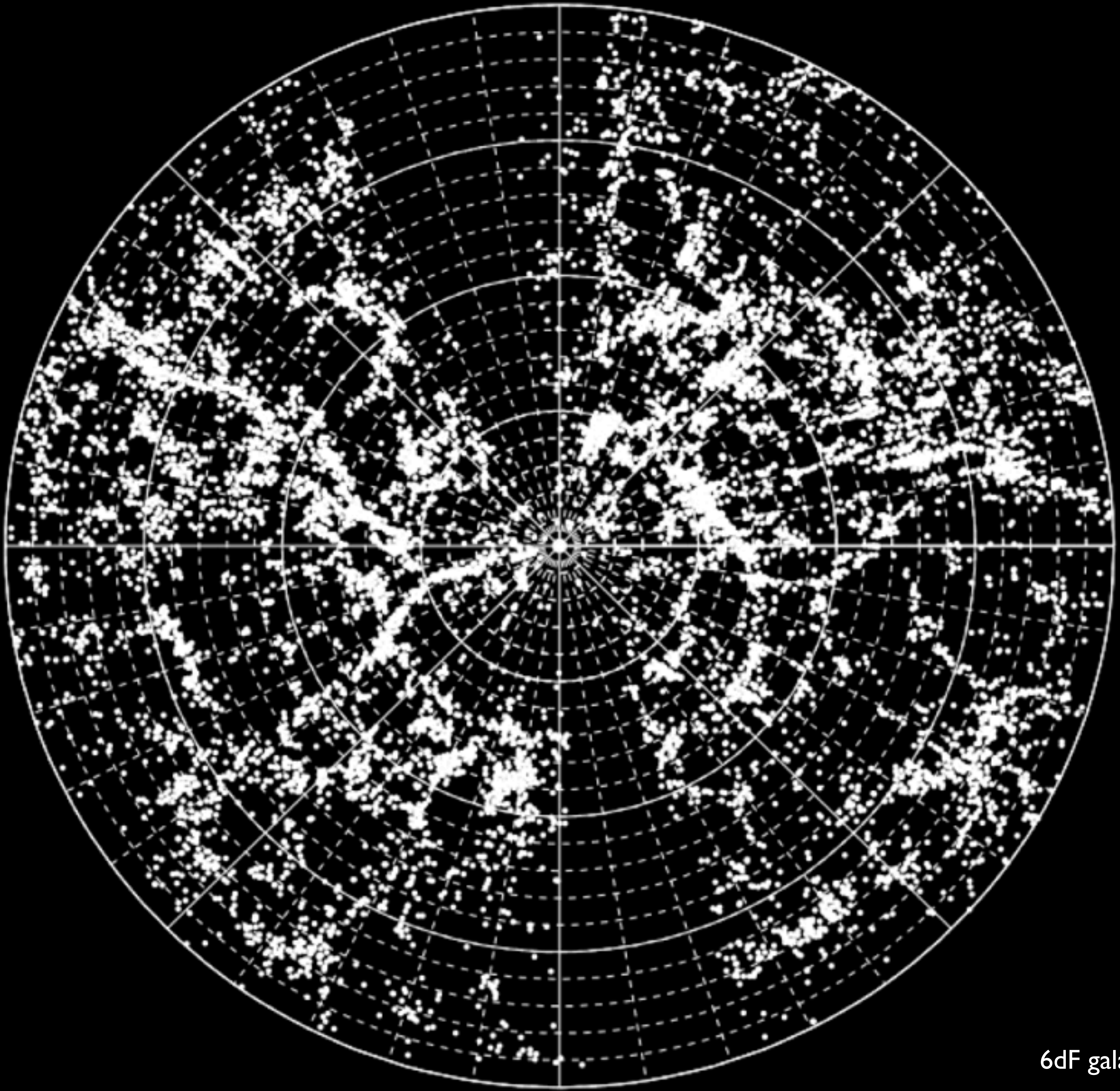
Example: Pausiris - Museum exhibition



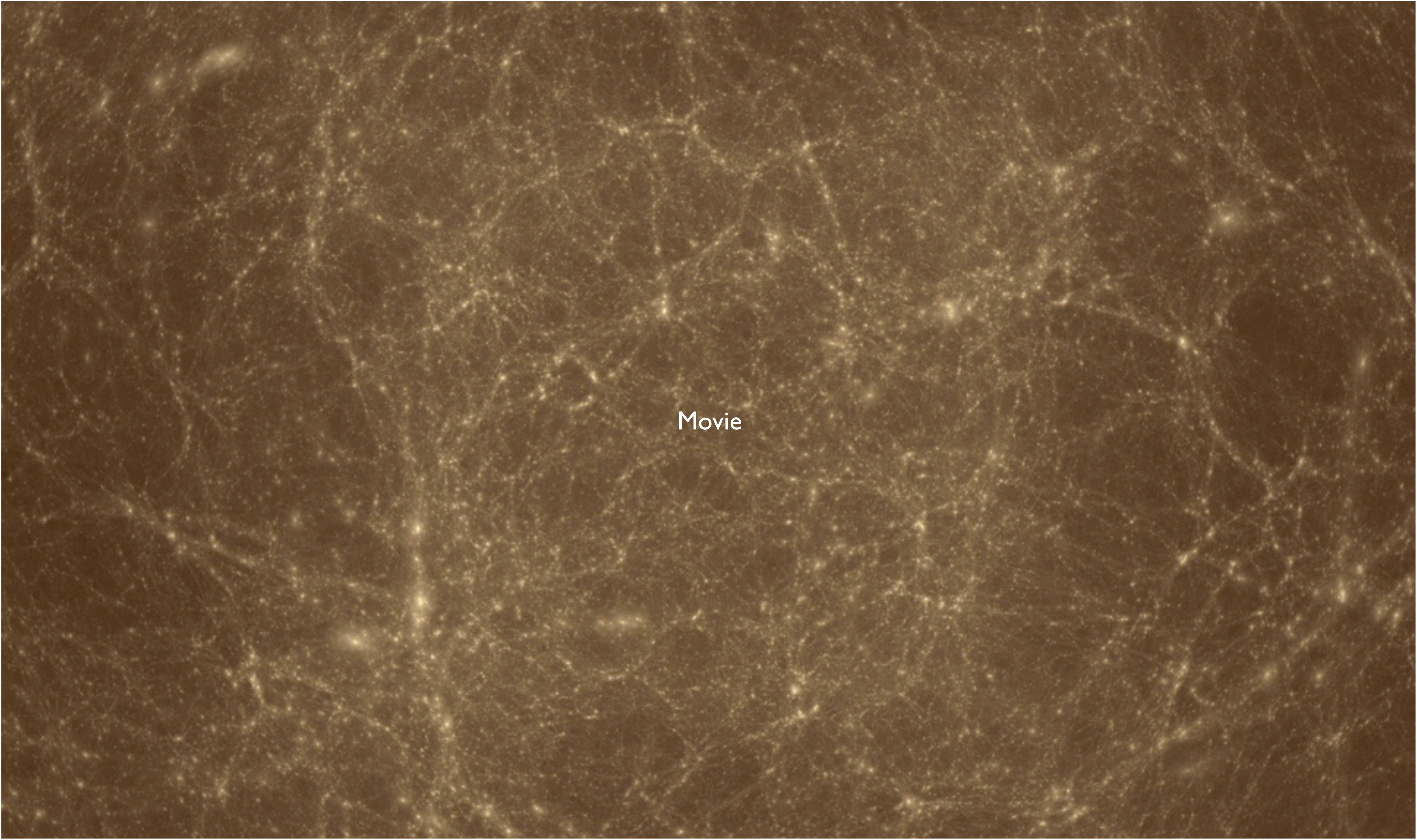
Movie

Example: Astrophysics

- Example of visualisation of simulation data in astrophysics.
- The formation of the large scale structure of the Universe.
- An exercise in computational design of reality.
- Proposed laws of Physics go into a simulation of the formation of the universe from the big bang.
- Original simulation computed on vayu (NCI).
  Used 1024 cores, 2.8TB RAM, took 19 hours (~20,000 CPU hours)
  Visualisation performed on epic (iVEC).



6dF galaxy survey



Movie

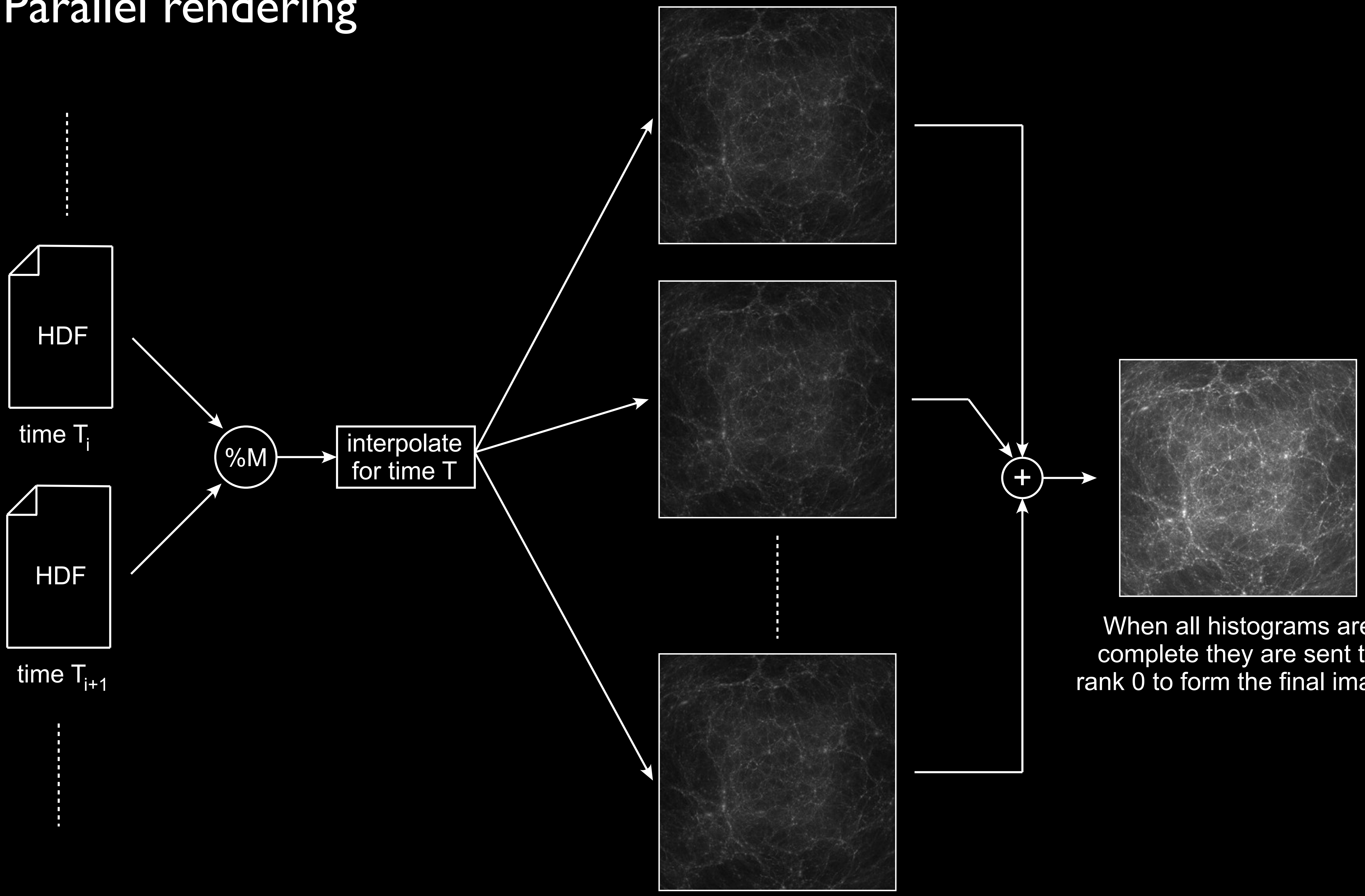
Serial vs parallel computing

- For some time CPUs have not been getting faster, or at least only modest yearly gains.
- Requirements in many area require orders of magnitude improvement in performance.
- The only way compute performance will increase significantly is through parallel processing.
- Challenging since much of software base is written for serial implementation.

- How often does software perform faster when you add more cores?
  How often when more CPUs are added?
  How often when a cluster is used?

- “Supercomputers” generally have the same processors as other computers, but lots of them.
- Require fast interconnection between the processors.
- Require parallel aware software!
- Concept of scalability, how does the software/algorithm performance scale with CPUs?

Parallel rendering



HDF

time T_i

HDF

time T_{i+1}

%M

interpolate for time T

+

When all histograms are complete they are sent to rank 0 to form the final image

N = 10^6 points each timestep

M independent MPI processes each working on 1/N of the data and each generating a histogram

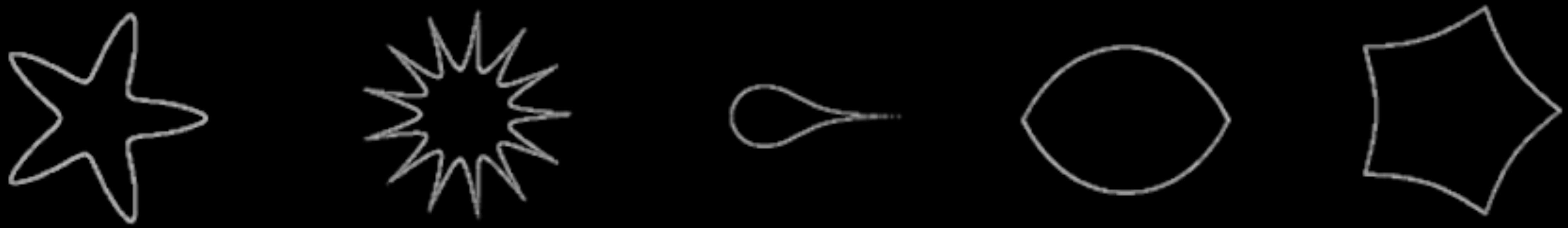
Examples

- Select a number of projects that illustrate computation and creation of 3D form.
- Includes:
- Parametric equations: equations control geometry
- Algorithmic generation: geometry created by a process
- Simulation: set up conditions and let software find a stable or minimal solution
- Constructive solid geometry (CSG)
- Fractal geometry (rule based, iteration, recursion): algorithmic

Supershapes: Parametric equation

- A simple example of a parametric model.
- Proposed as a model for generating plant structures and other organic shapes by Johan Gielis.
- Polar coordinates: Vary “ø” from 0 to 360 degrees, the formula gives the distance “r” at that angle.
- Parameters are “m”, “n1”, “n2”, “n3”.

$$\frac{1}{r} = \sqrt[n_1]{\left|\frac{1}{a}\cos\left(\frac{m}{4}\text{ø}\right)\right|^{n_2} + \left|\frac{1}{b}\sin\left(\frac{m}{4}\text{ø}\right)\right|^{n_3}}$$



Extension to 3D

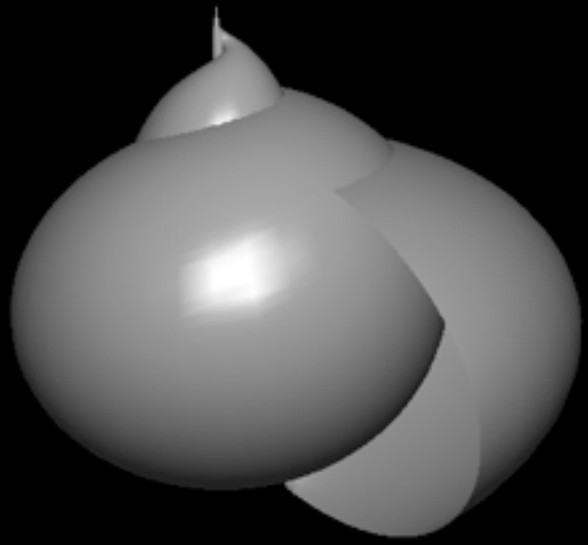
- Similar to 2D except polar coordinate in 3D consist of two angles and radius.

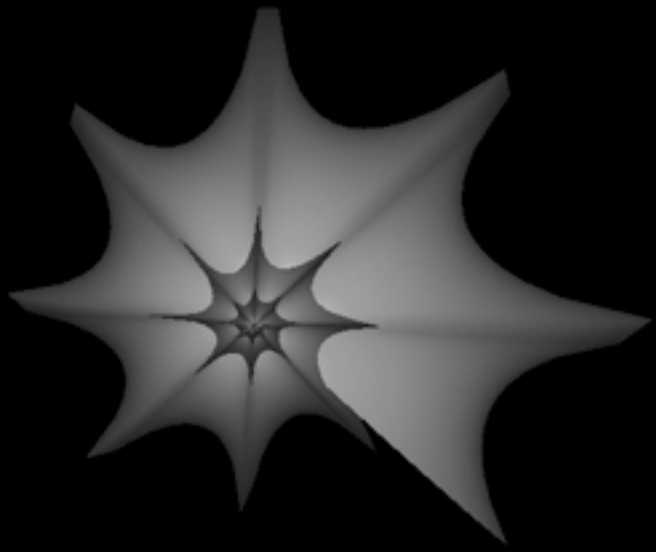
$$r(ø) = \left[\left| \frac{1}{a} \cos(m\, ø\, /4) \right|^{n2} + \left| \frac{1}{b} \sin(m\, ø\, /\, 4) \right|^{n3} \right]^{-1/n1}$$

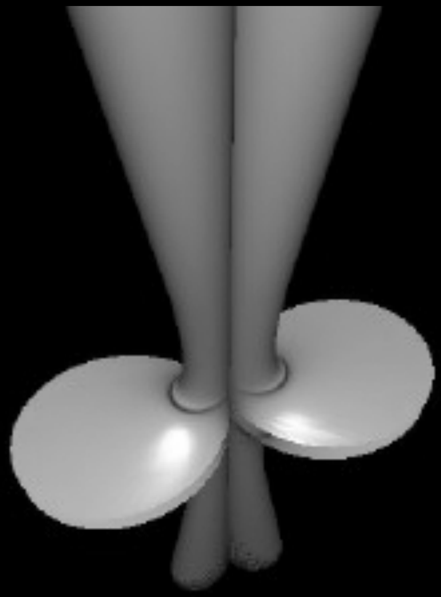
$$x = r1(\theta)\cos(\theta)\, r2(\varphi)\cos(\varphi)$$
$$y = r1(\theta)\sin(\theta)\, r2(\varphi)\cos(\varphi)$$
$$z = r2(\varphi)\sin(\varphi)$$

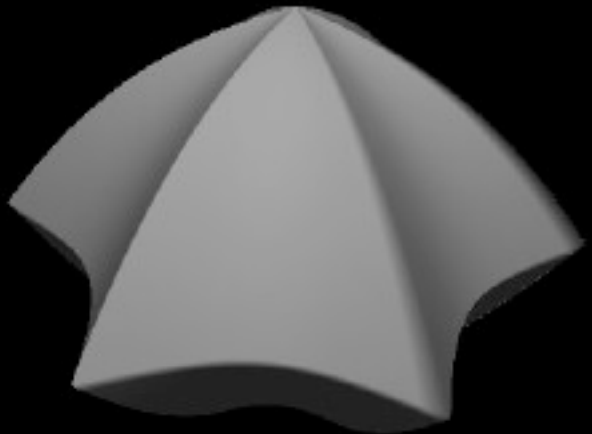
$-\pi/2 \leq \varphi \leq \pi/2$ eg: latitude

$-\pi \leq \theta \leq \pi$ eg: longitude









Questions

- When one has a parametric equation for creating geometry, questions are:

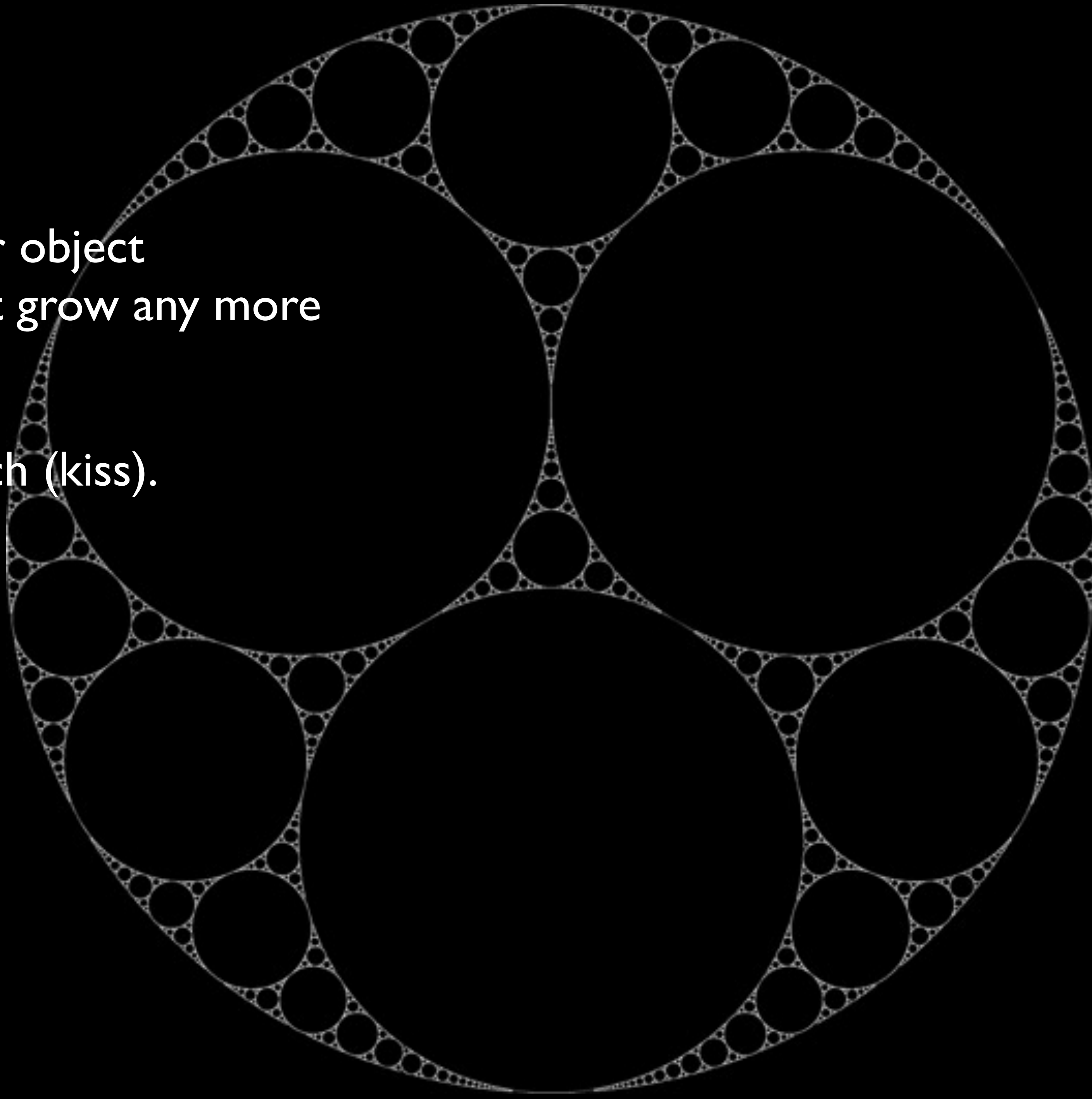
Does varying the parameters lead to predictable outcomes?
Can one choose parameters in such a way to create a predefined object?
Do the parameters have intuitive meaning?

- Elegant when a few number of parameters can define a wide range of shapes.

- Quote: John von Neumann
“ With four parameters I can fit an elephant, and with five I can make him wiggle his trunk.”

Example: Space filling - algorithmic

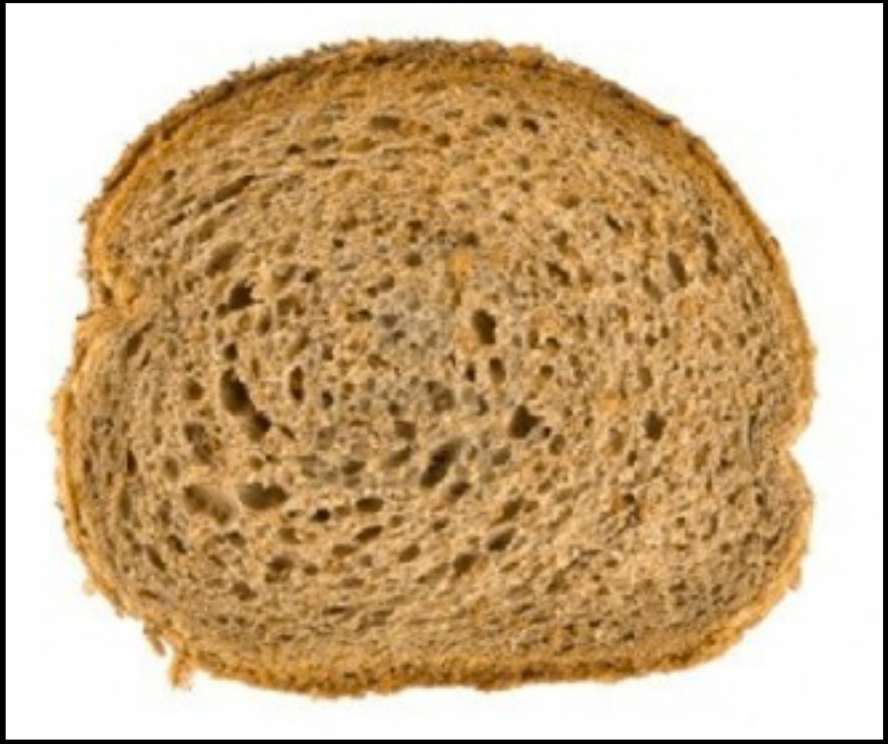
- Many natural structures tend to fill space.
- Space filling arises in nature due to competition for some resource.
- A previous model for creating these space filling has been so called Apollonian packings.
- Apollonian algorithm (or variations)
  - find some empty space
  - seed that location with a new object
  - grow the object until it touches another object
  - optionally shift the object until it cannot grow any more
  - place the object and repeat the process
- Key characteristic is that the objects touch (kiss).
- Not an equation but a process.



Non-Apollonian packings

Bubbles in a plate

Rocky river shore

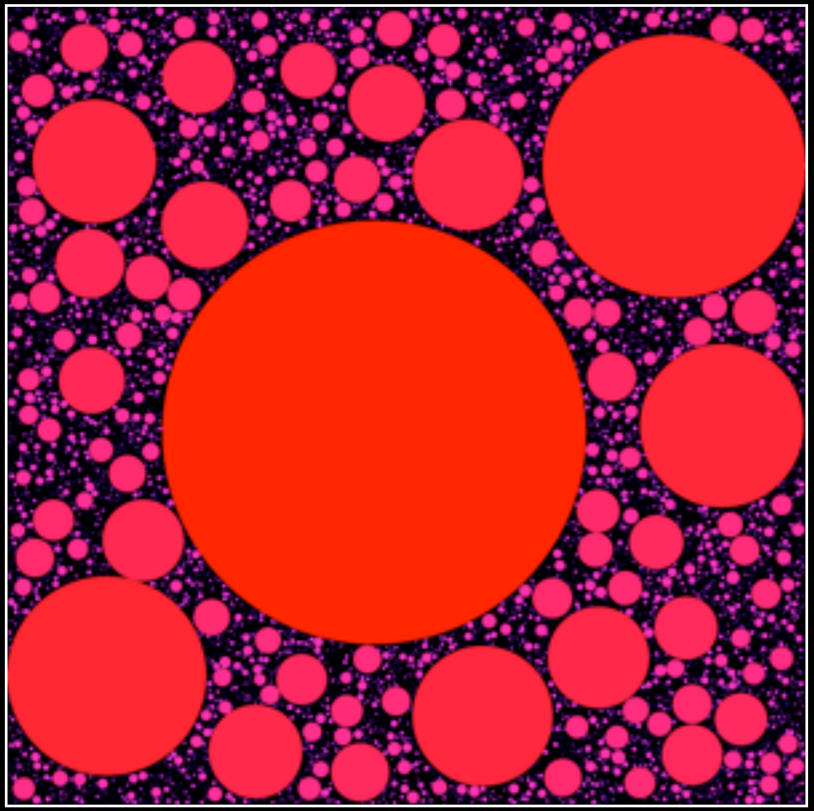


Bread air pockets

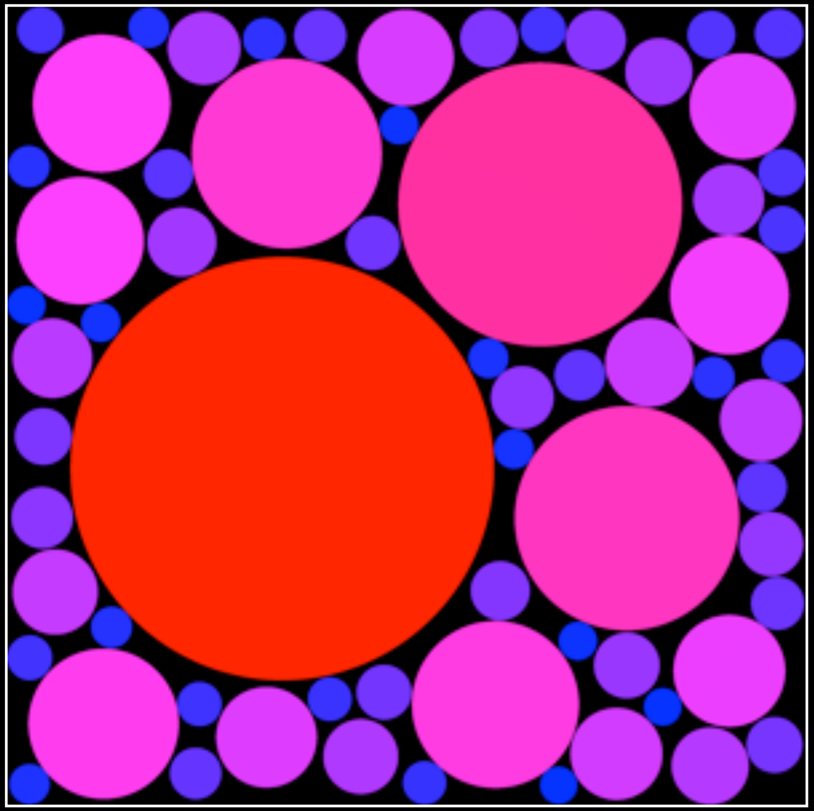
Lily pond

New model

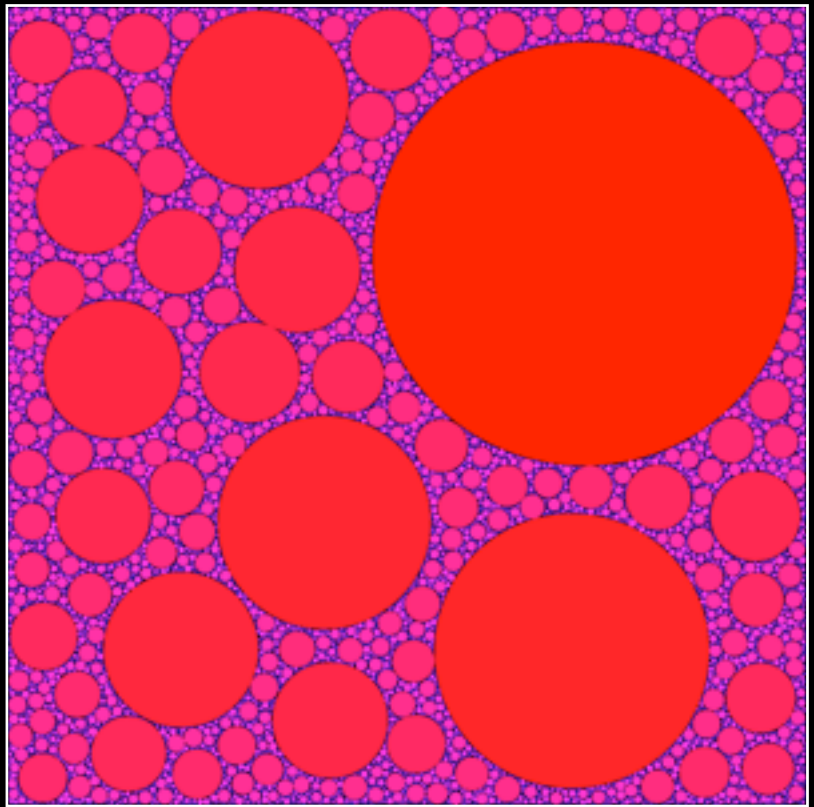
- Algorithm:
  - randomly find a place to locate the next object of a predetermined size without intersecting existing objects
  - add that to the database of existing objects
  - reduce the size of the object
  - repeat until some object count is reached or space is filled to some pre-specified level
- The trick ("magic") is how to reduce the size of the object such that the process never stops and it fills space (without gaps).



If size is reduced to fast space is not filled

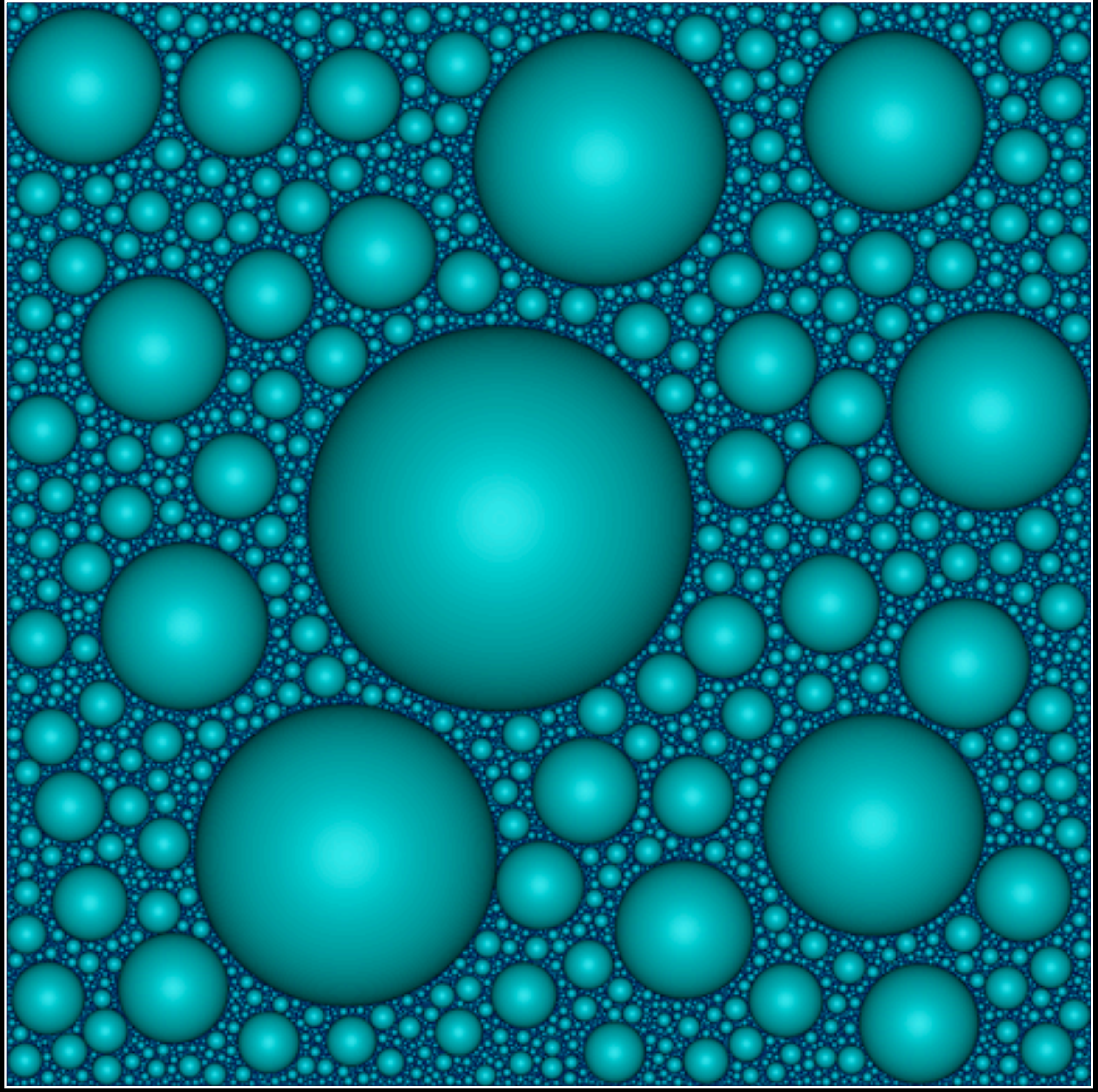


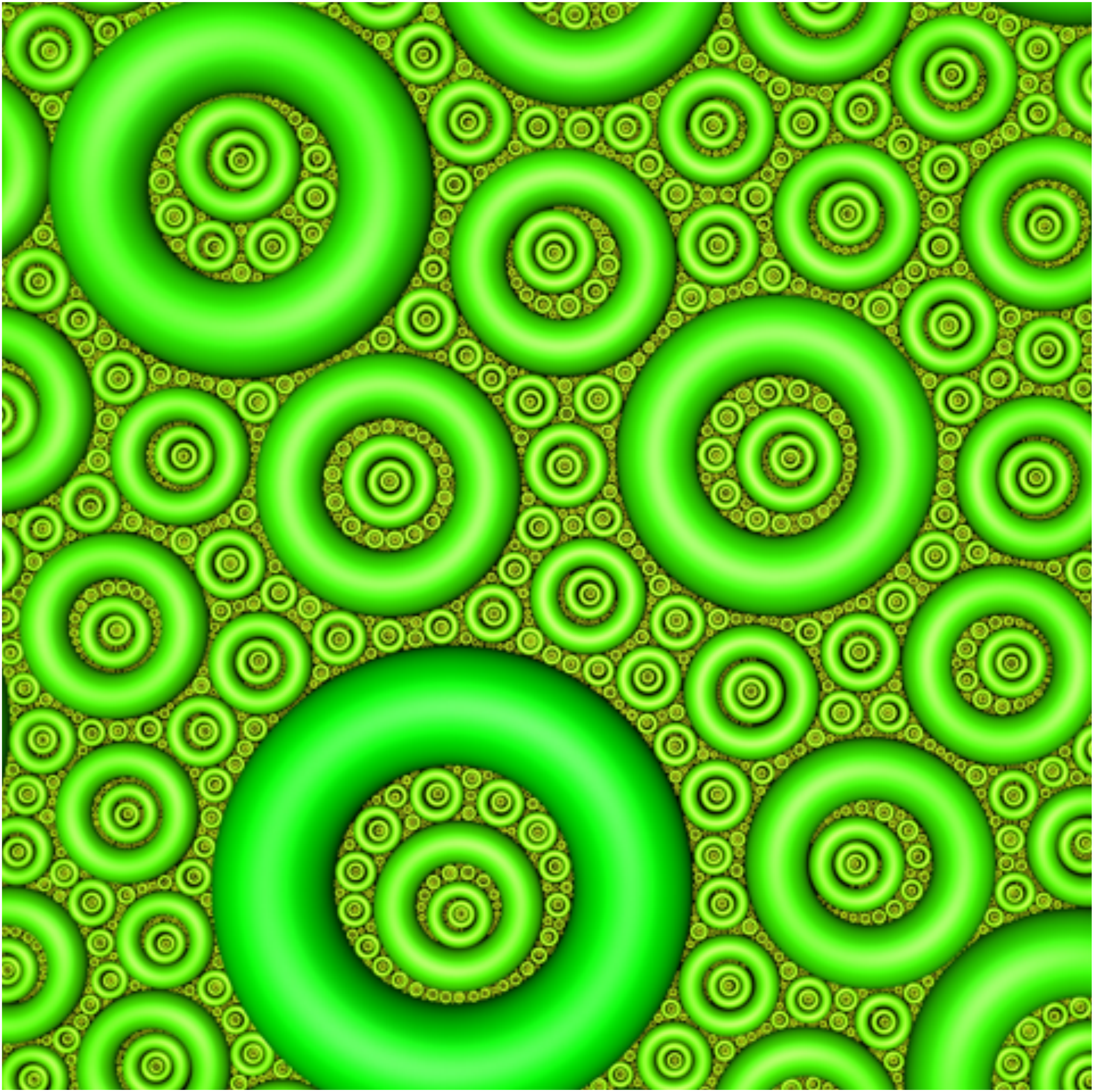
If the size is not reduced fast enough there will be no space for the next object of the intended size



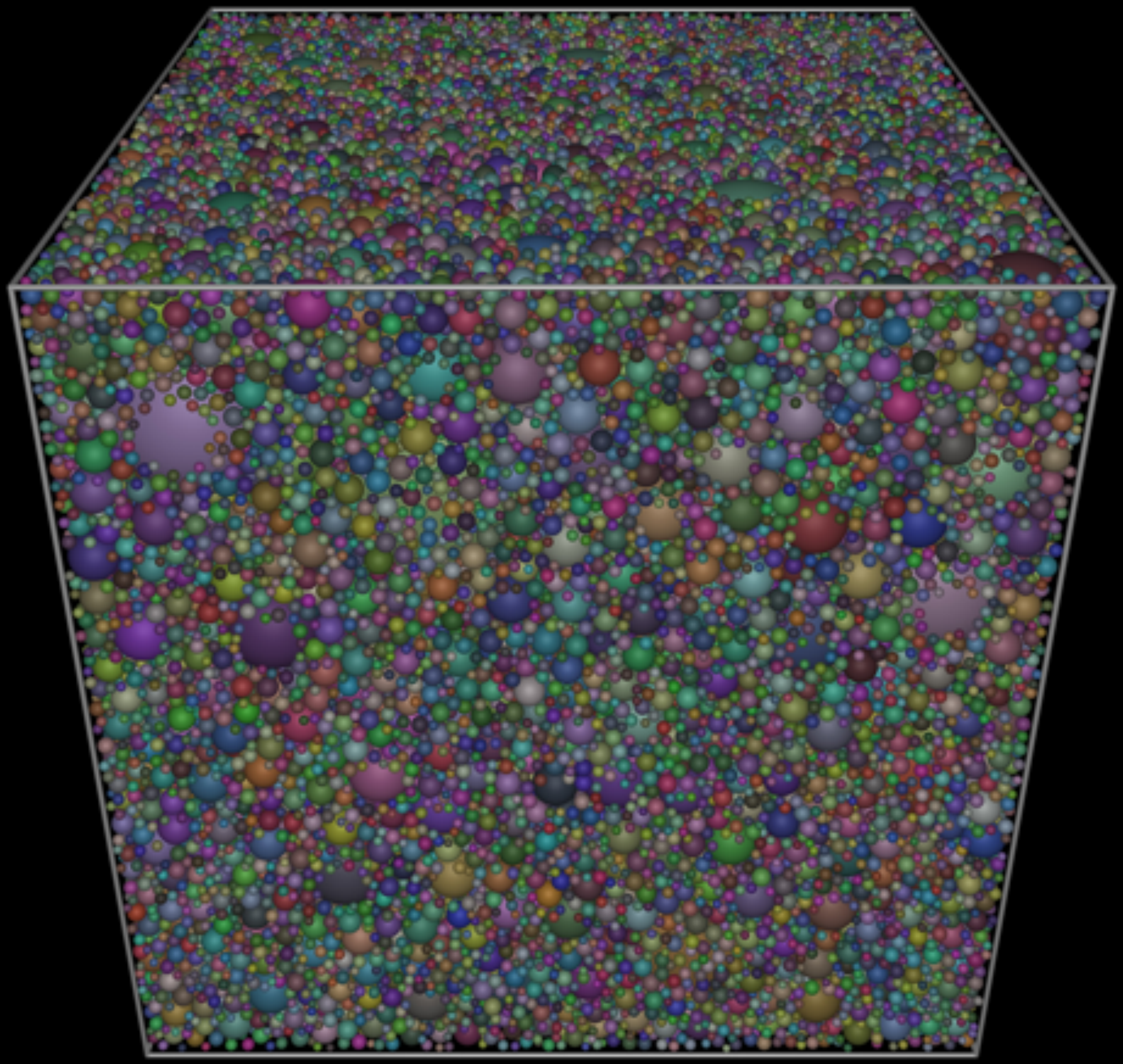
If reduced exactly right then space is filled.

2 dimensions

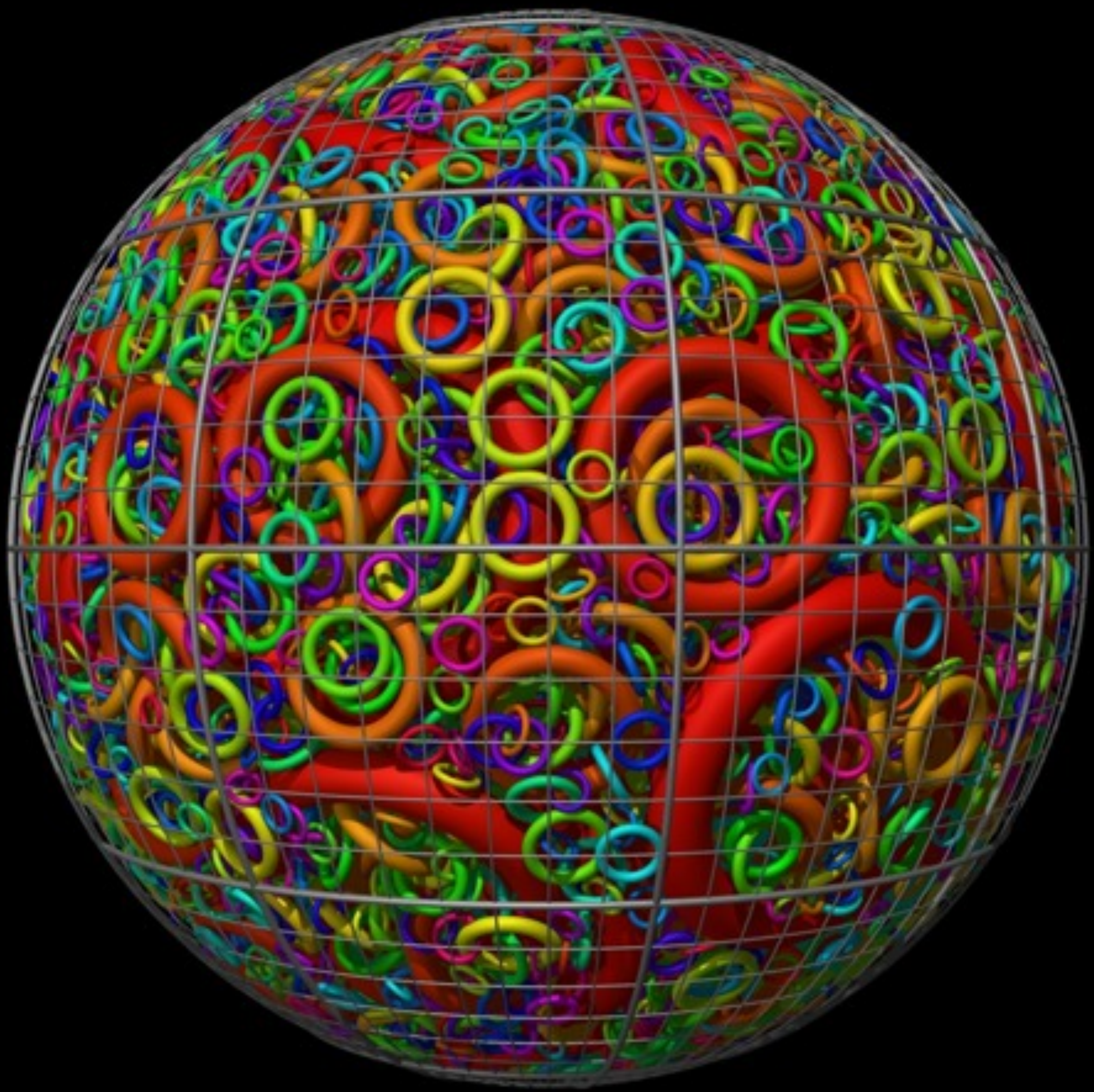




3 dimensions

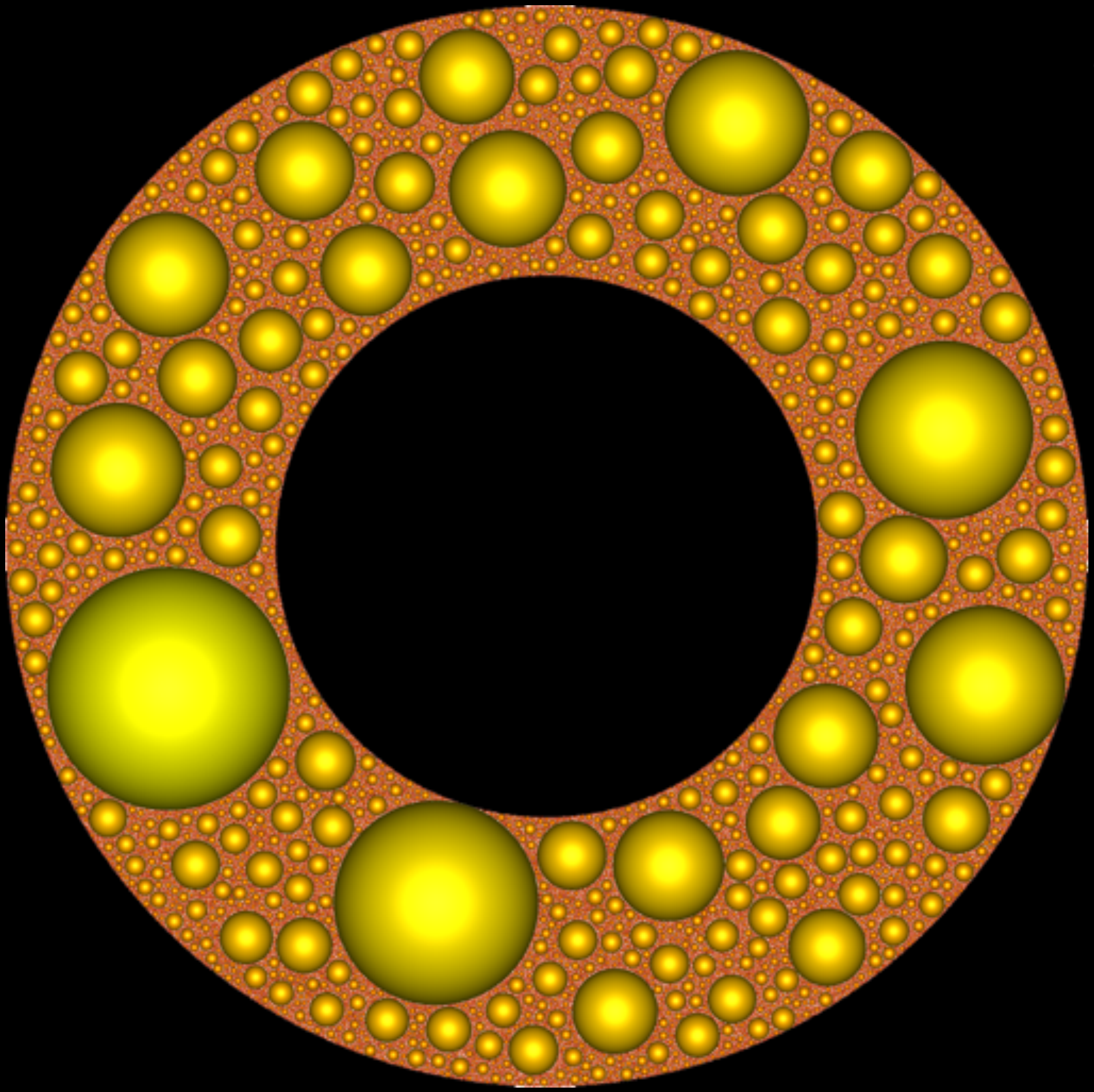


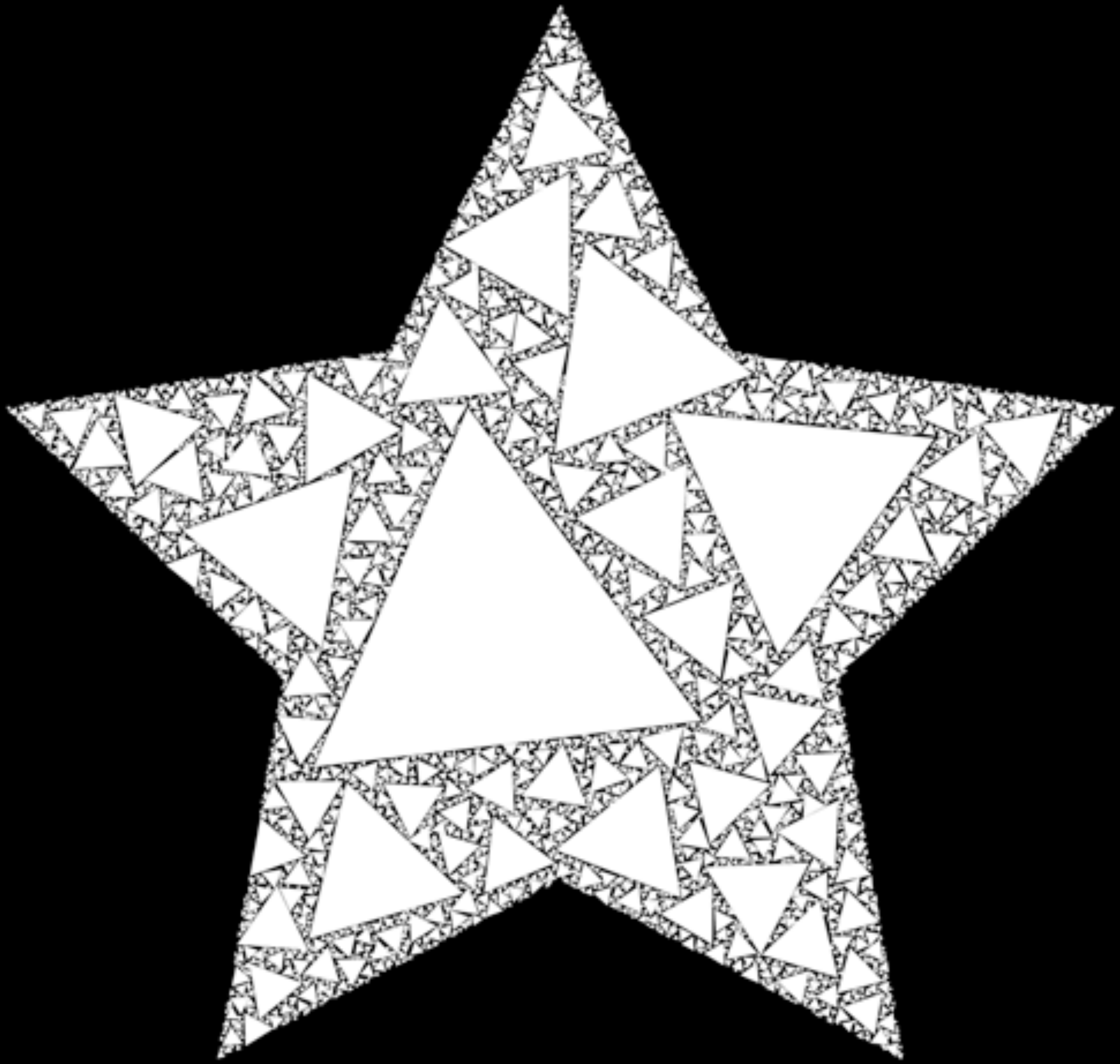
100,000 spheres



10,000 torii

Fill any shape with any shape



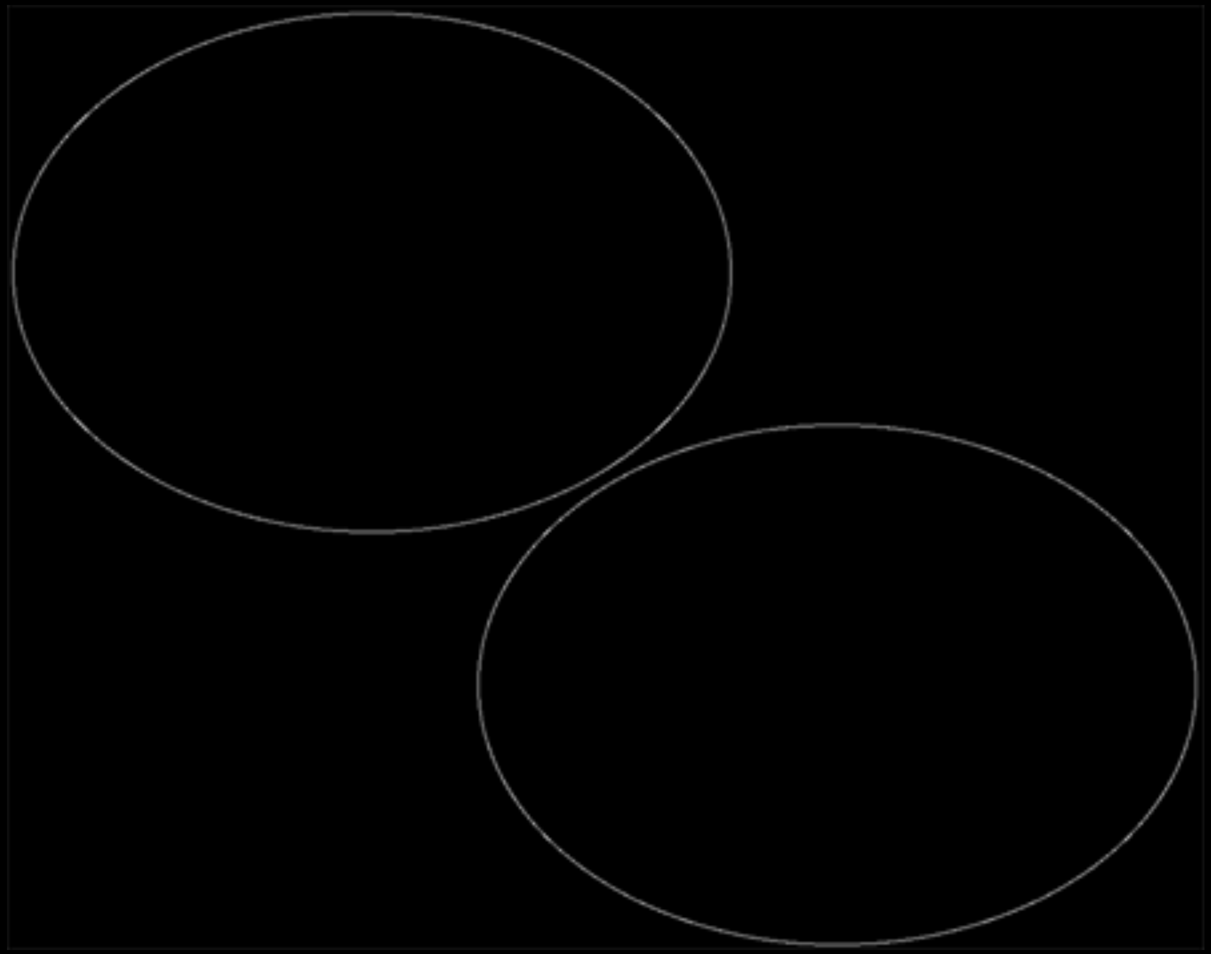


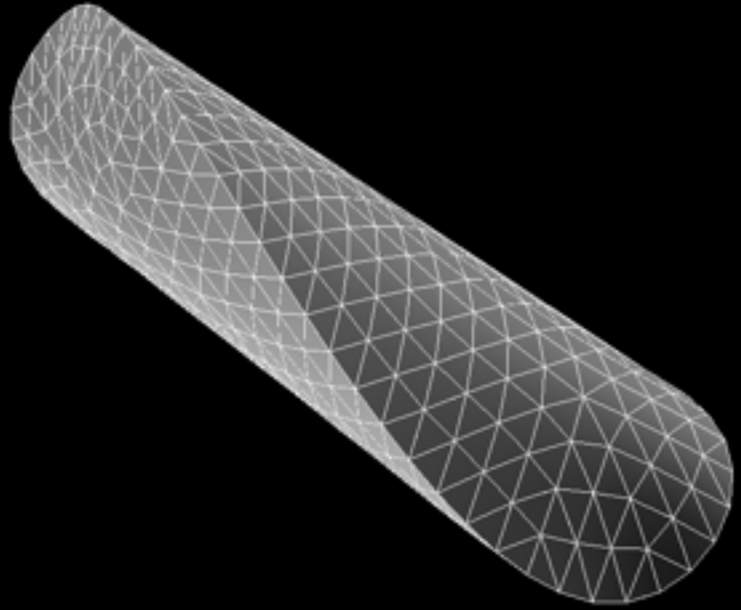
dForm surfaces: Simulation - find surface of least stress

- Credited to Tony Wills.
- Example of a 3D shape that while simple to understand involves complex simulation to form digitally.

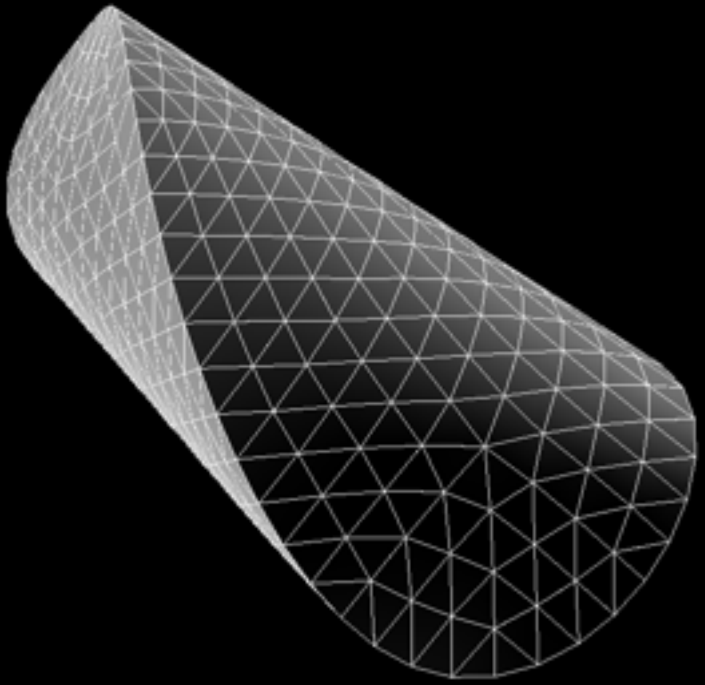
Concept

- Take two outlines of identical length.
- Non-elastic material.
- Stitch them together, possibly starting at different positions. What 3D shape do they form?
- Simplest case is 2 ellipses, 2 circles is always boring.

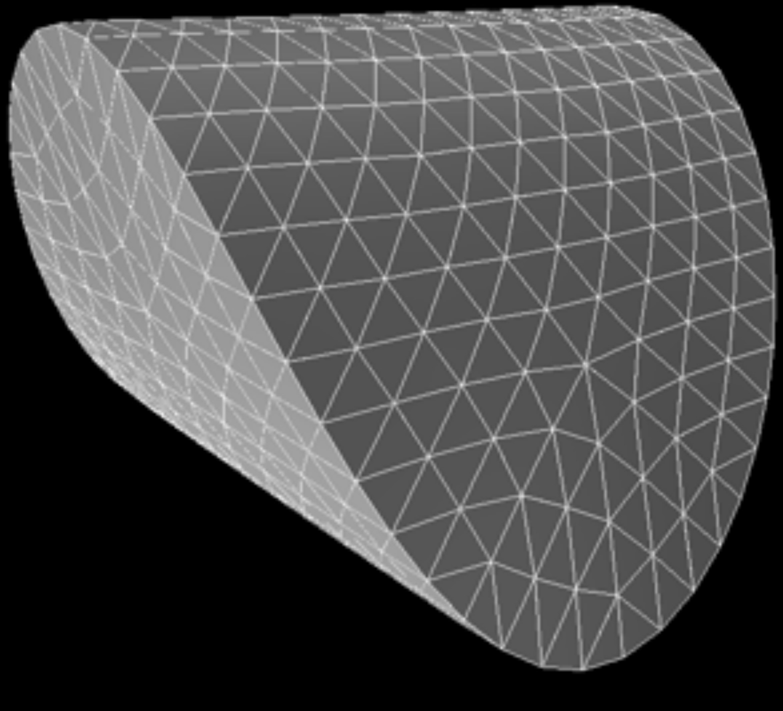




22.5 degrees

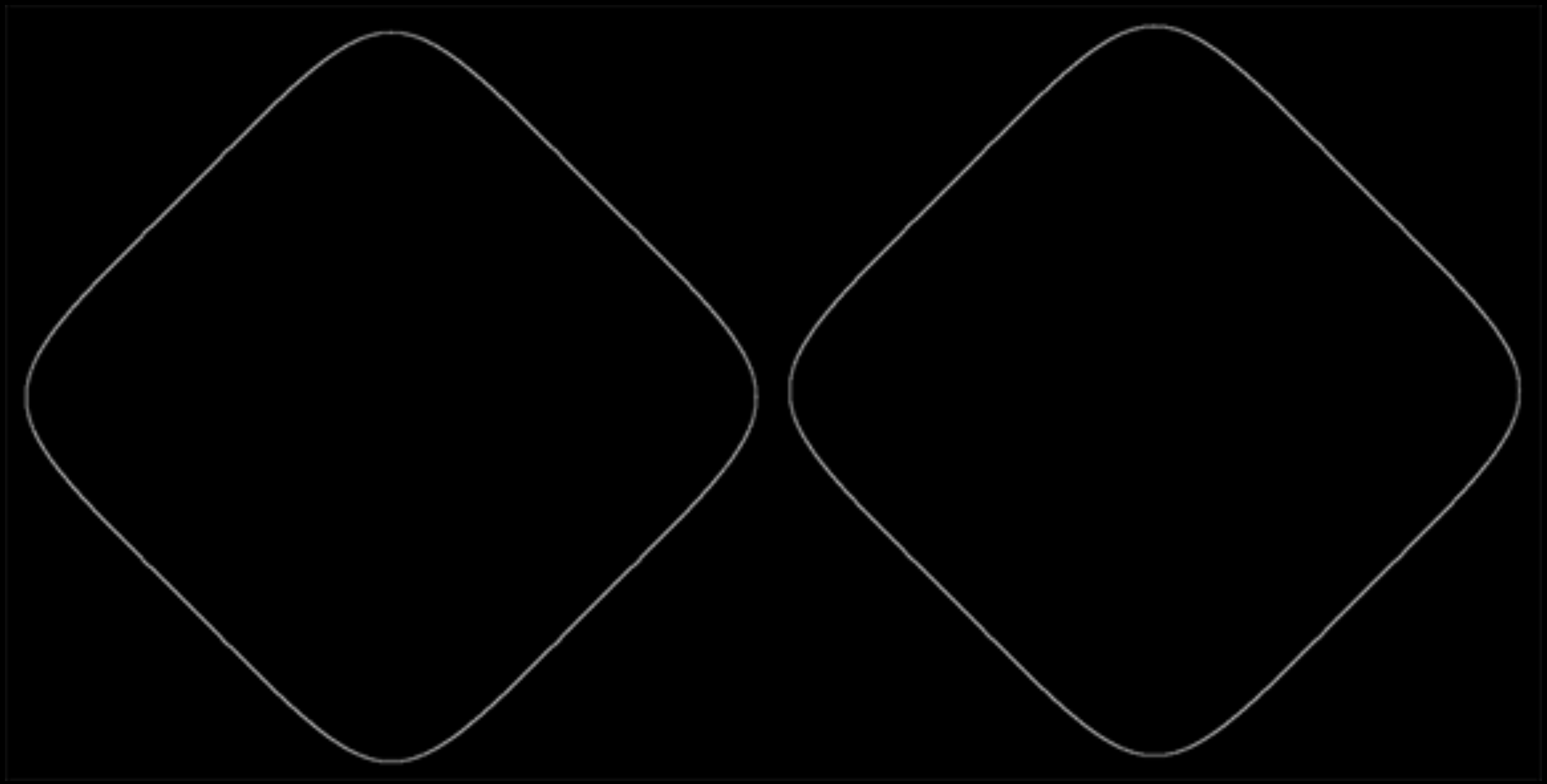


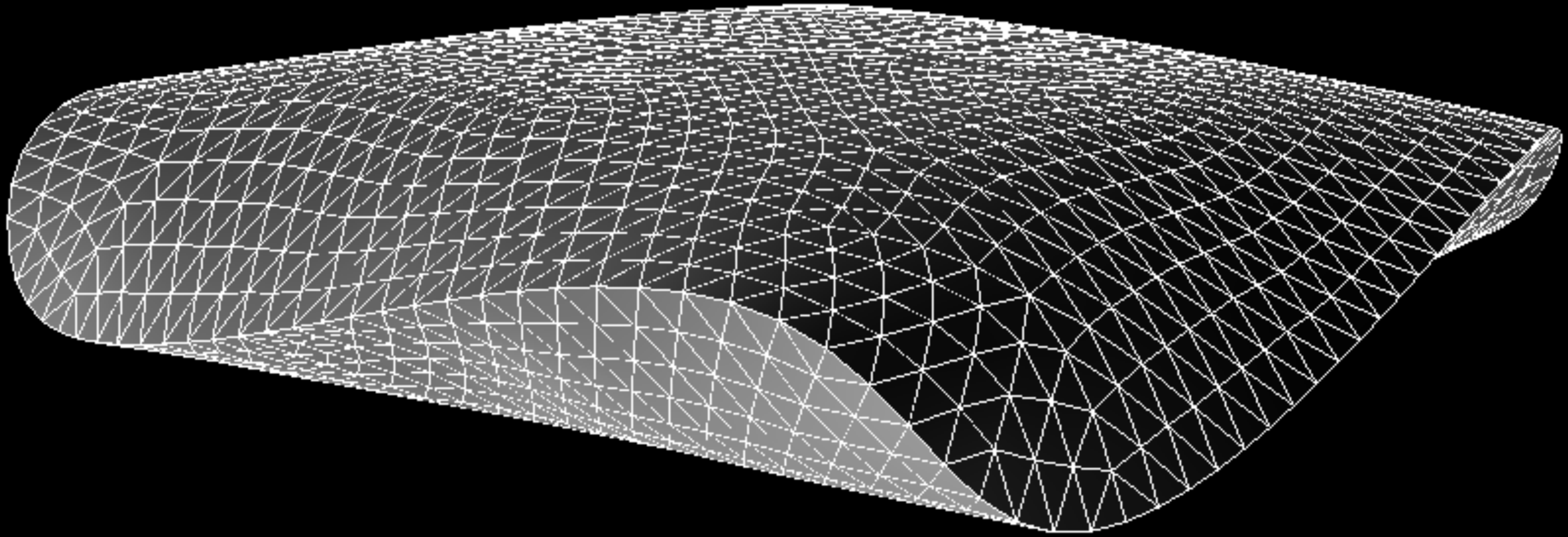
45 degrees



90 degrees

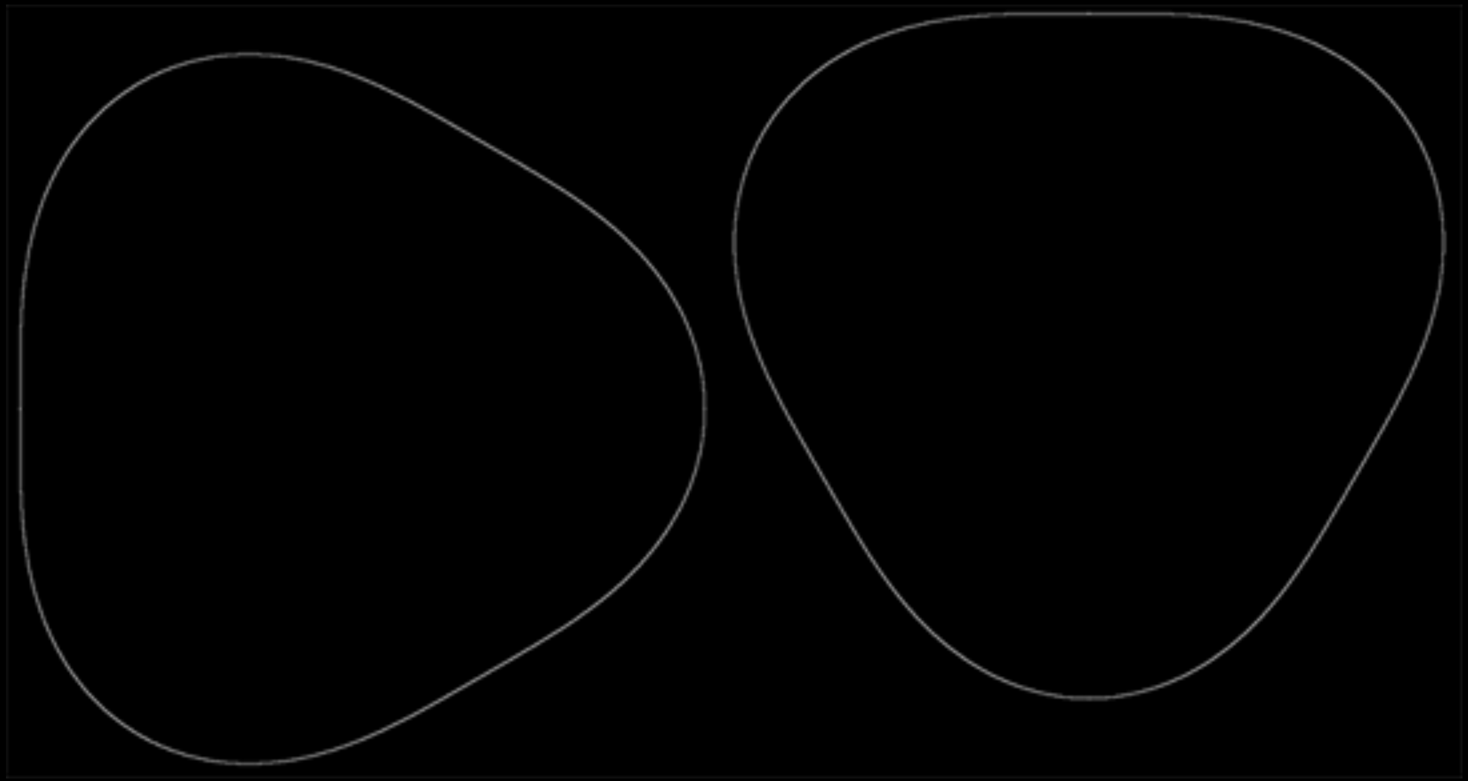
Example: Rounded squares

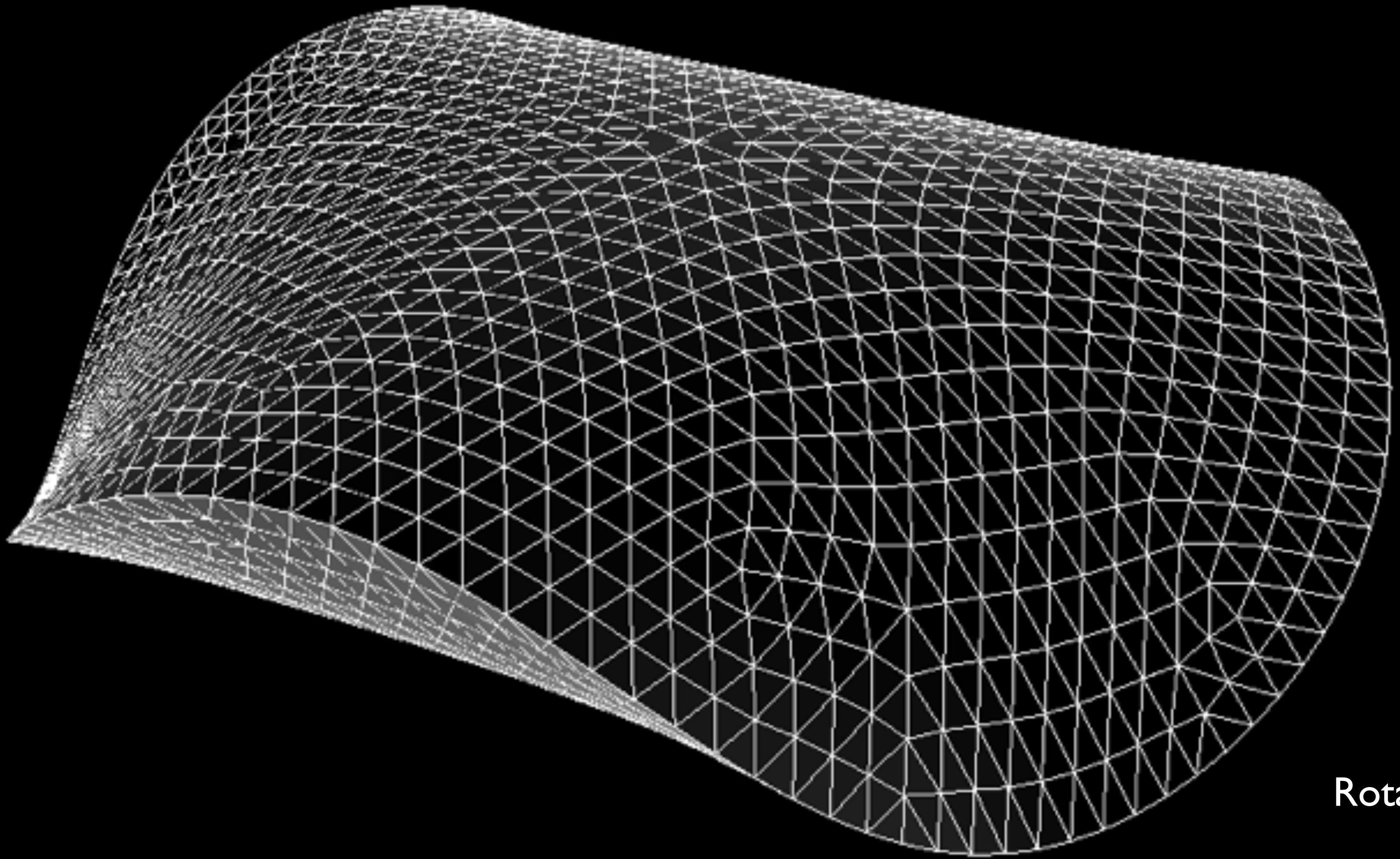




Rotated 30 degrees

Example: Rounded triangles





Rotated 60 degrees

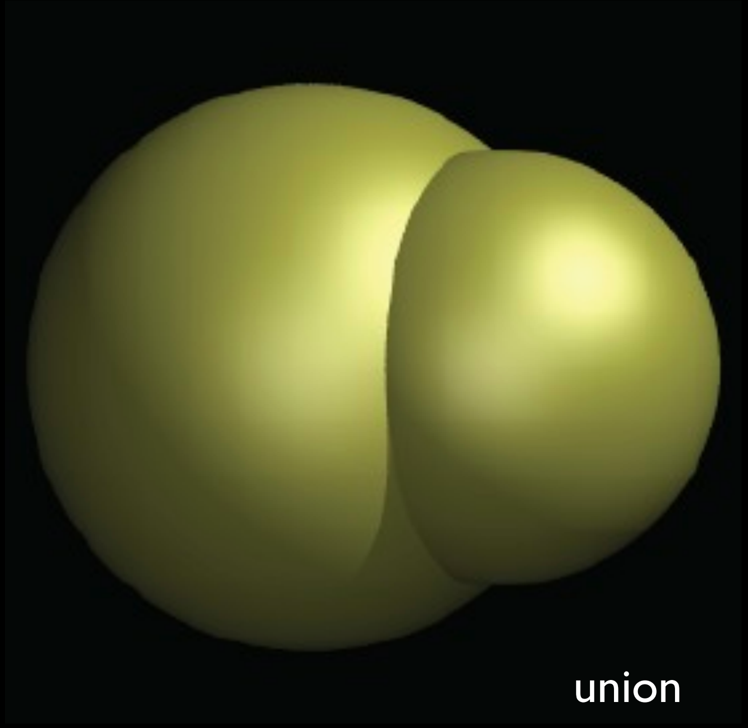
Algorithm

- Algorithm involves creating a mesh representation of the two surfaces.
- Virtually stitching them together = joining together the boundary vertices of the mesh.
- Assuming an elastic surface ... this will result in elastic stress/stretching of the surfaces.
- Every possible configuration of these meshes has some metric, total stress say.
- Apply physics to minimise that stress by deforming the surfaces.

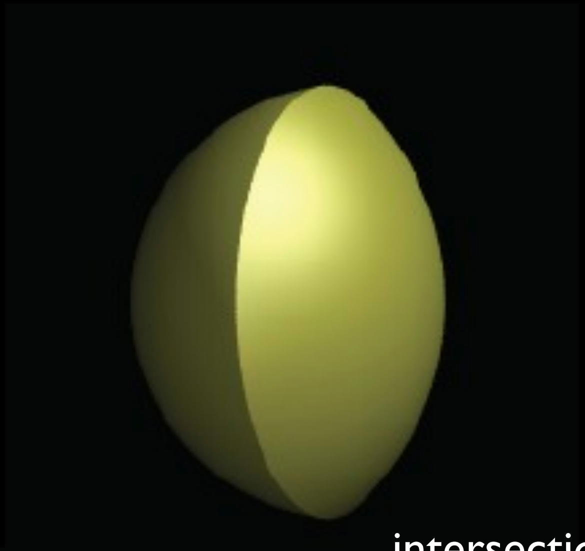
- Computationally impossible to scan the entire solution space.
- The algorithm attempts to move the system towards the configuration of minimum stress.
- Question, how does one know the algorithm will find the global minimum rather than just a local minimum?

Constructive solid geometry (CSG)

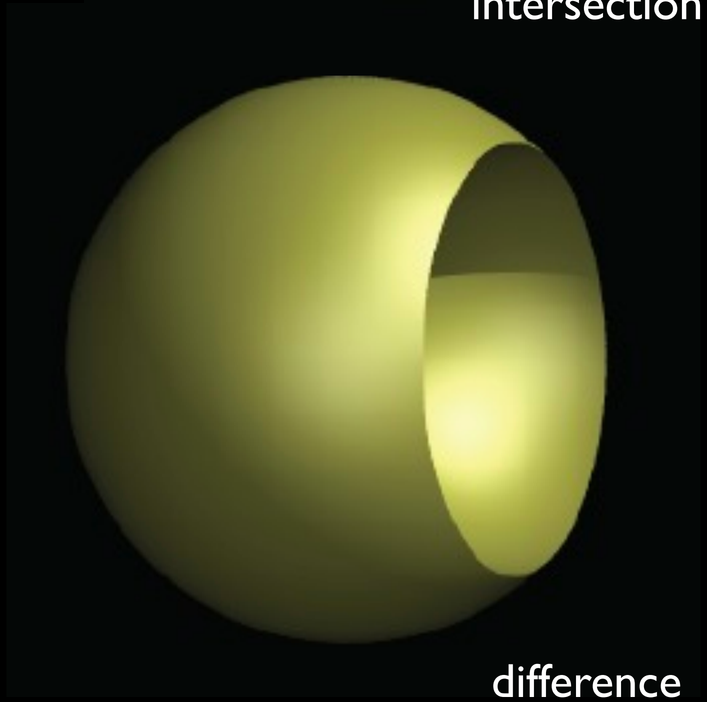
- A well established branch of computer based modelling.
- Everything has physical thickness and is solid. Has a clear notion of the inside and the outside.
- As distinct from more traditional modelling with infinitely thin lines or planes.
- Solid objects are combined in pairs using logical operations
  union - add the two objects together
  intersection - result is the space contained inside both objects
  difference (subtraction) - subtract one object from the second
- In the extreme case there is only one geometric primitive, a "half space".
  A cube is built from 6 half spaces suitable rotated and with the intersection operator applied.
- A very useful construction for modelling objects defined by such logical operations.
  Very difficult to construct solutions otherwise, for example, as a mesh definition.



union



intersection

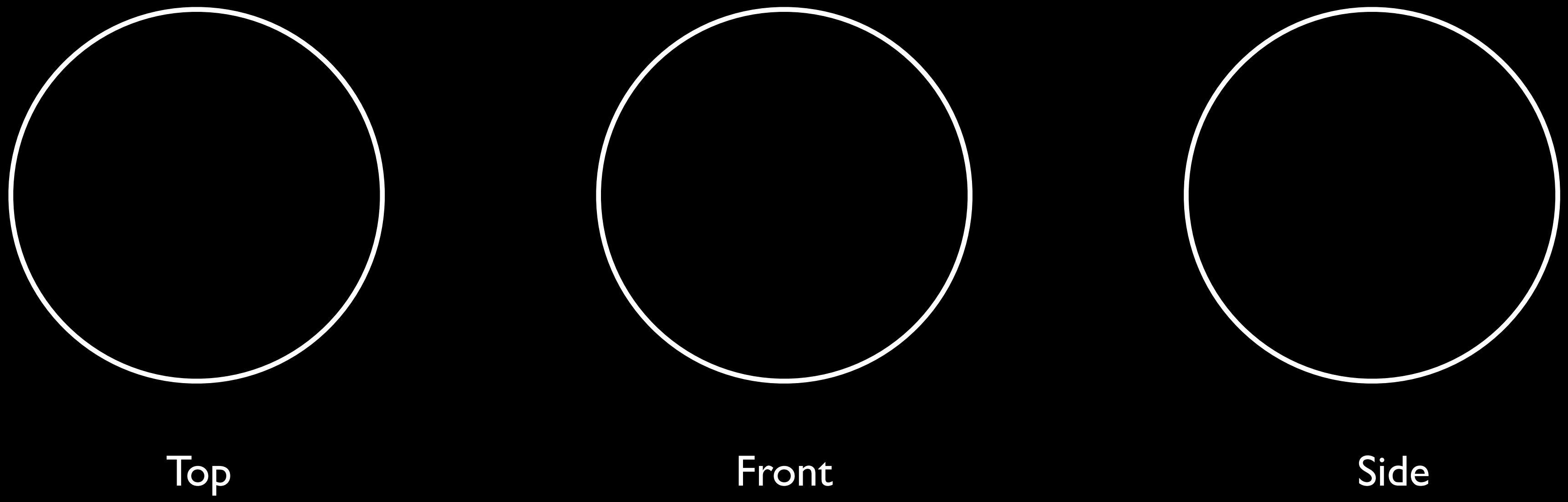


difference

Example: Question

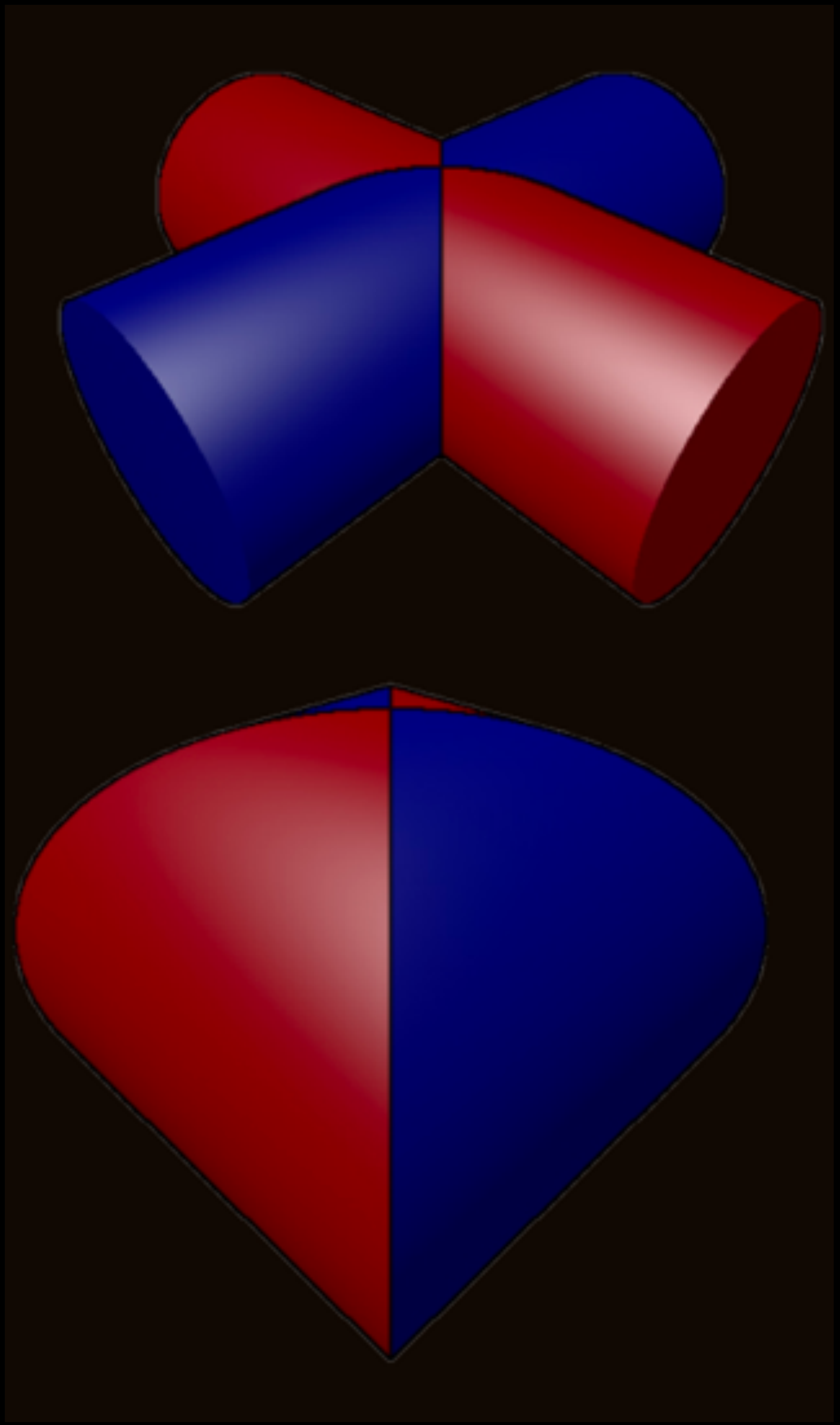
- Question: what is the object that is a circle in plan, front, and side view?

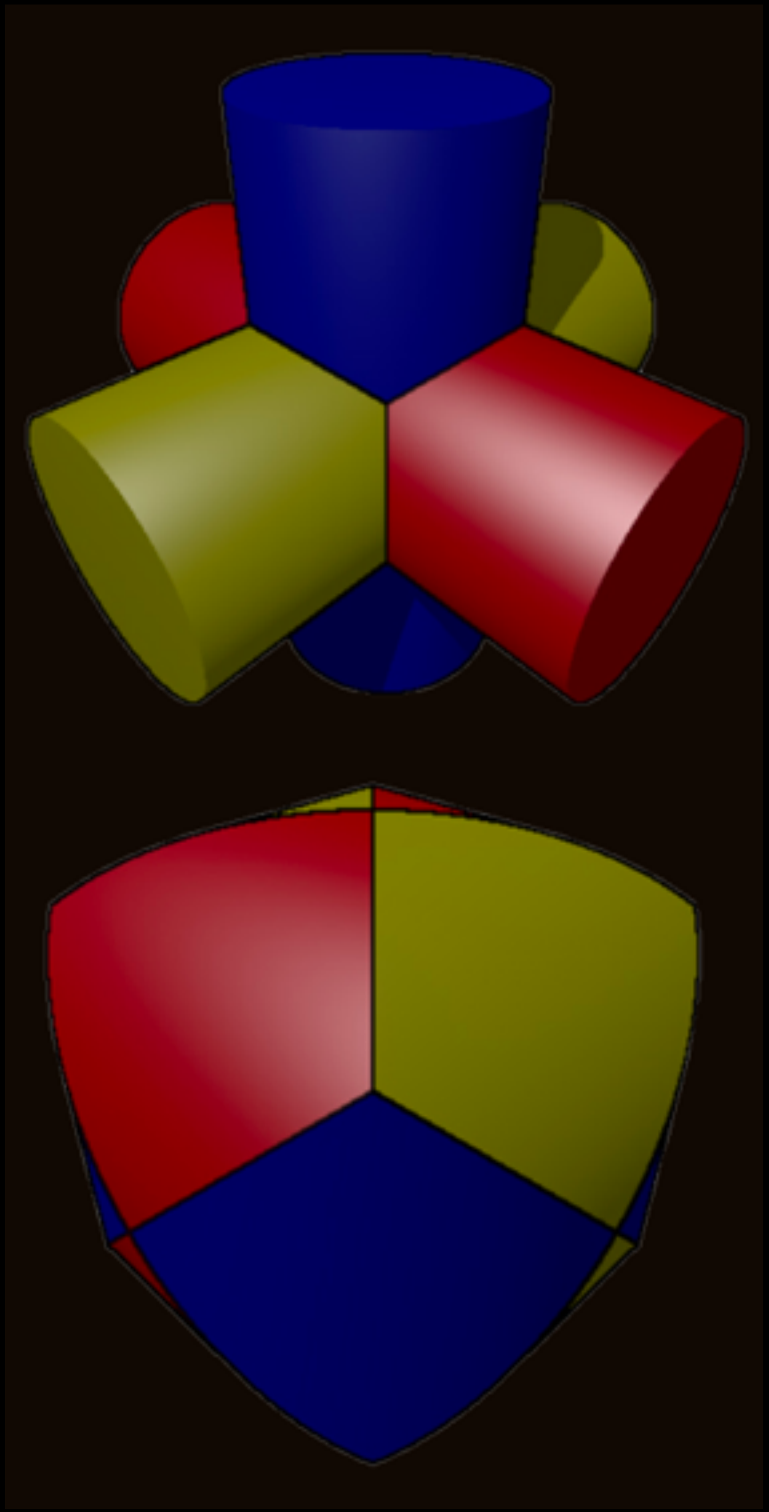
- Besides a sphere ...



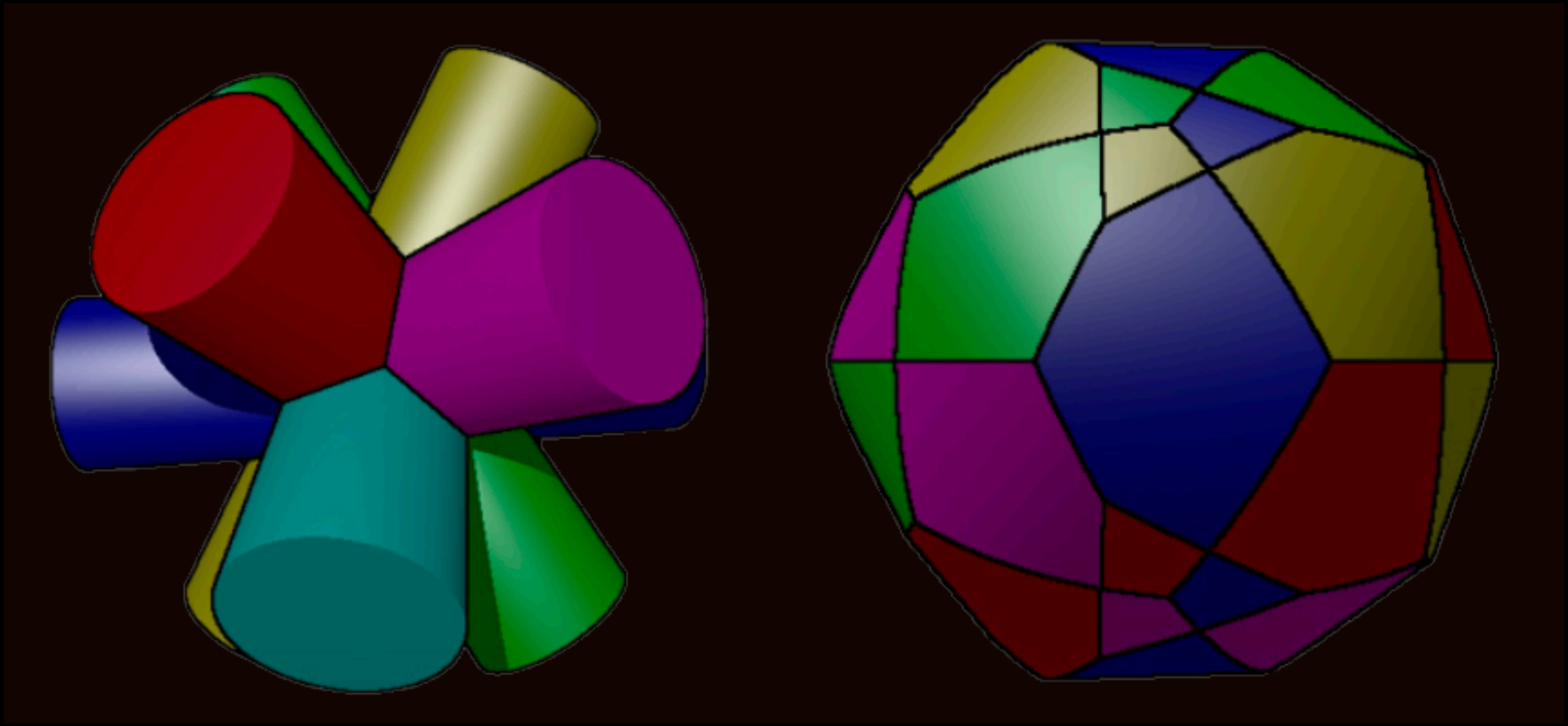
Example: Answer

- What is the geometry resulting from the intersection of three cylinders?



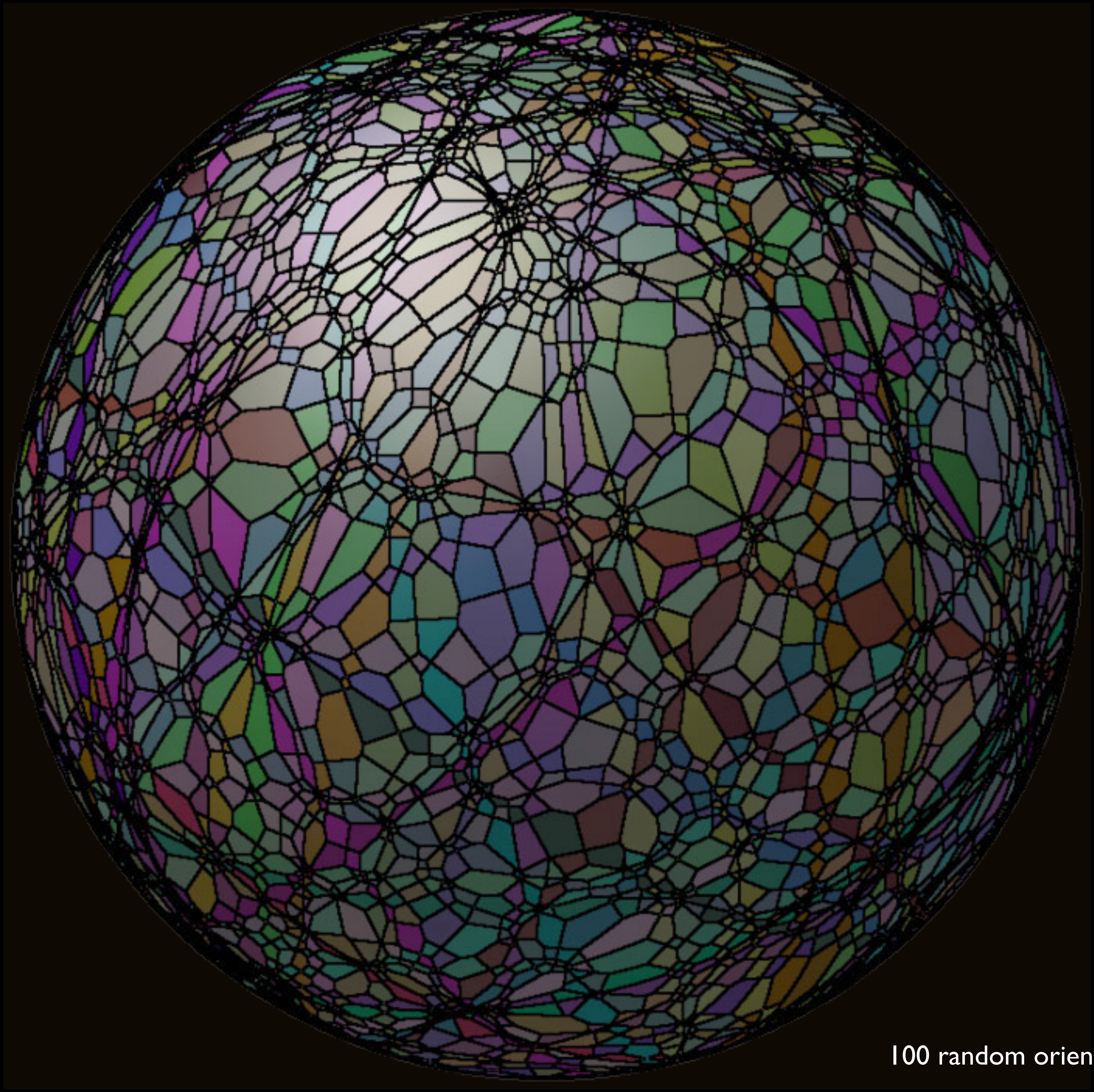


Example



5 cylinders

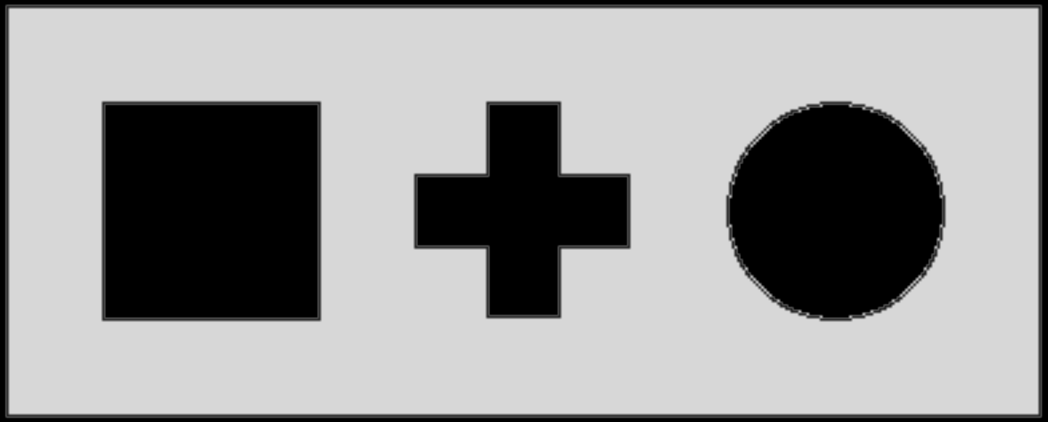
Example

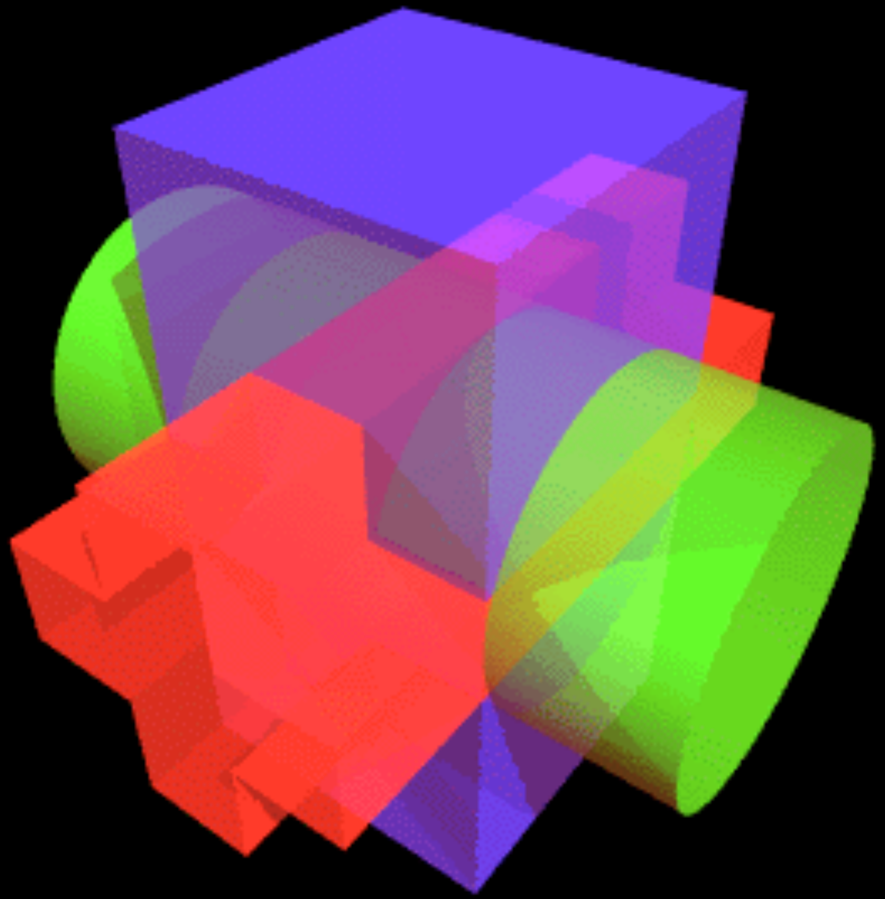


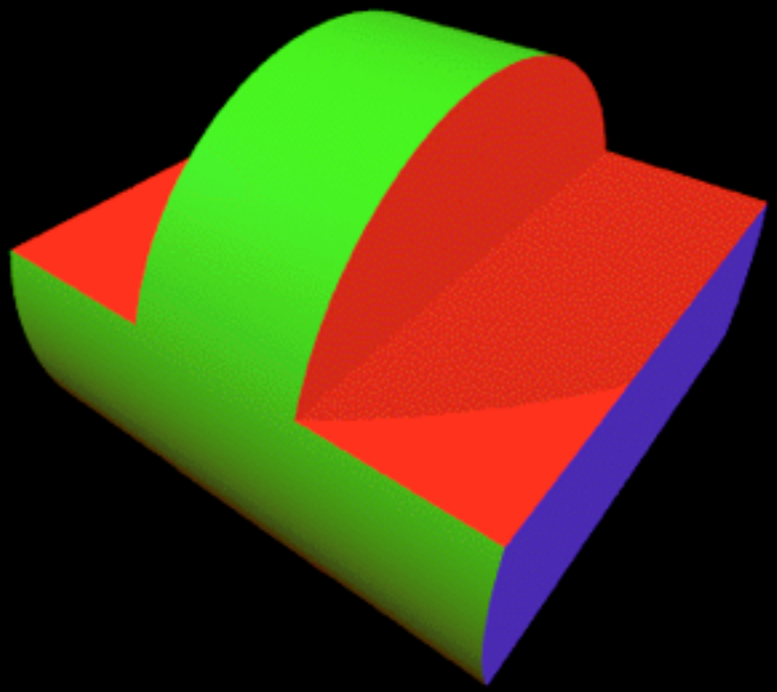
100 random orientated cylinders

Example

- What single object can slide though all slots in the following?

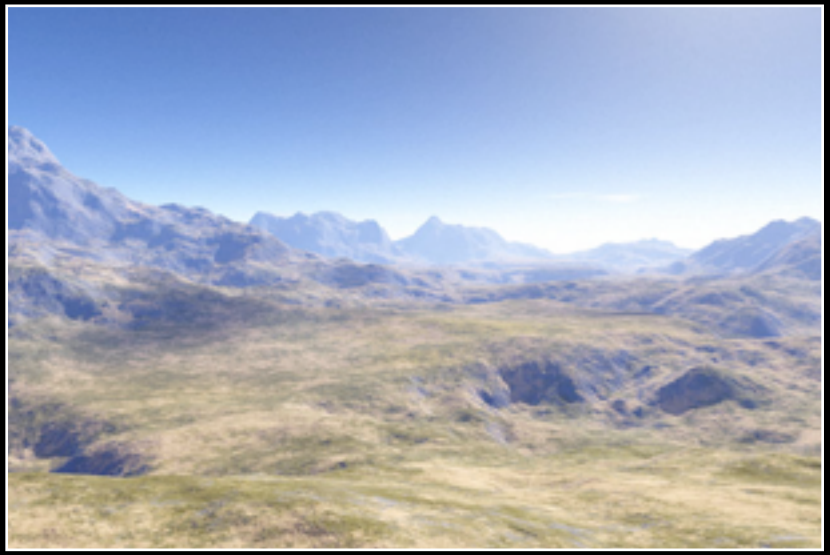




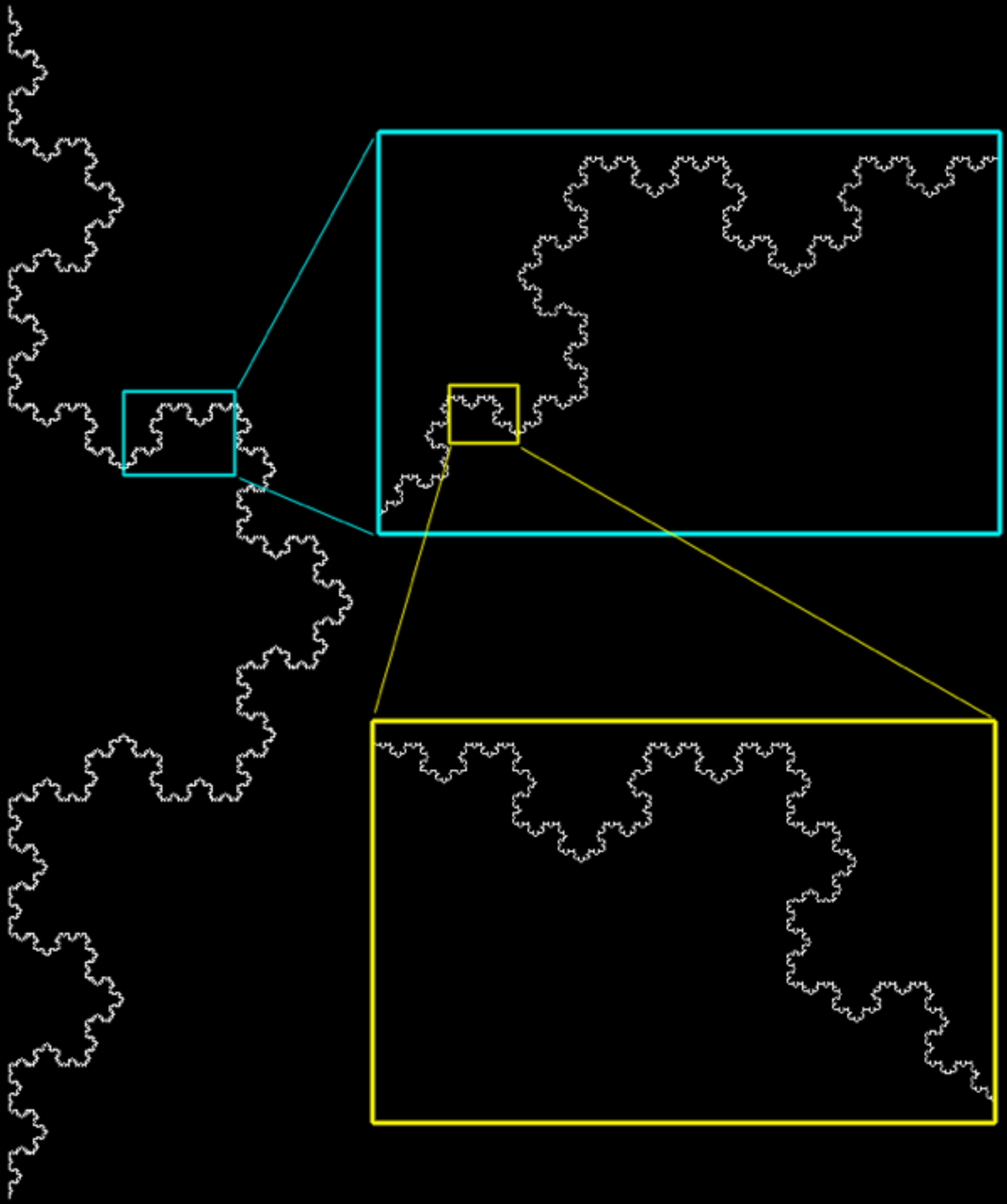


Fractal geometry

- Generation of form and/or texture.
- Random and fractal generators have been widely used to create game assets, objects for virtual environments, and in the animation/movie industry.
- Well know examples include
  - Perlin noise for clouds
  - landscape and terrain generation
  - fractal plant creation
  - ocean waves
  - texture generation



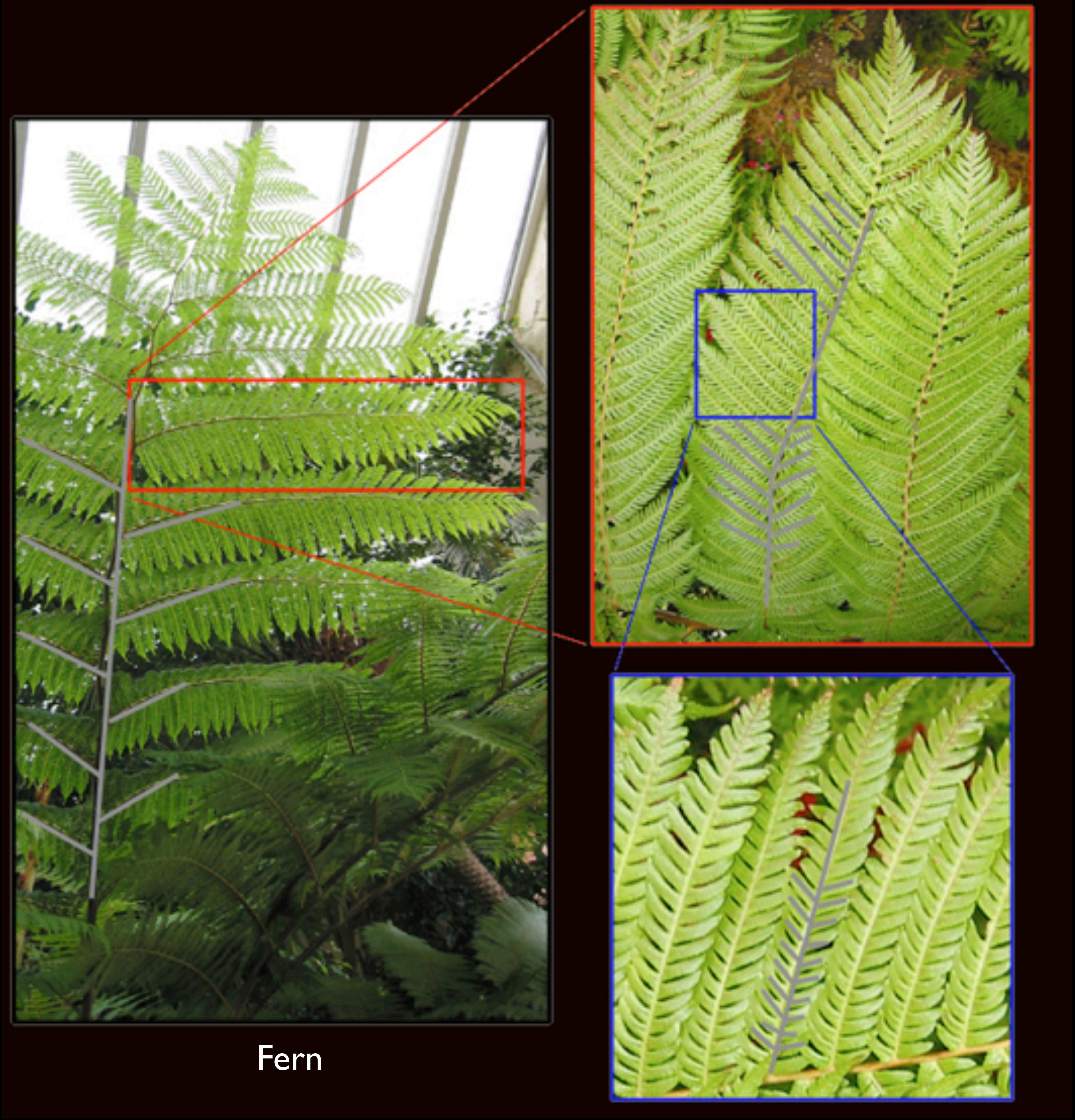
Fractal geometry



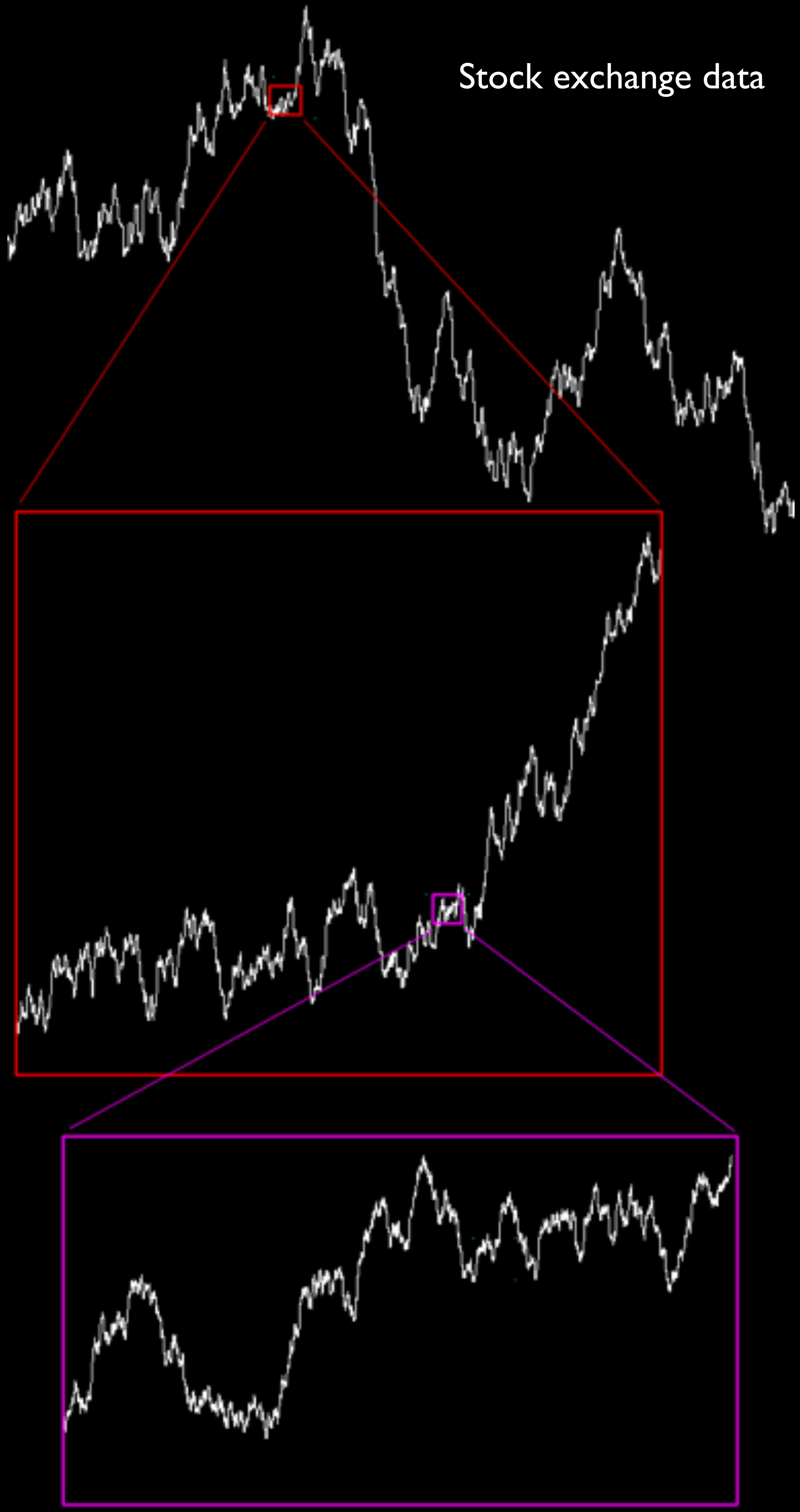
- Fractal geometry vs Euclidean geometry.
- Self similarity across scales.
- Euclidean geometry gets boring the more one zooms in.
- Koch snowflake is "self exact" across scales

Self similarity

- Real objects are generally approximations to mathematical fractals.
- Generally across a smaller range of scales.



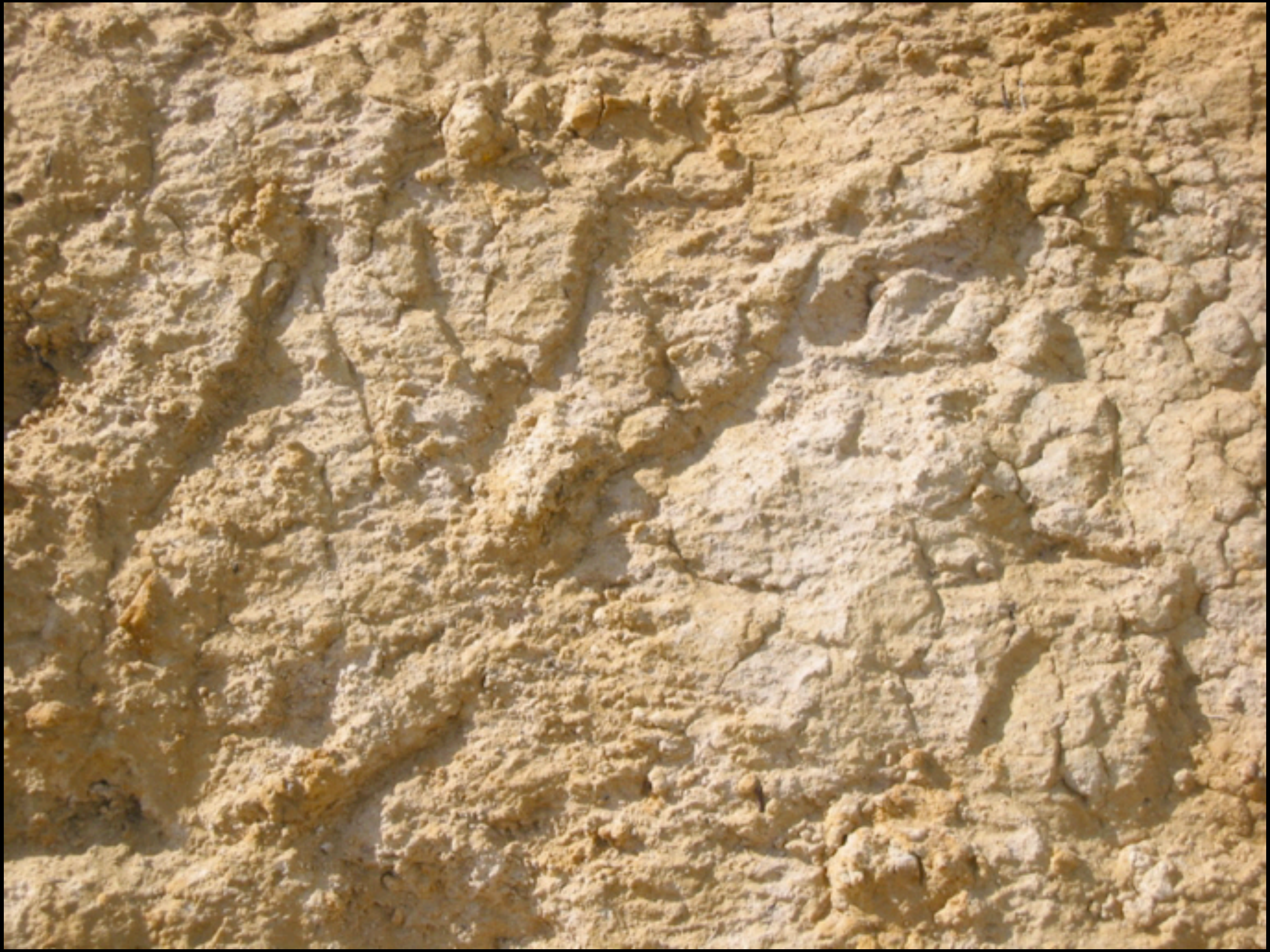
Fern



Stock exchange data

Self similarity

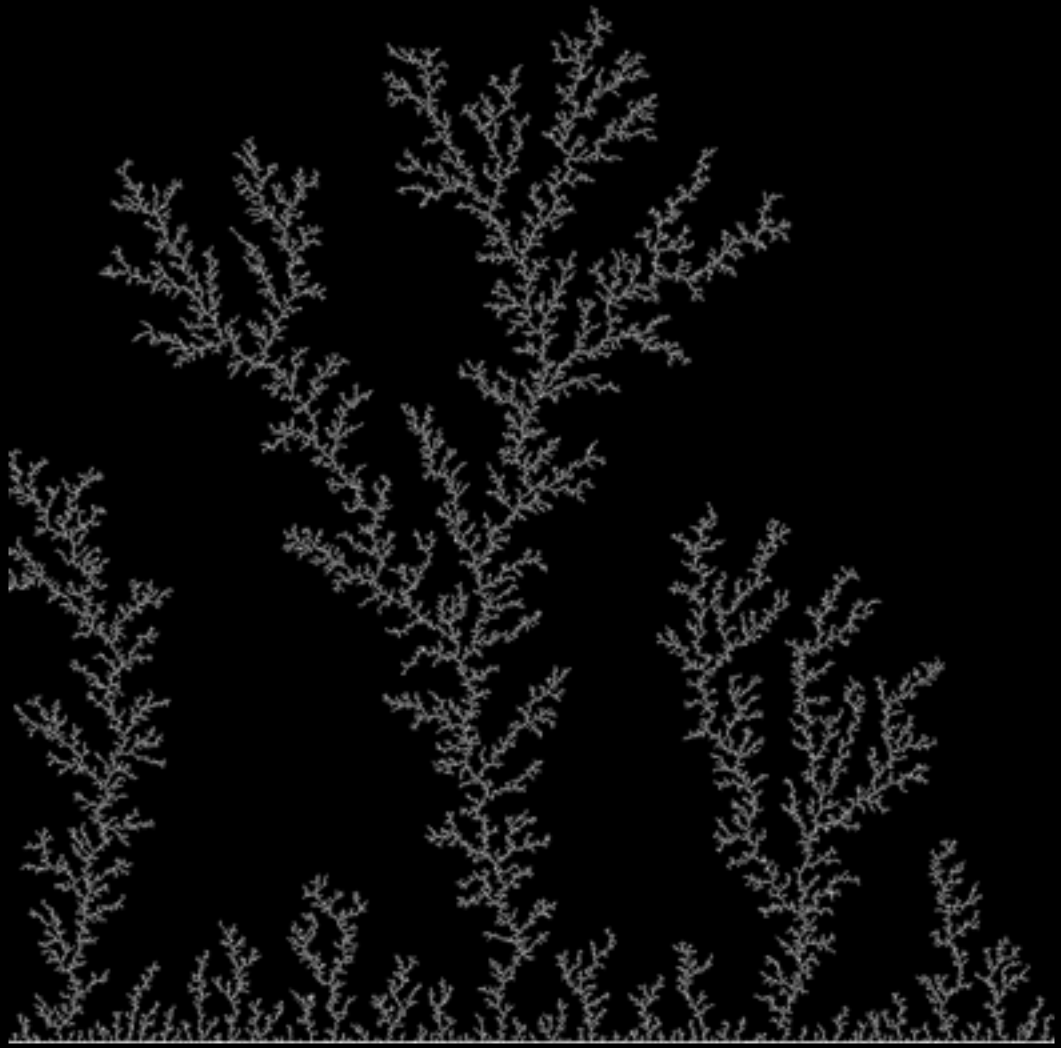
- Consequence of self similarity is the difficulty of judging the scale of an object without context.

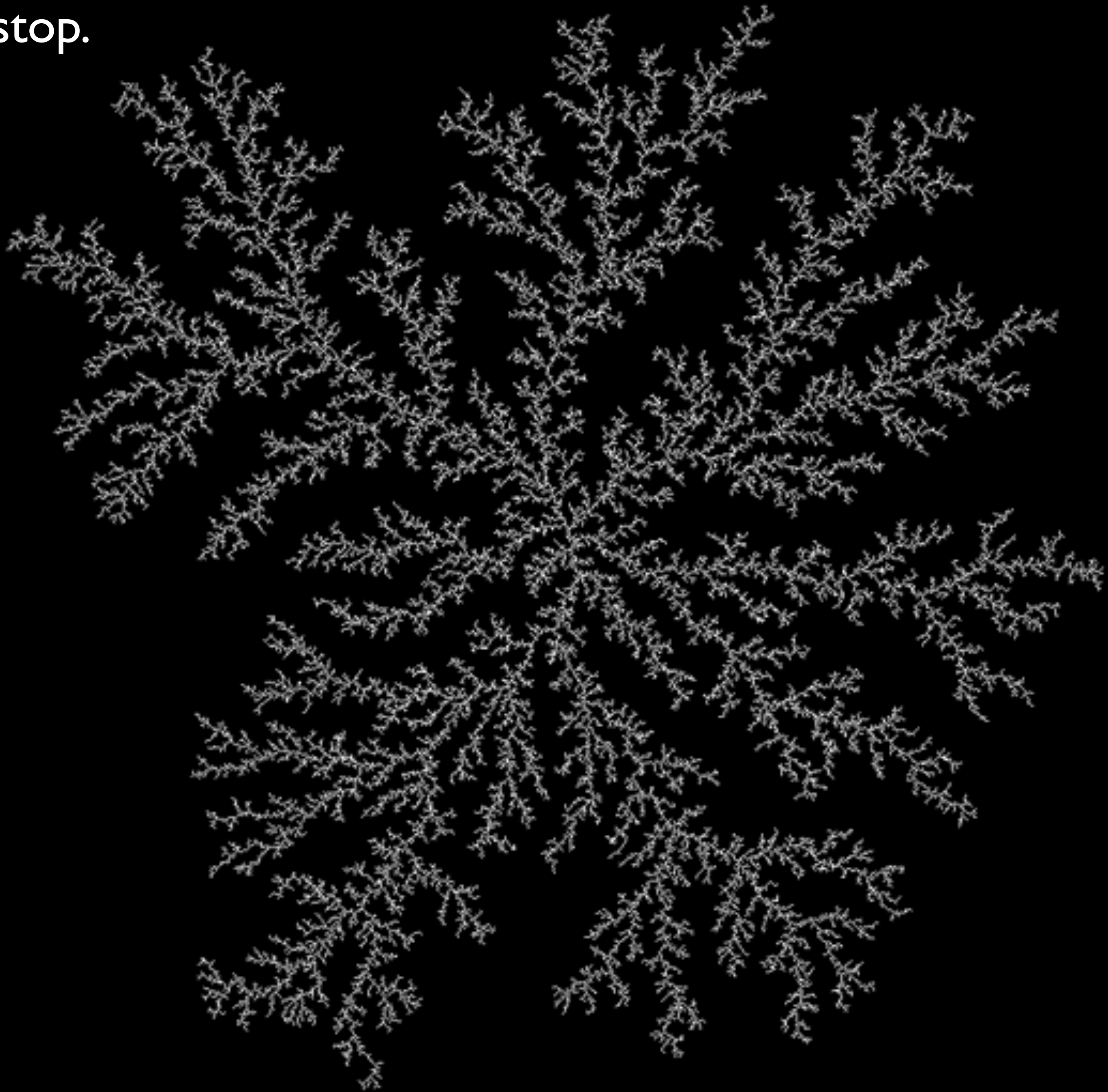


Rough stone? Rocky beach? Small cliff? Mountain side? Aerial view?

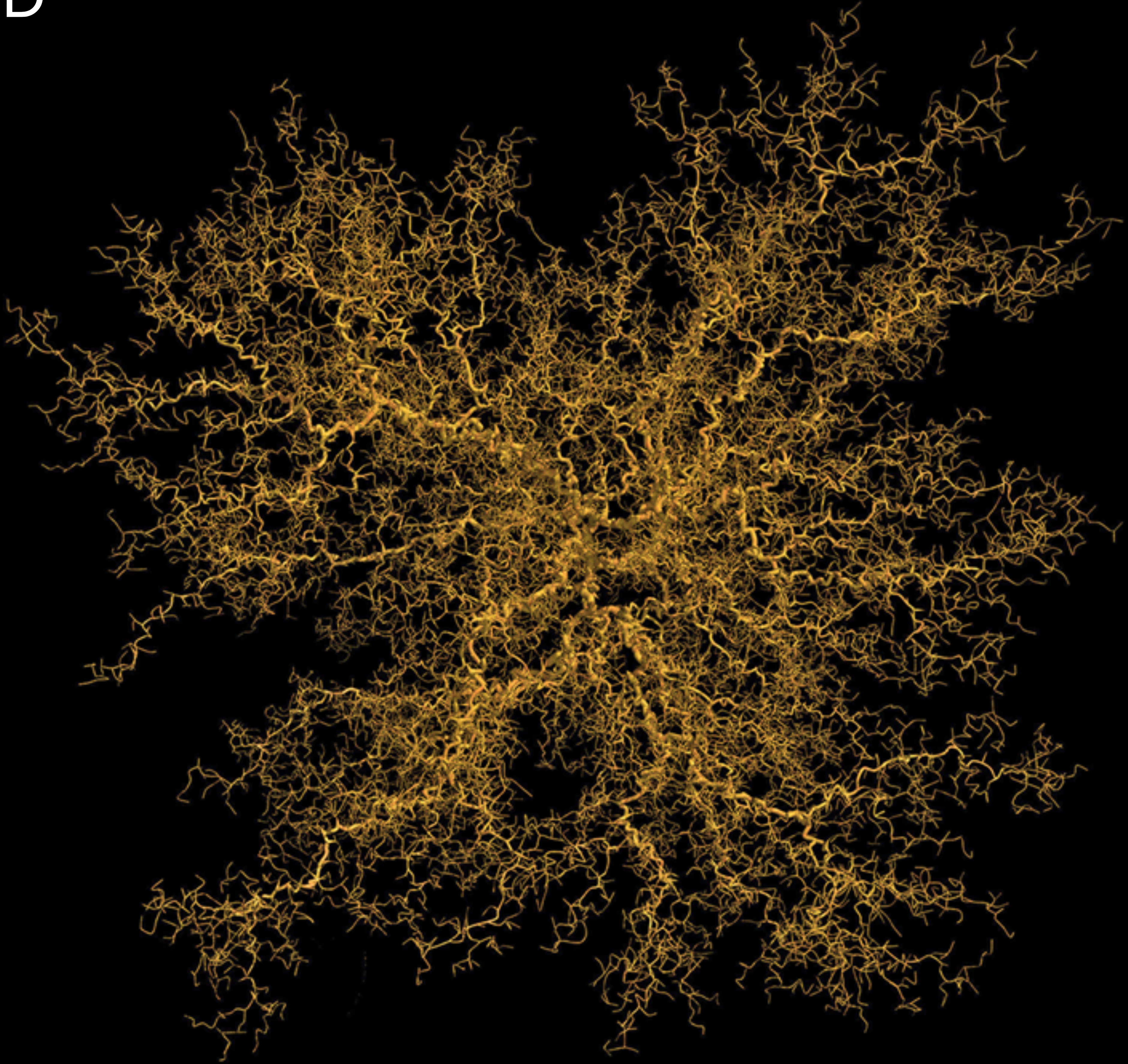
Diffusion limited aggregation (DLA)

- Model for a number of processes in chemistry.
- Algorithm
  1. Particles enter the plane from the surroundings.
  2. Move around randomly.
  3. When they strike another particle they stop.
  4. Got to step 1.
- Drunk analogy.

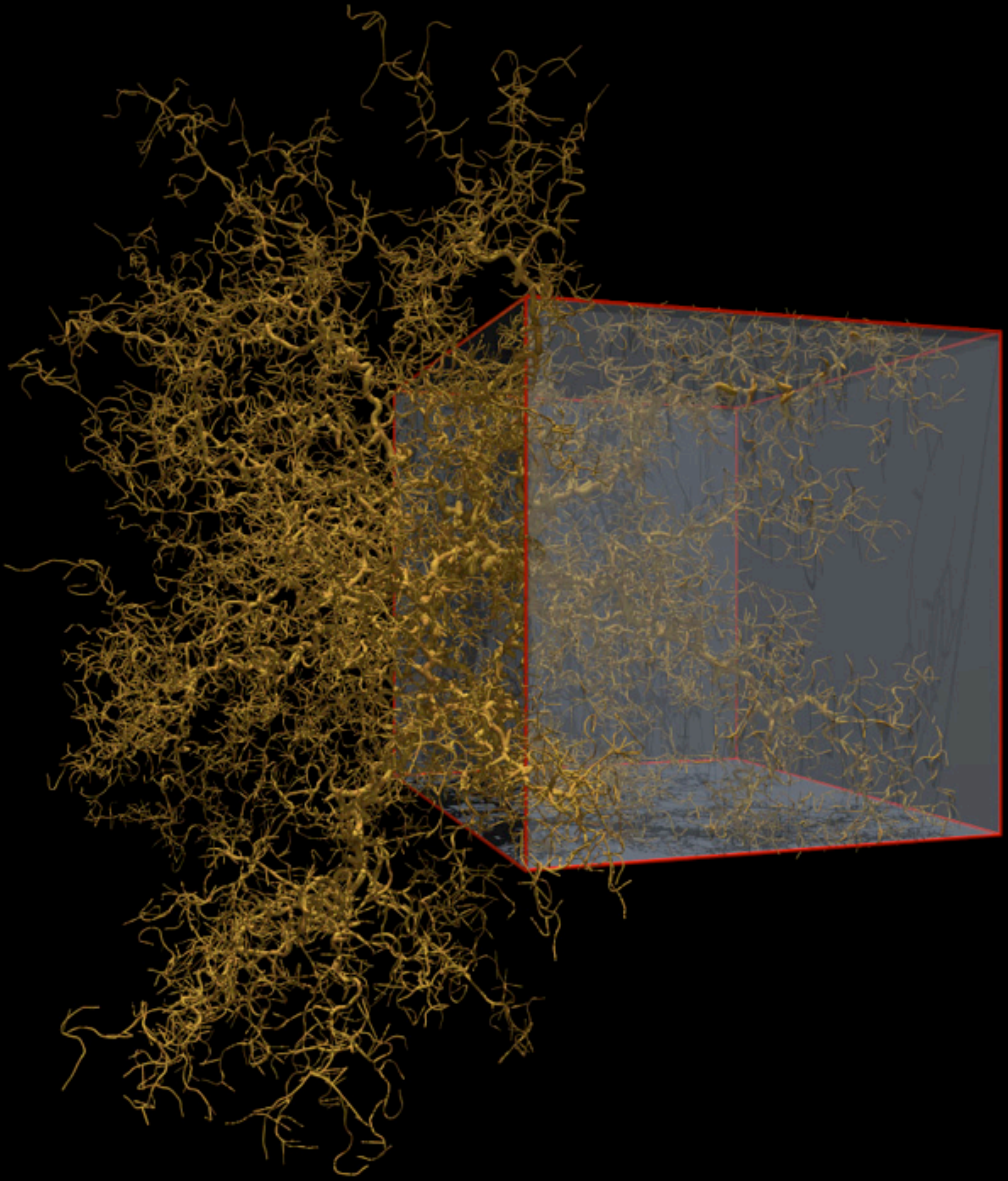




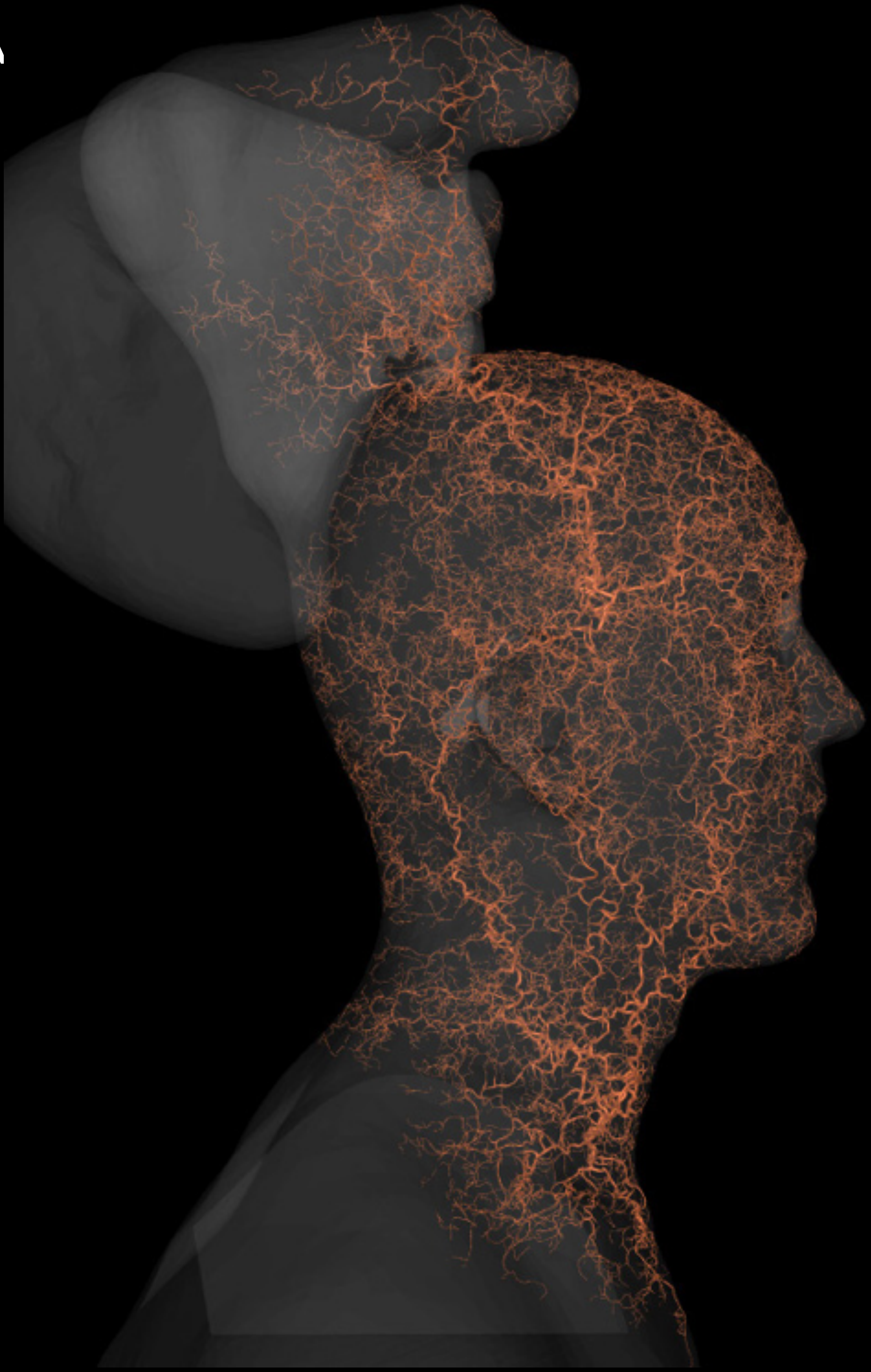
DLA in 3D

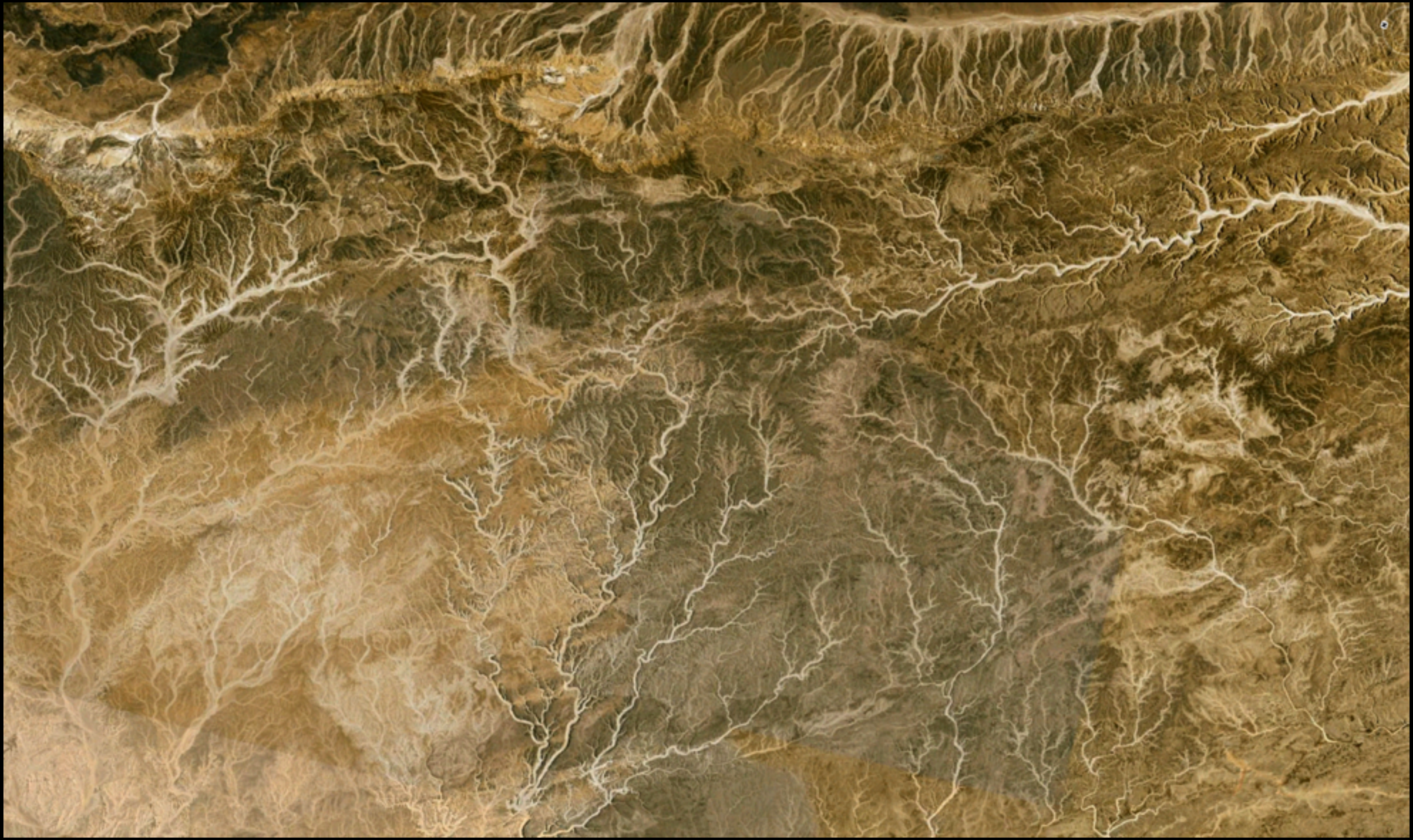


Constrained DLA



Constrained DLA





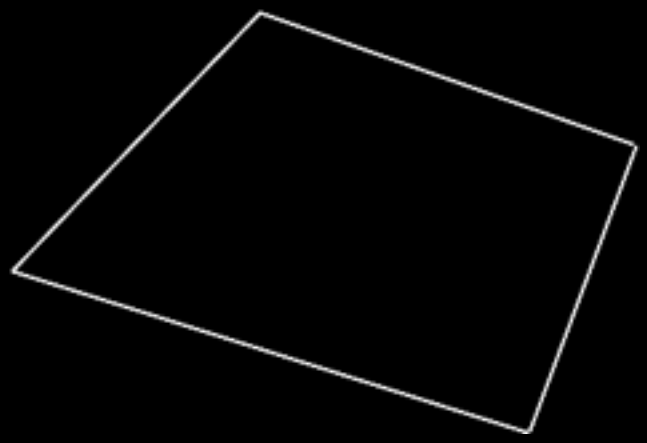
Model for river systems, Egypt

Landscape and planet modelling

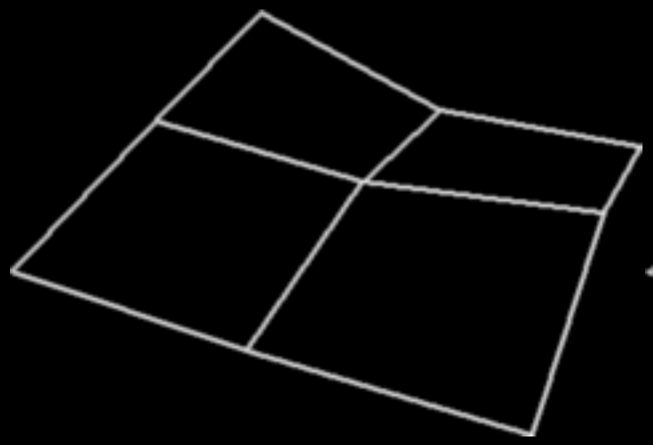
- Unlike Euclidean parametric modelling described earlier, the parameters for fractal process are generally very few yet result in infinitely detailed objects.

- Are generally algorithmic rather than close equations, need to be computed rather than just a given.

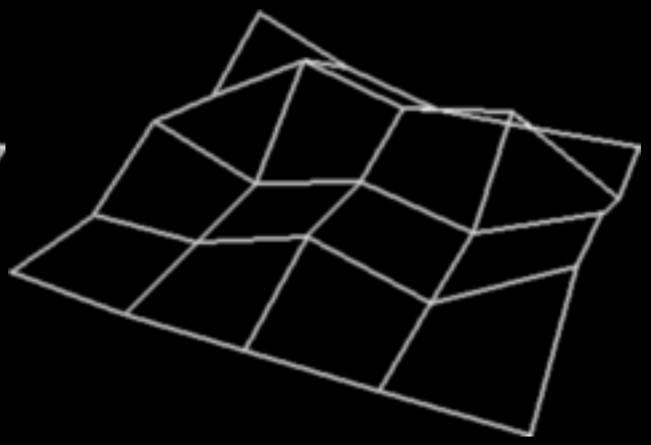
- Random displacement algorithms.
  1. Start with a single polygon
  2. Subdivide into each polygon into 4 pieces
  3. Random perturb each vertex
  4. Reduce the amount of random variation
  5. Go to 2



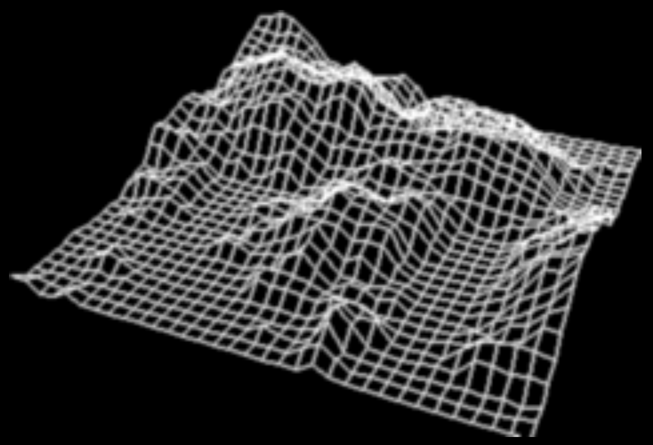
Initial polygon



Iteration 1

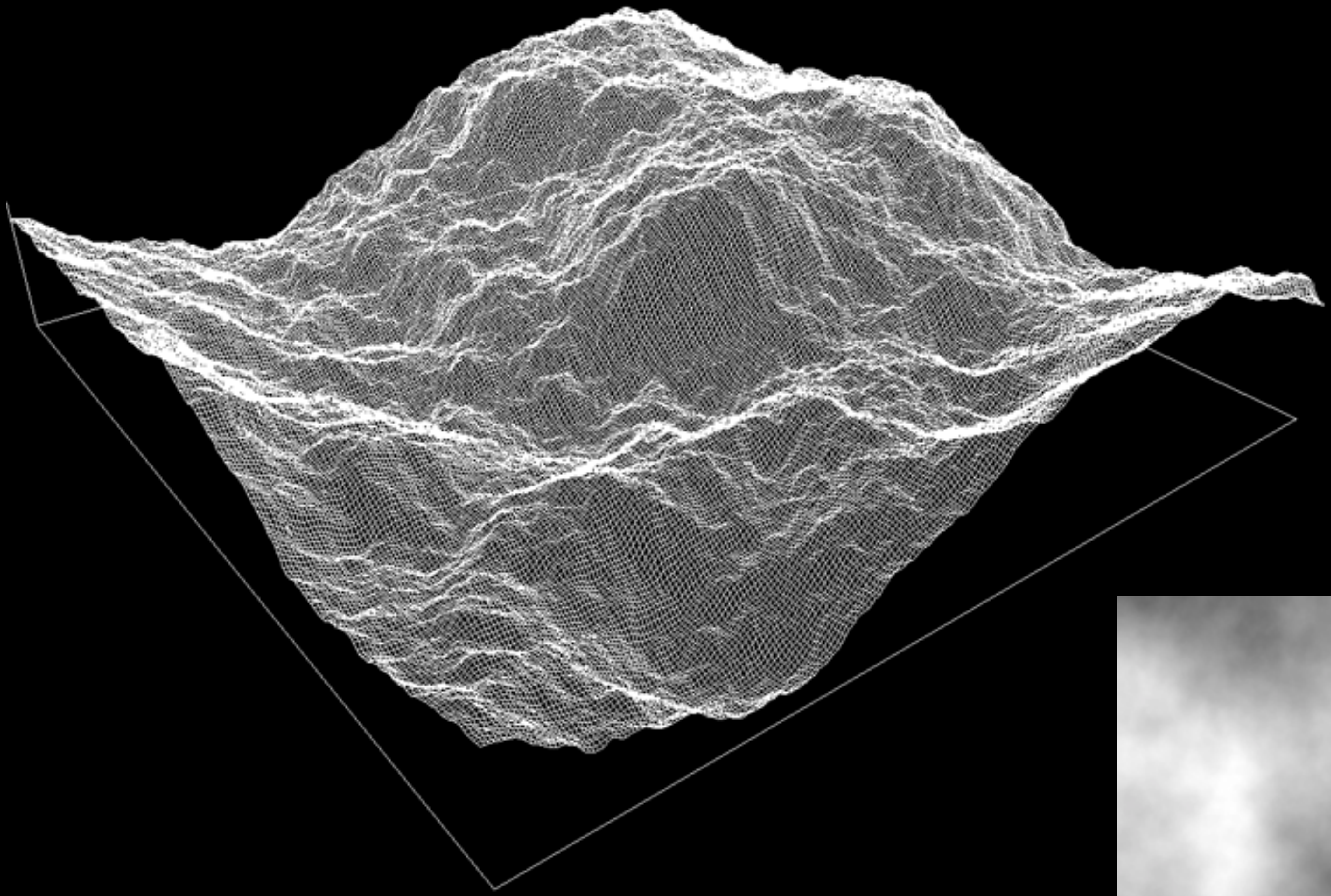


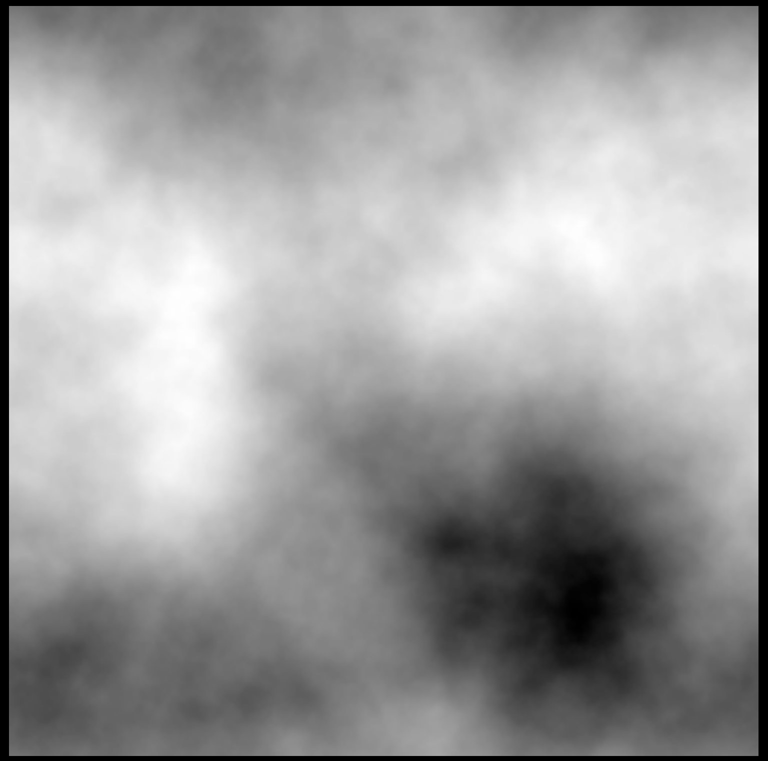
Iteration 2

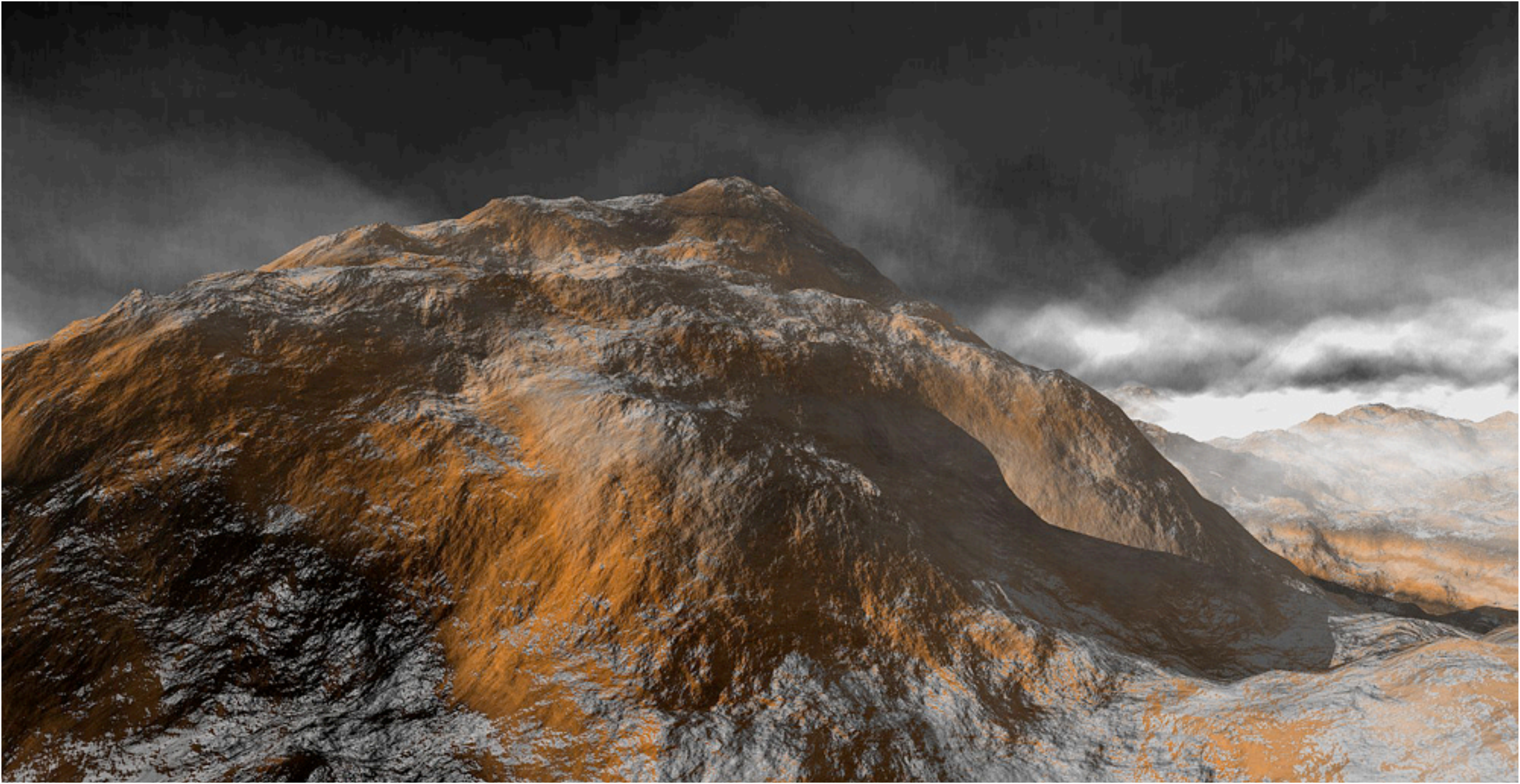


Iteration 5

Landscape modelling

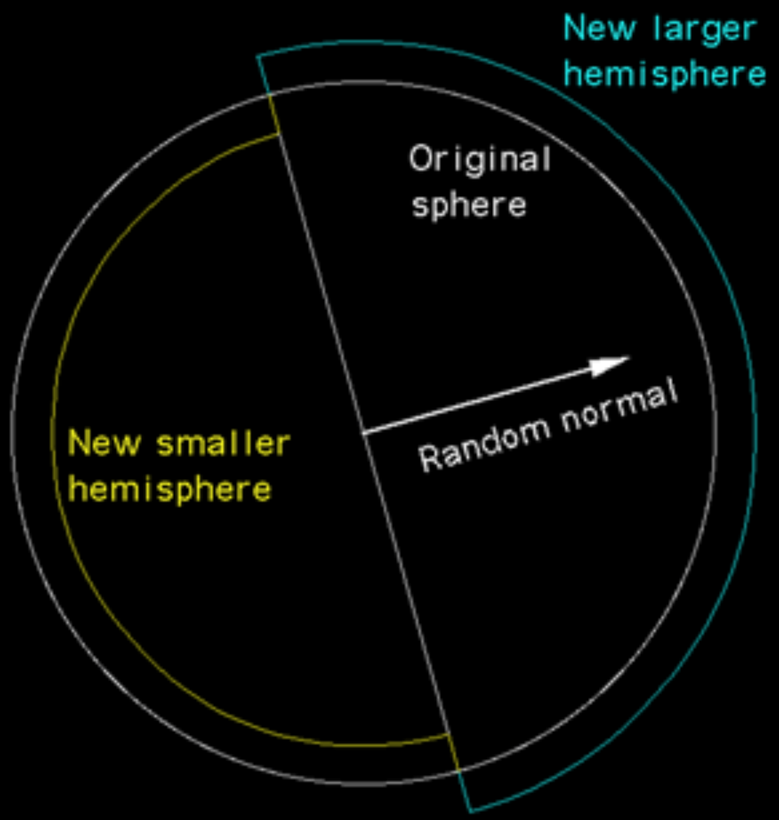


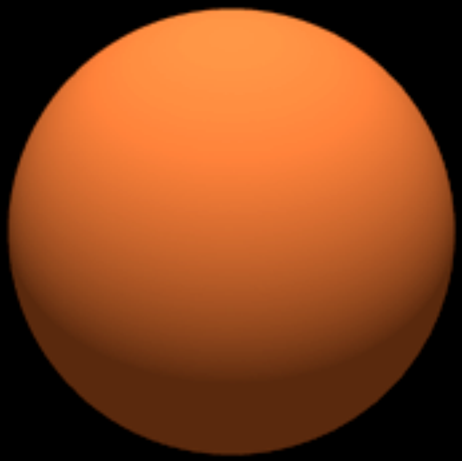


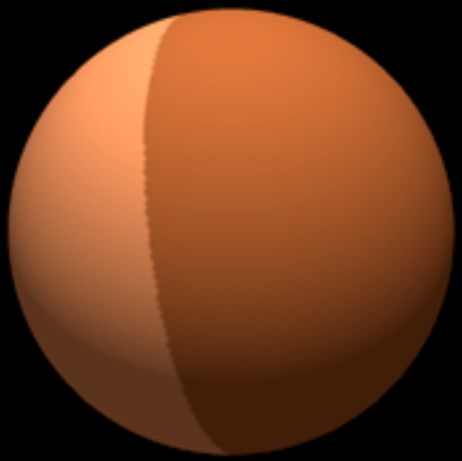


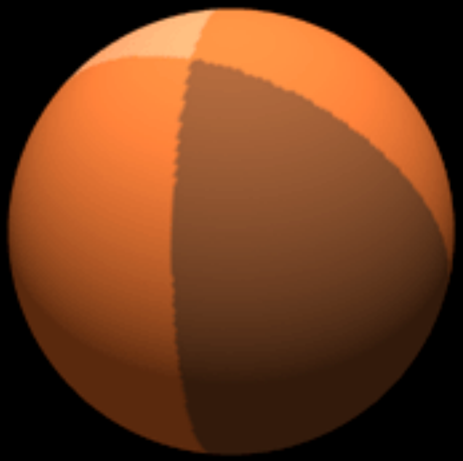
Planet modelling

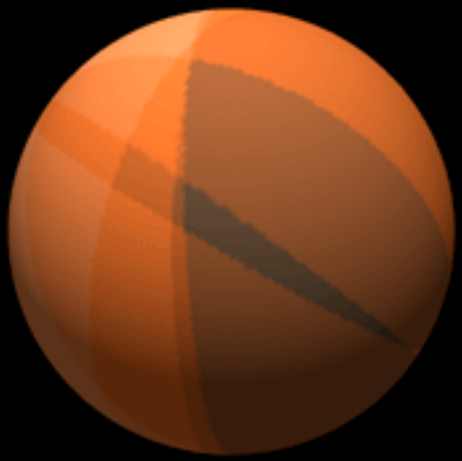
- Radial displacement algorithm.
- Similar idea except applied to a sphere rather than a plane.
- On each iteration split the sphere at a random angle and displace each half of the surface.

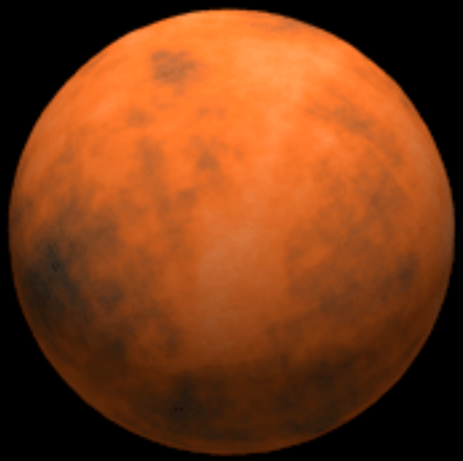



Initial sphere

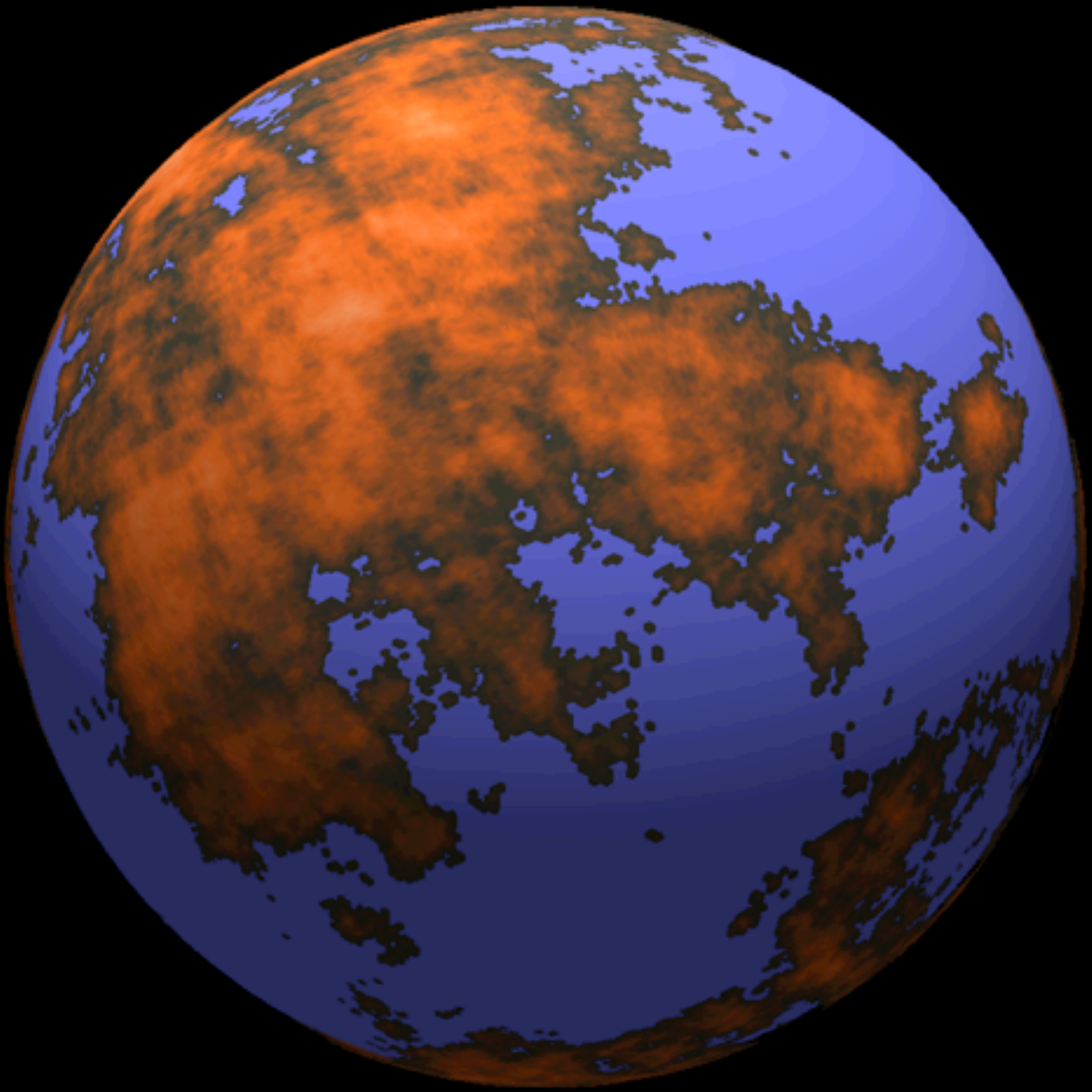

Iteration 1

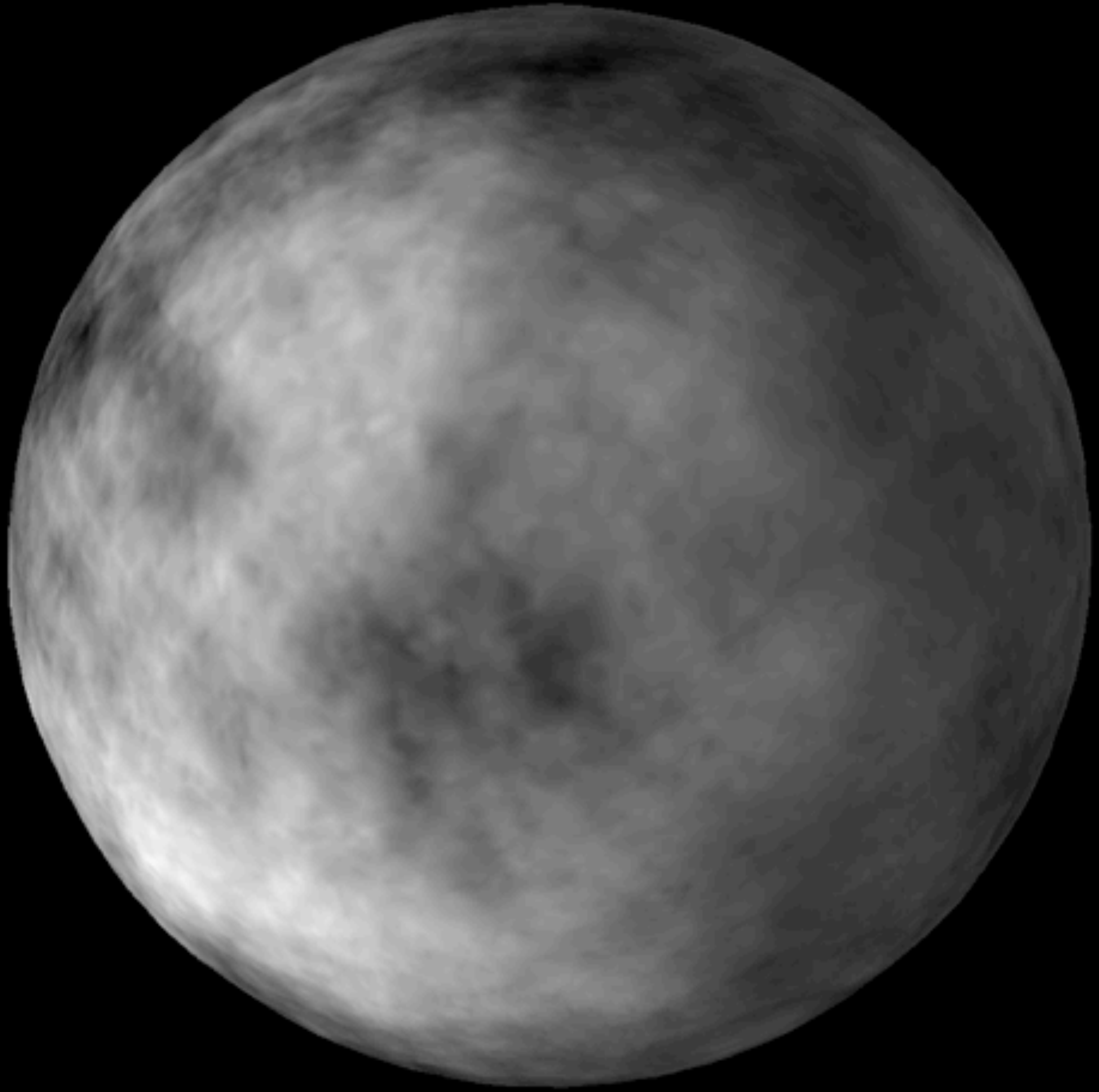

Iteration 2


Iteration 10


Iteration 1000

Planet modelling





Lindenmayer Systems (L-Systems)

- Early seminal publication: Lecture Notes in Biomathematics” by Przemyslaw Prusinkiewcz and James Hanan.

- Based upon so called “rewriting rules”.

- A string of characters is rewritten based upon replacement rules.
  Some characters are given graphical meaning.

- Example of an initial string (axiom) might be: F+F+F+F
  A rewriting rule may be: F --> F+F-F-FF+F+F-F
  That is, on each iteration replace every instance of F with F+F-F-FF+F+F-F

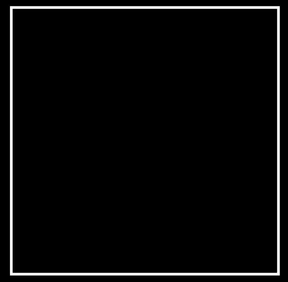
- So first iteration would be a new string: F+F-F-FF+F+F-F + F+F-F-FF+F+F-F + F+F-F-FF+F+F-F + F+F-F-FF+F+F-F

- Second iteration would result in the string: F+ F-F-FF+ F+ F-F+ F+ F-F-FF+ F+ F-F-F+ F-F-FF+ F + F-F-F+ F-F-FF+ F+ F-FF+ F-F-FF+ F+ F-F+ F+ F-F-FF+ F+ F-F+ F+ F-F-FF+ F+ F-F-F+ F-F-FF+ F+ F-F+ F+ F-F-FF+ F+ F-F+ F+ F-F-FF+ F+ F-F-F+ F-F-FF+ F+ F-F-F+ F-F-FF+ F+ F-FF+ F-F-FF+ F+ F-F+ F+ F-F-FF+ F+ F-F+ F+ F-F-FF+ F+ F-F-F+ F-F-FF+ F+ F-F+ F+ F-F-FF+ F+ F-F+ F+ F-F-FF+ F+ F-F-F+ F-F-FF+ F+ F-F-F+ F-F-FF+ F+ F-FF+ F-F-FF+ F+ F-F+ F+ F-F-FF+ F+ F-F+ F+ F-F-FF+ F+ F-F-F+ F-F-FF+ F+ F-F+ F+ F-F-FF+ F+ F-F+ F+ F-F-FF+ F+ F-F-F+ F-F-FF+ F+ F-F-F+ F-F-FF+ F+ F-FF+ F-F-FF+ F+ F-F+ F+ F-F-FF+ F+ F-F+ F+ F-F-FF+ F+ F-F-F+ F-F-FF+ F+ F-F

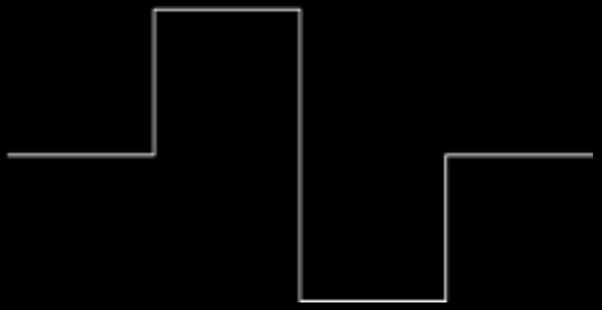
- And so on ...

L-Systems

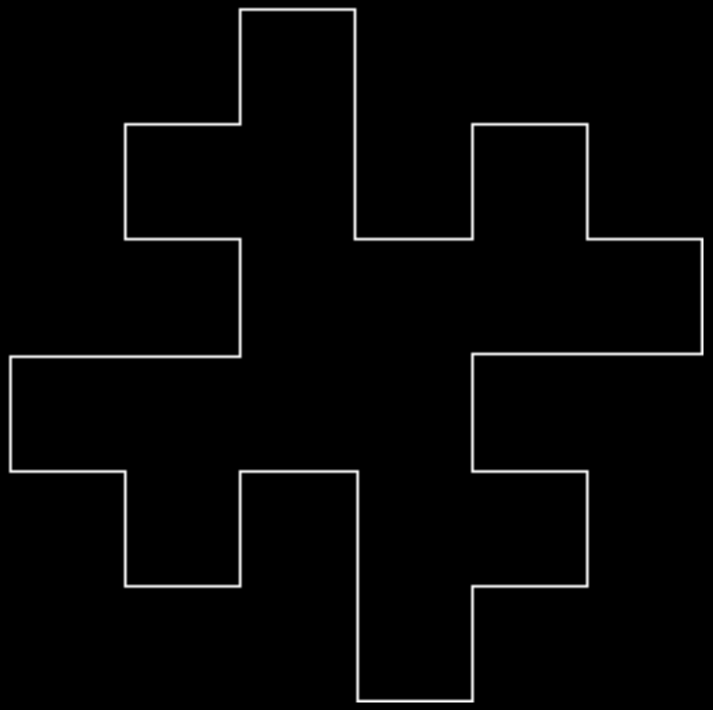
- If the characters are given meaning such that:
  “F” means move forward one unit.
  “+” means turn 90 degrees clockwise
  “-” means turn 90 degrees anticlockwise
  There is a standard library of meanings.
- Then the axiom F+F+F+F is just a square.
- Replacement rule F --> F+F-F-FF+F+F-F is



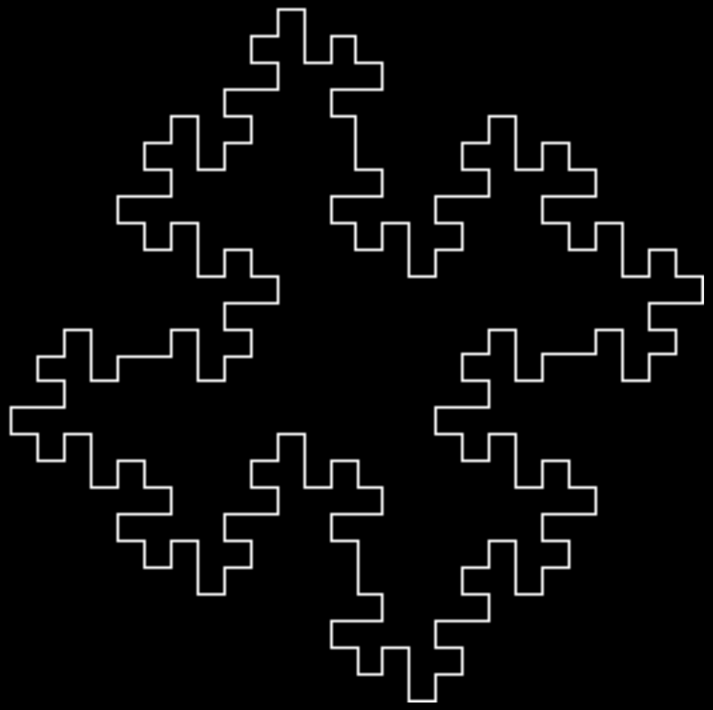
Axiom



Replacement rule



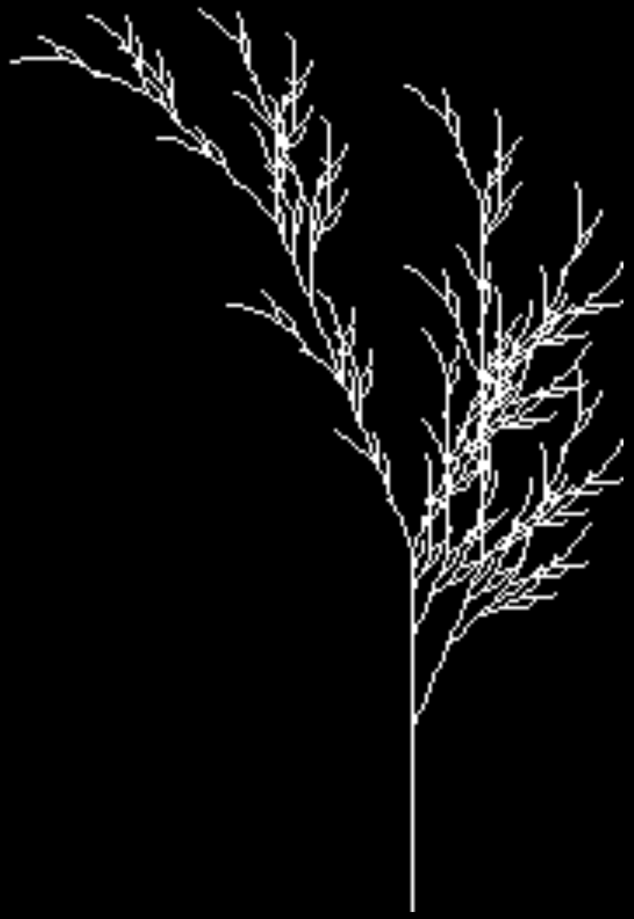
First iteration



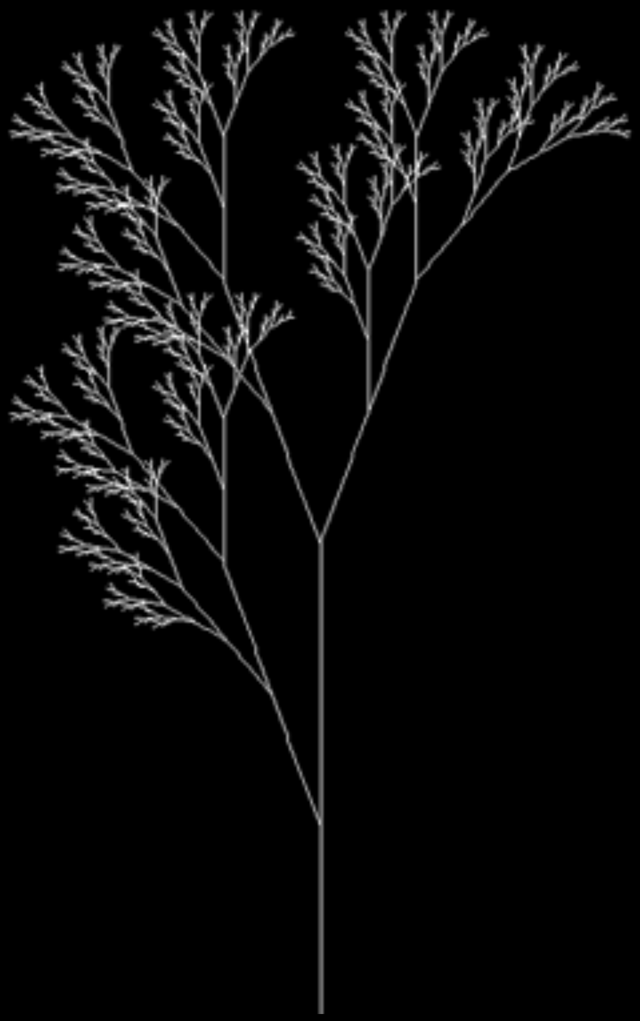
Second iteration

Example

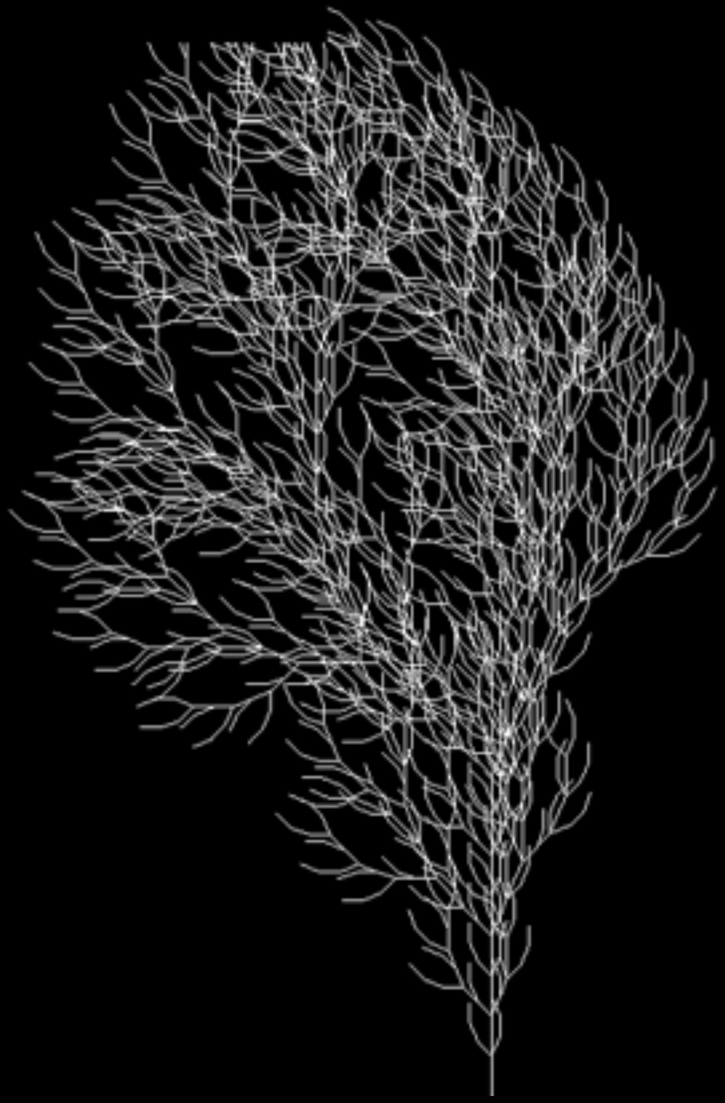
Axiom = X
F --> FF
X --> F-[[X]+X]+F[+FX]-X
angle = 22.5



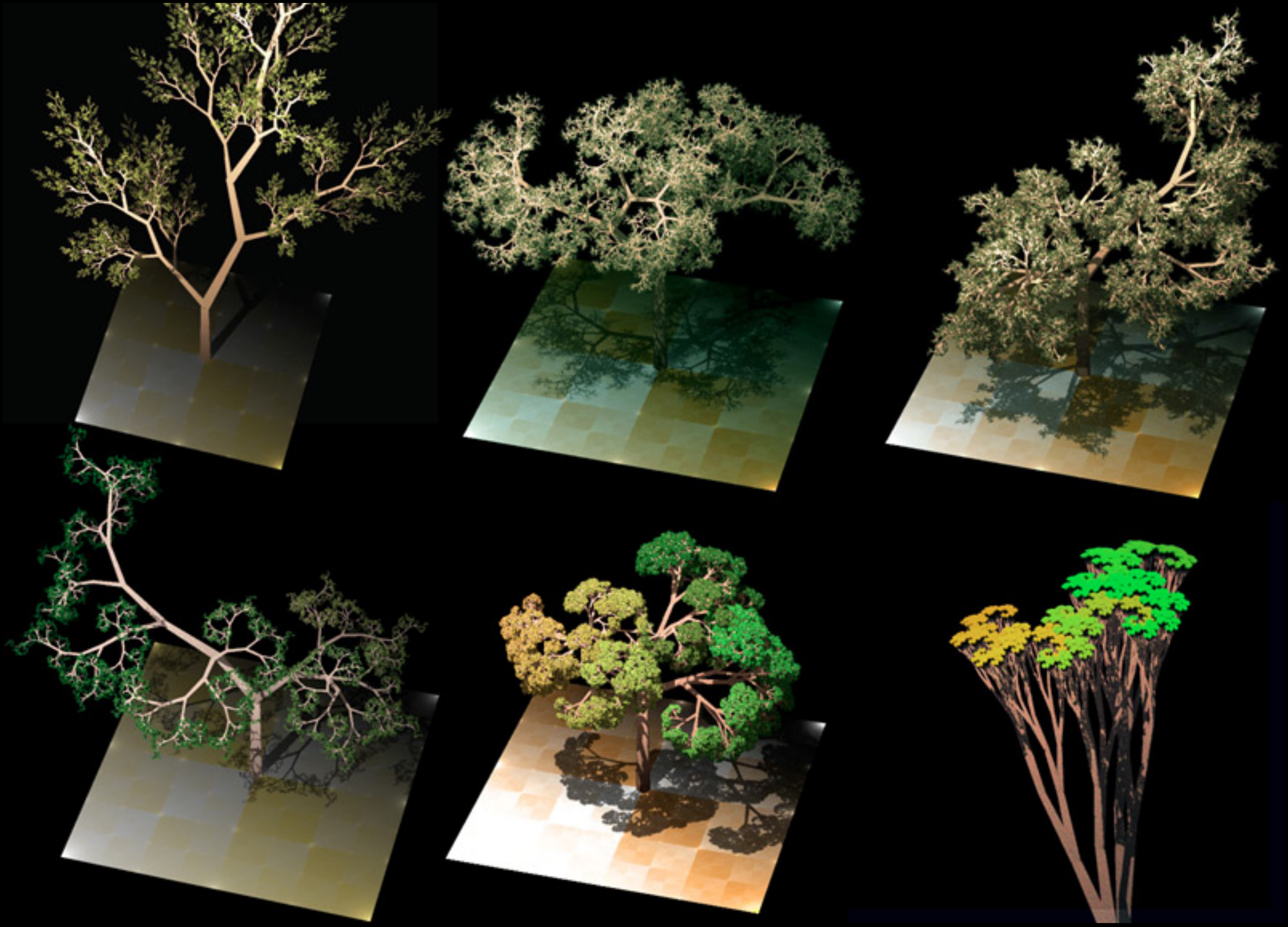
Axiom = X
F -> FF
X -> F[+X]F[-X]+X
angle = 20



Axiom = F
F -> FF+[+F-F-F]-[-F+F+F]
angle = 22.5



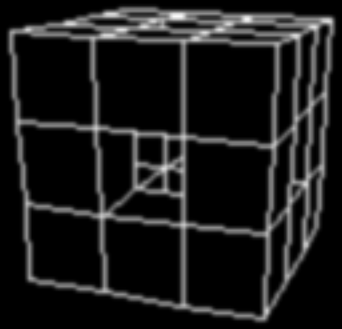
Example 3D



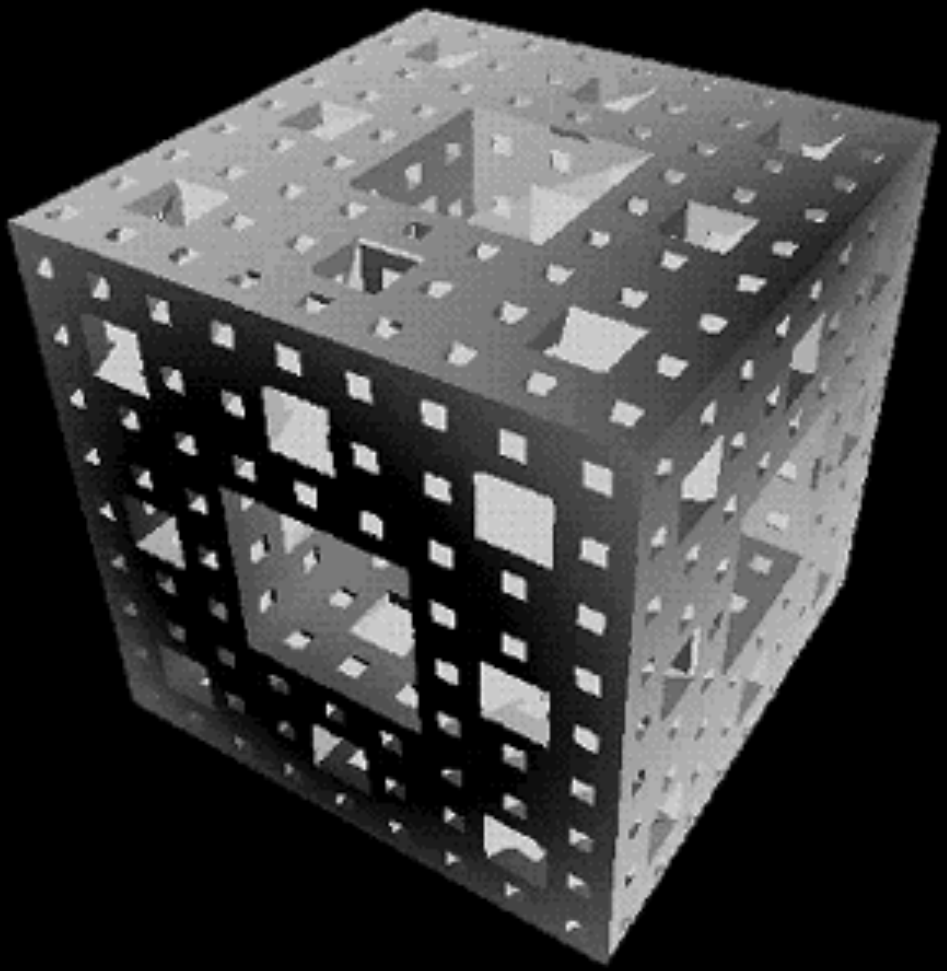
3D replacement rules

- L-System principle can be extended into 3D and rules simplified to iteratively replacing shapes with other shapes.
- Well known example is the Menger sponge.
- The replacement shape is the same as the original shape just scaled.

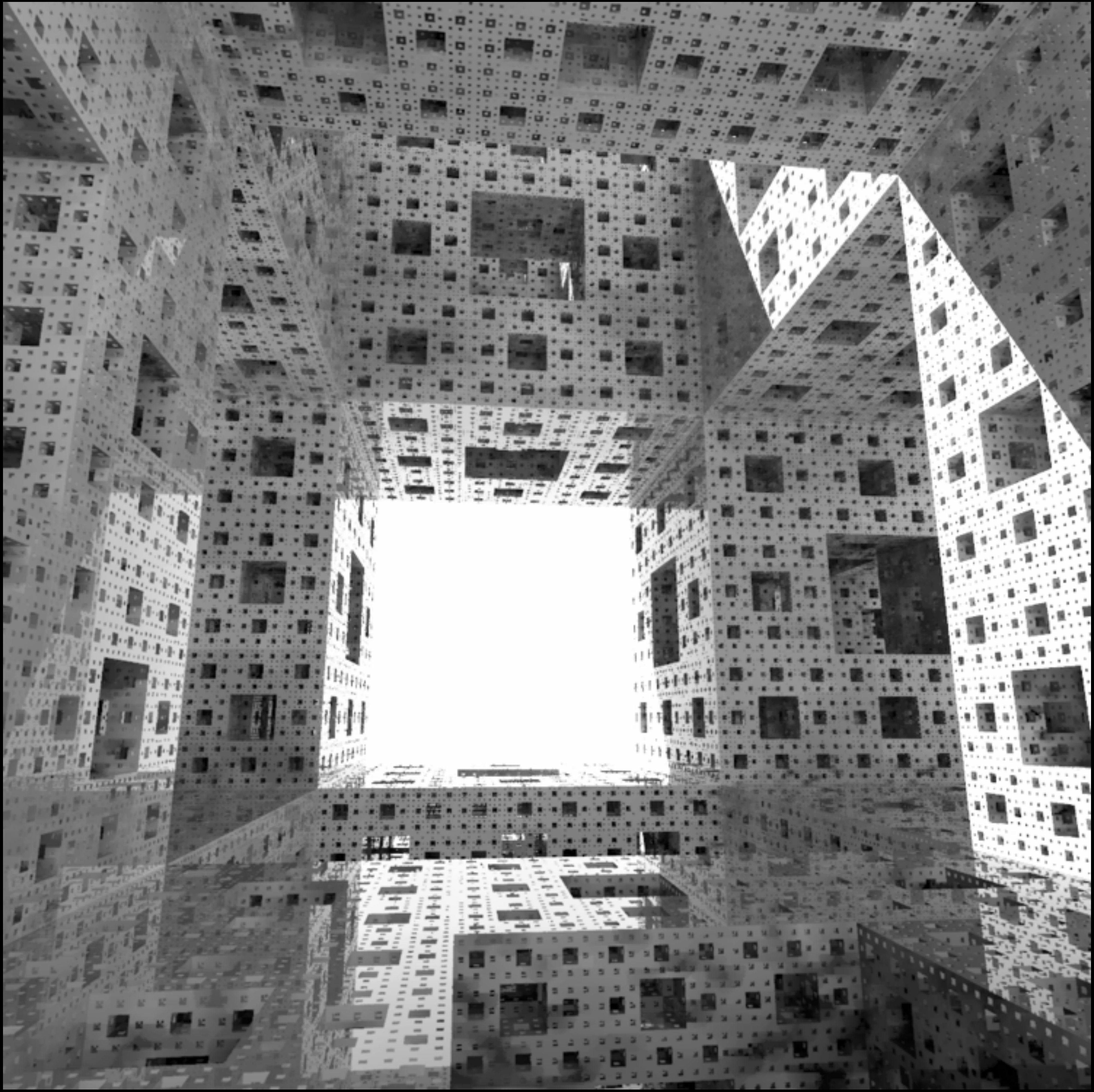
Axiom



Replacement rule



Second iteration



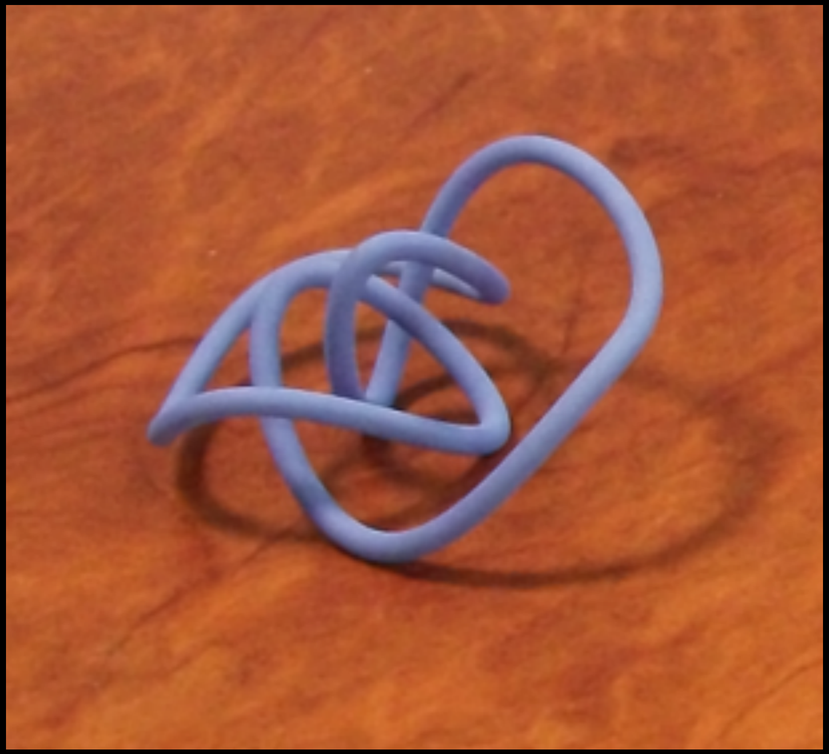
Rapid prototyping (RP)

- Has been available for 20+ years but the technology was expensive and imposed constraints on what could be built.
- Increasingly accessible process.
- A number of online bureau services.
- ZCorp revolutionised the process perhaps 10 years ago with their range of colour 3D printers.
- Now two main players/technologies
  - Zcorp: colour but limited structurally
  - ObJet: highest resolution but monochrome
- Still limitations to colour fidelity.

Constrained DLA

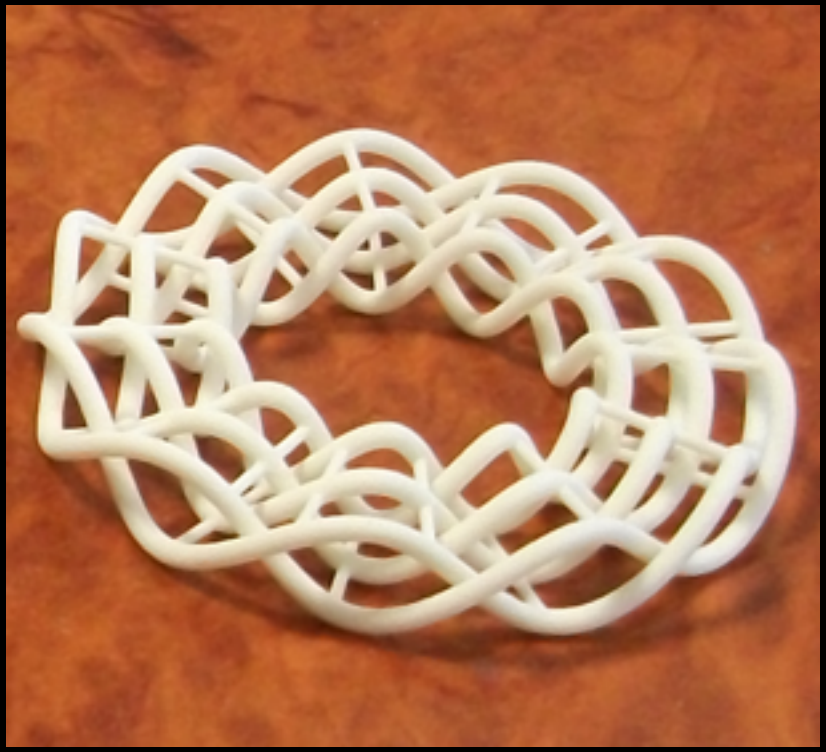
RP in visualisation

- Visualisation is the process of applying advanced computing techniques to data in order to provide insight into the underlying structures, relationships and processes.
- RP allows us to explore geometry in the same way as we explore objects in real life.



Visualisation in knot theory

Printing in metal

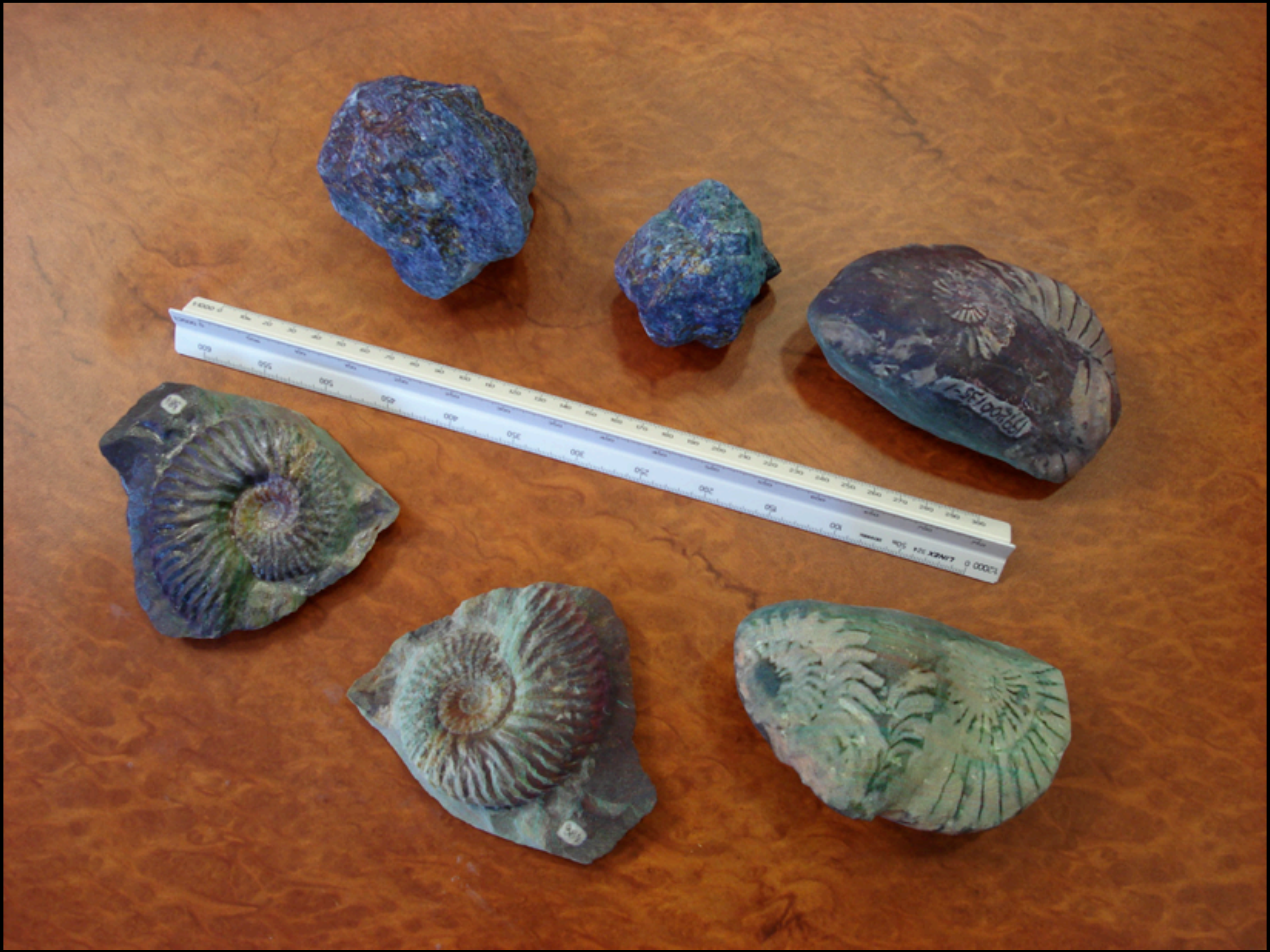


Visualisation in neuroscience

Example

Series of peptides (Chemistry UWA)

Example



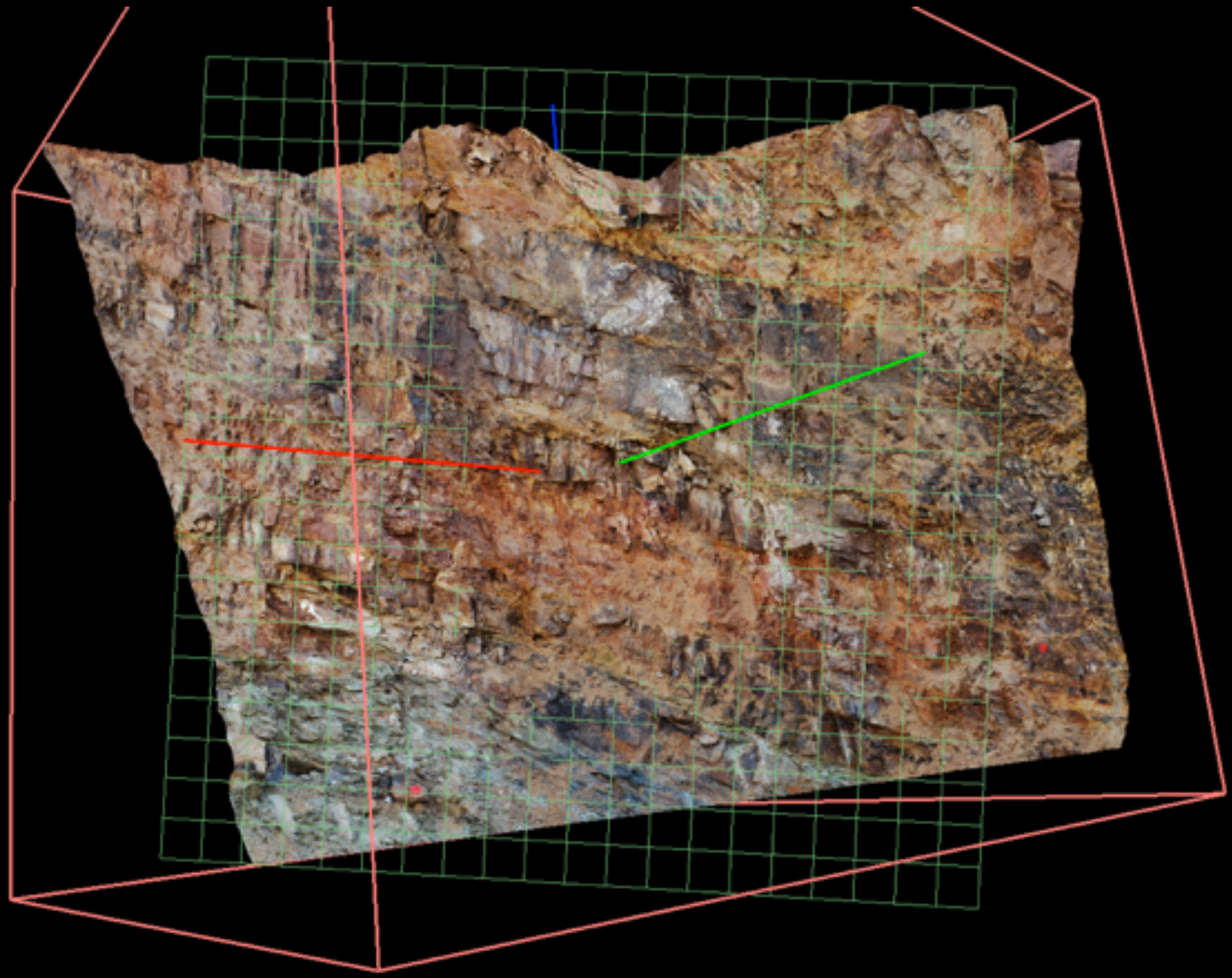
Fossils (Geology)

3D reconstruction from photographs

- Photogrammetry: The process of deriving some 3D quantity from a collection of photographs.
- Algorithms have developed significantly in recent years.
- A relatively low number (< 10) of photographs are required for 2.5D objects.
- Full 360 objects may require more than 30 photographs.
- Some skill in image capture to achieve best results.
  - requires fixed focal (prime lens), as such point and click cameras can be used.
  - cannot reconstruct what is not photographed (obviously).
  - no point taking multiple photographs from the same position.
- Online services exist for performing the reconstruction.
  Main one is 123D Catch from AutoDesk.
  PhotoSynth by MicroSoft is less useful because one cannot extract the model data.
- There are a number of open source implementation of "bundler" as well as affordable commercial solutions such as PhotoScan.

Motivations

- Creating 3D textured assets for virtual worlds and games.
  Avoid time consuming 3D modelling.
- Recording objects of historic or archaeological importance.
- Non-intrusive capture for medical and forensic applications.
- Capturing geological structures for analysis.



Other technologies

- In some areas it is starting to replace technologies such as laser scanning. LIDAR - light detection and ranging.
  - particularly so for capture of object in difficult locations
  - only requires a modest investment

- Another technology are so called depth cameras
  - Primesense (eg: Kinect)
  - Structured light techniques (eg: Artec Scanner)

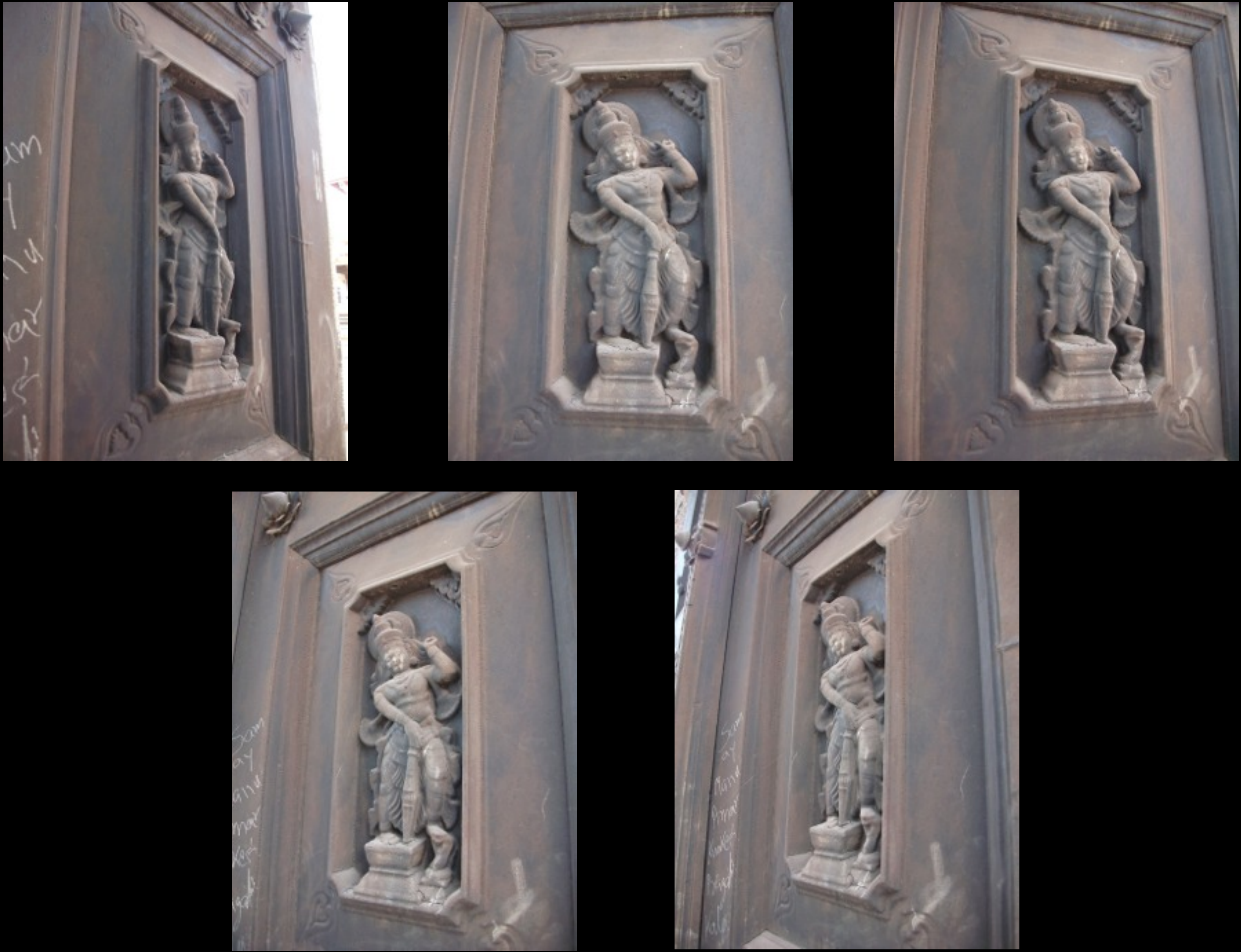
- The above do have some advantages
  - LIDAR generally gives better accuracy
  - Structured light can cope with (limited) motion unlike photogrammetry and LIDAR.

- Future: Light field cameras (plenoptic camera).

LIDAR

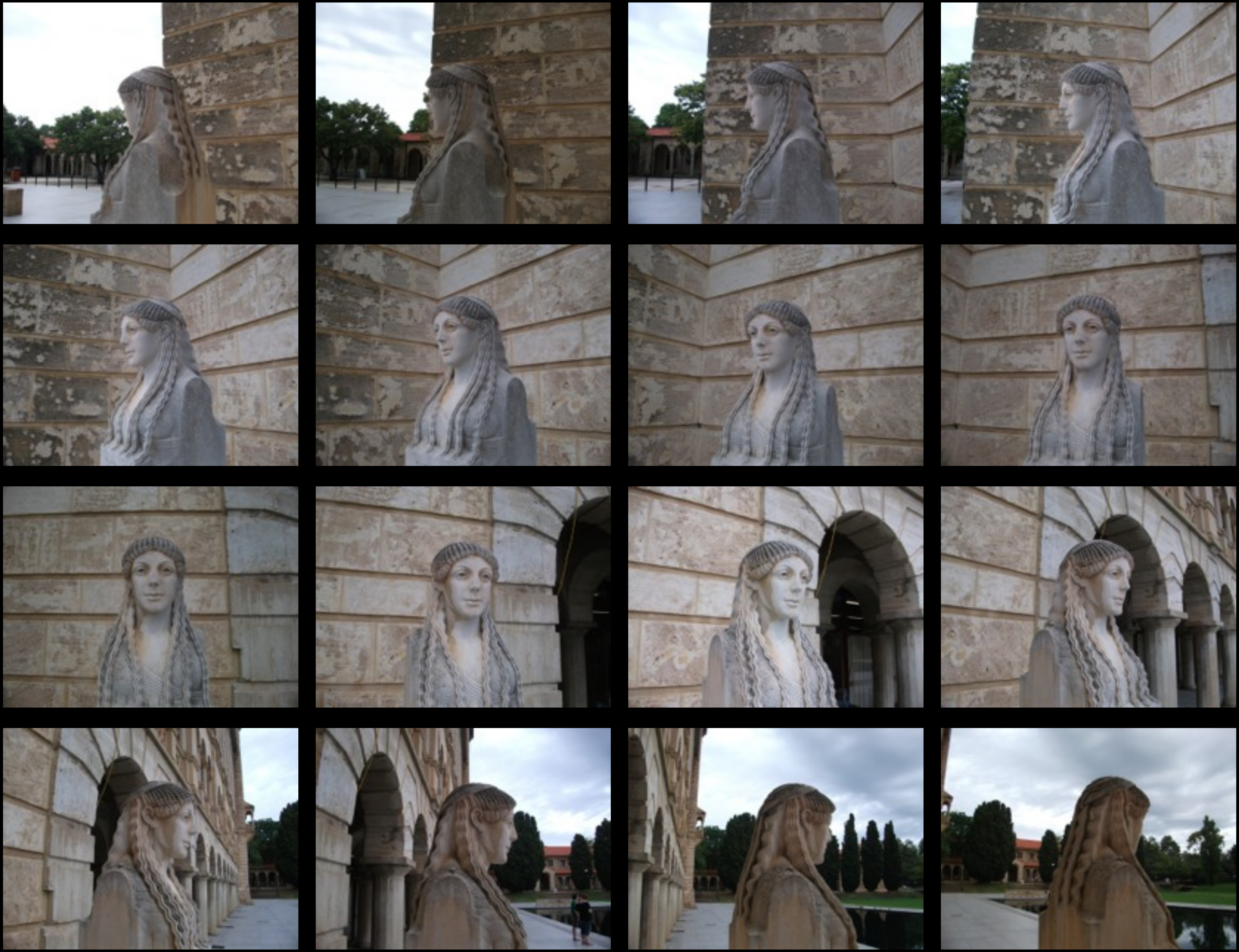
Structured light

Example: Indian temple engraving



Movie

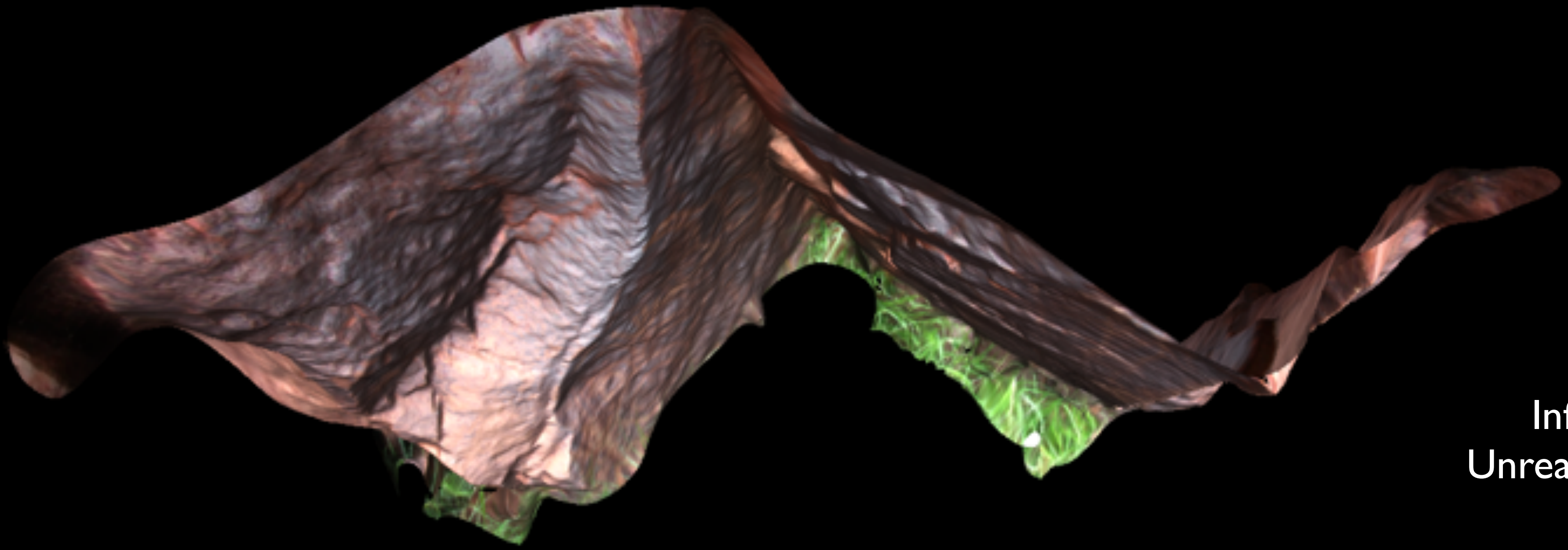
Example: Aphrodite (UWA)



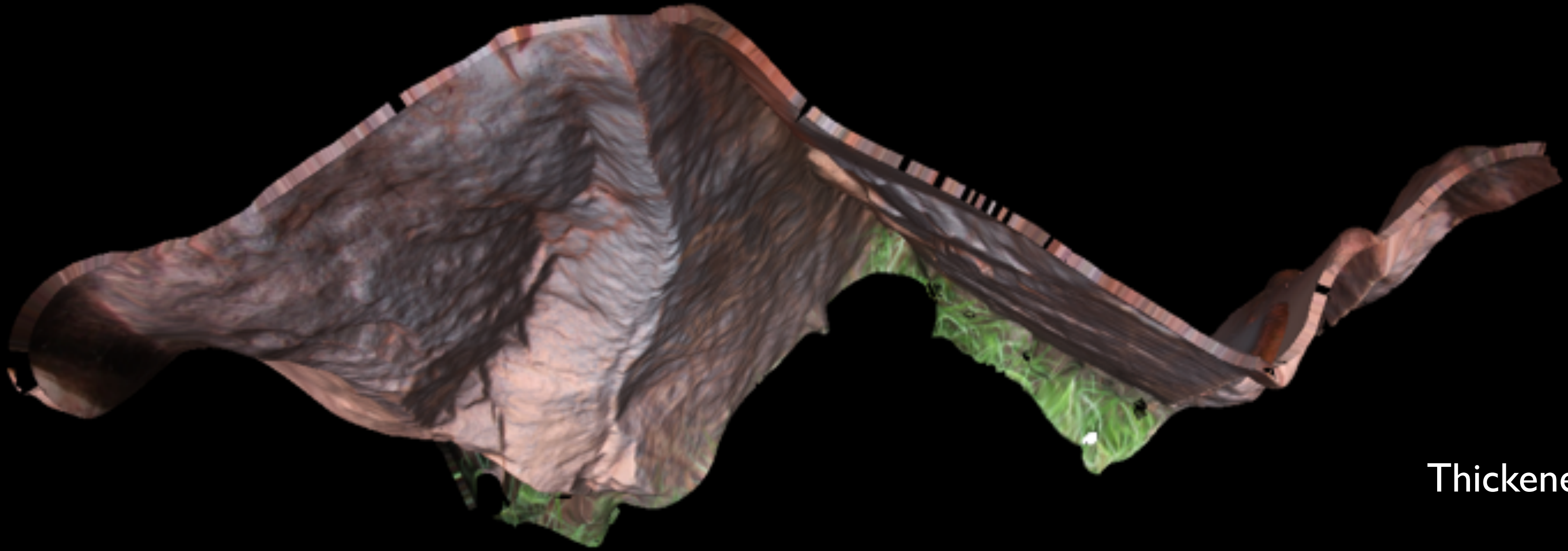
Movie

Closing the loop

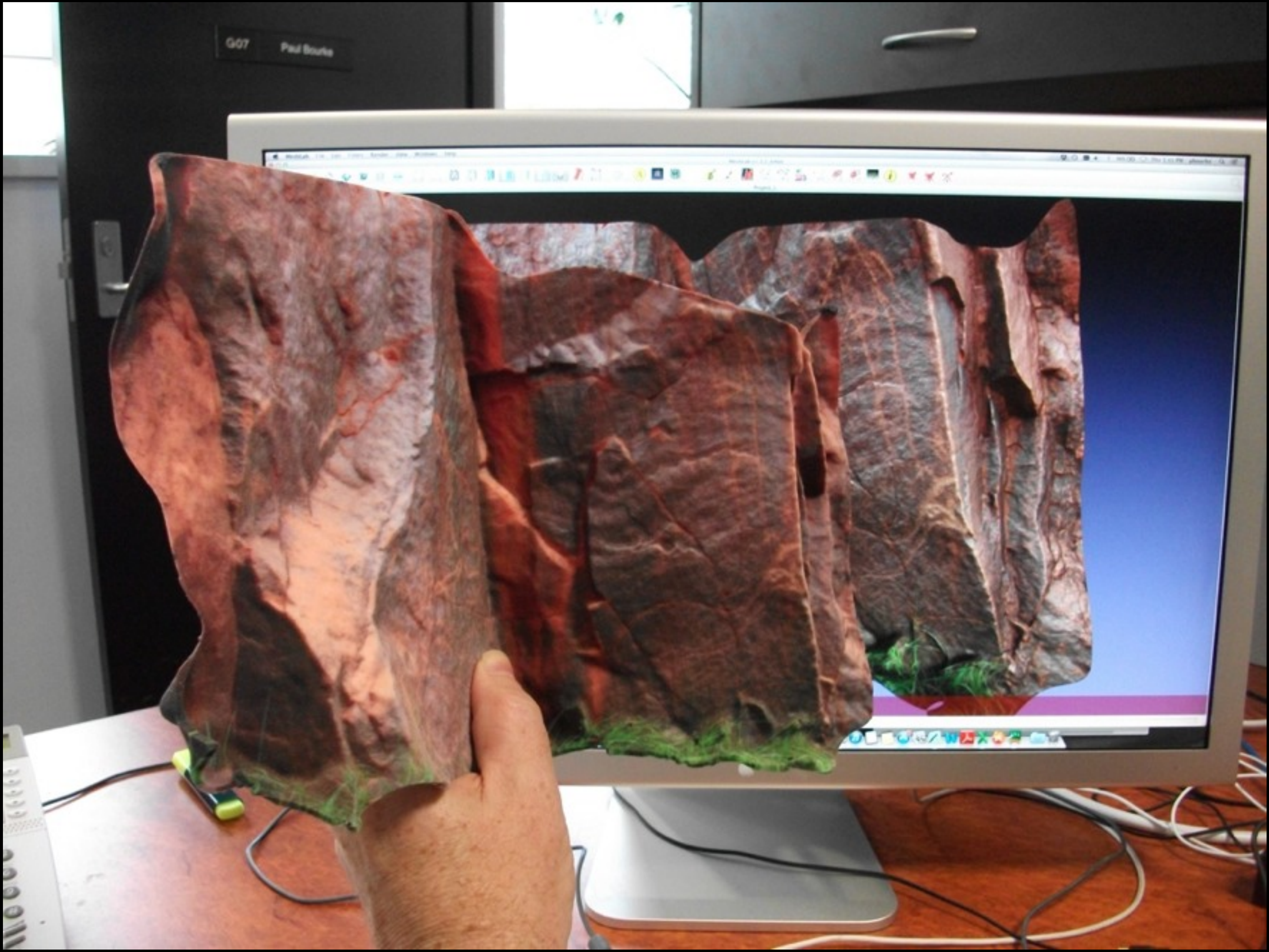
- Reconstruct 3D model from photograph - edit/transform - 3D print.

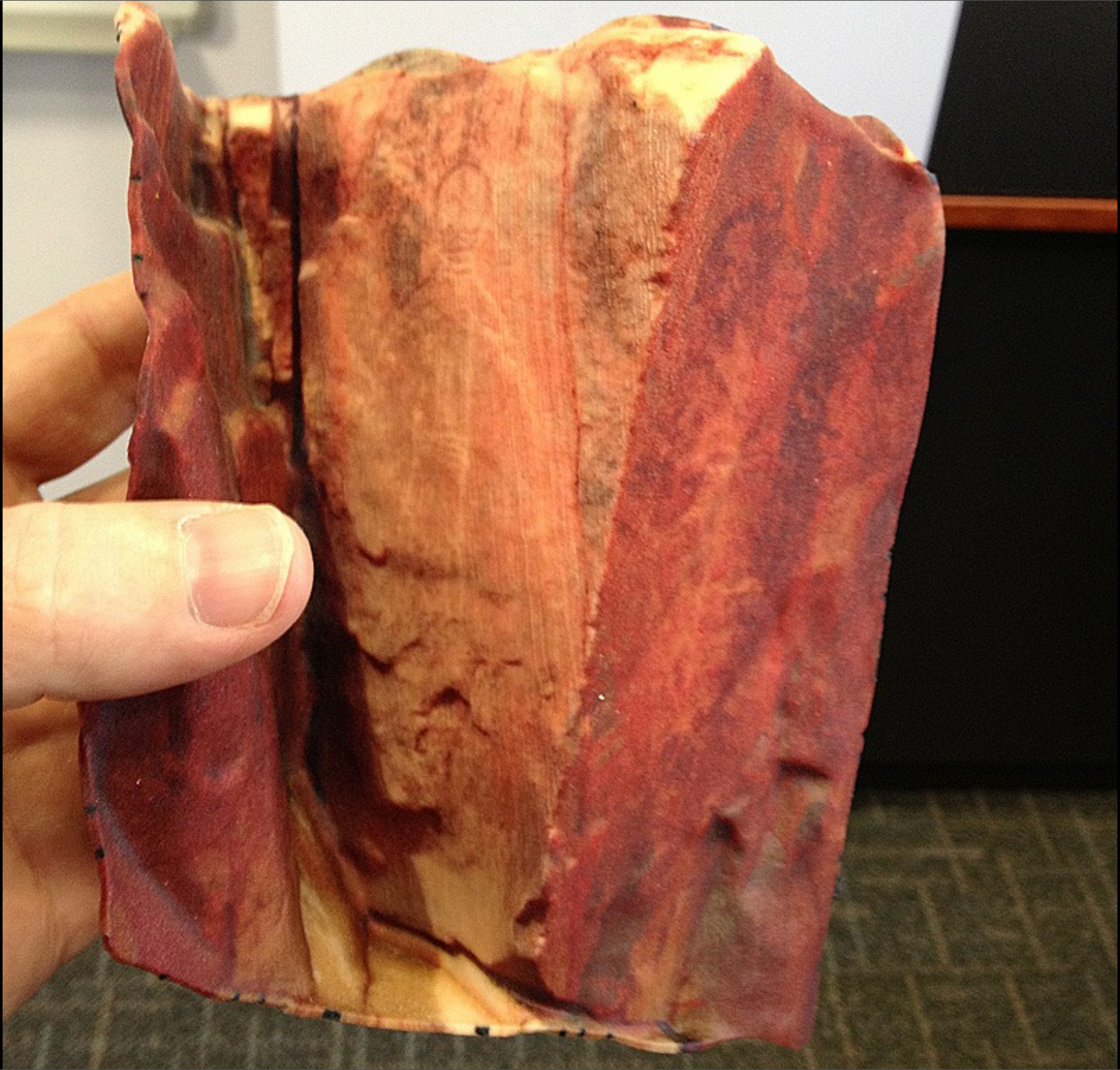


Infinitely thin surface
Unrealisable by a 3D printer



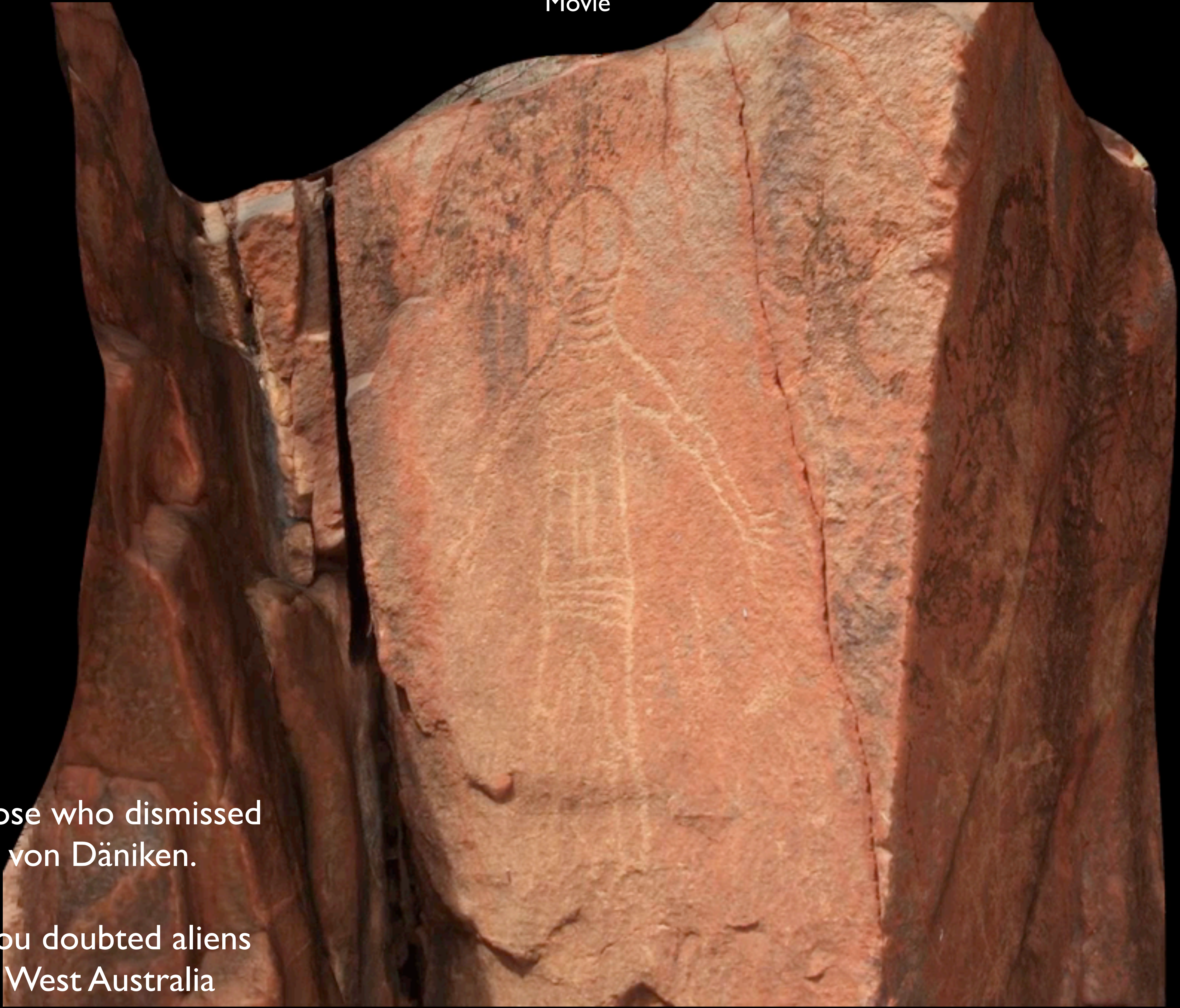
Thickened "realisable" surface


G07
Paul Bourke



Questions?

Movie



For all those who dismissed
Erich von Däniken.

In case you doubted aliens
visited West Australia