Differential growth

From a closed curve to a controllable architectural system



RESEARCH / COMPUTATIONAL SYSTEMS / SPATIAL DESIGN

COVE / architectural application

Rhino · Grasshopper · Kangaroo · embedded Python · vector documentation

A pattern becomes a design system

A digital investigation into continuous curves, local control and surface-constrained form.

How can a single closed curve develop complex form while remaining controllable?

The project translates a growth-inspired principle into an inspectable workflow. A fixed segment network relaxes on a prescribed host; local field assignments change spacing, target length and bending resistance. Comparative studies expose the behaviour before the system is applied to COVE, a rounded pavilion canopy.

PROJECT CONTEXT

Cameron Hendey
ARC3201, University of Toronto / 2024 origin
Developed digital studies and portfolio documentation / 2026

TECHNICAL WORK DEMONSTRATED

Computational modelling, spatial parameter design, geometry preparation, comparative testing, source-based analysis and technical visual communication.

READING THE DOCUMENT

01 Research & project intent 03-04

02 System & mechanics 05-09

03 Evolution & local control 10-17

04 Boundary & surface studies 18-20

05 Implementation & file states 21-22

06 COVE / architectural application 23-26

07 Findings, evaluation & sources 27-29

From fabrication ambition to controlled geometry

The original project asked how growth loops might inform continuous-line architectural systems.

2024 / ORIGINAL QUESTION

Can a continuous growth loop become a basis for three-dimensional assembly?

The initial research connected differential-growth patterns with parametric design and additive fabrication. Thallus by Zaha Hadid Architects was a direct formal precedent; the ICD/ITKE research pavilions framed the broader relationship between computation and material systems.

2026 / DEVELOPED INVESTIGATION

The finished studies focus that ambition into a digital method: prepare a reliable seed, expose local controls, compare outcomes across domains, and document how the solver produces the curve.

The delivered evidence concerns geometry and behaviour. Material savings, structural capacity, toolpaths and fabrication feasibility remain open questions.



ARCHIVE / ORIGINAL 3D EXPERIMENT

Student-generated geometry from the 2024 presentation. The Thallus-inspired test established the move from a planar loop to a prescribed 3D host.

Context: OriginalProjectWriteUp.pdf and OriginalProjectPresentation.pdf. The 2024 scope excluded material properties and full-scale testing.

From living growth to a design system

A shared principle: incompatible preferred dimensions can produce form through constraint.

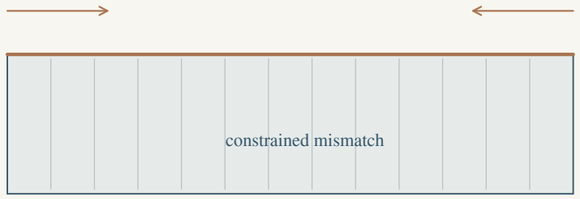
BIOLOGICAL PRINCIPLE / ILLUSTRATIVE STRIP, NOT A SPECIES MODEL

01 / Unequal growth



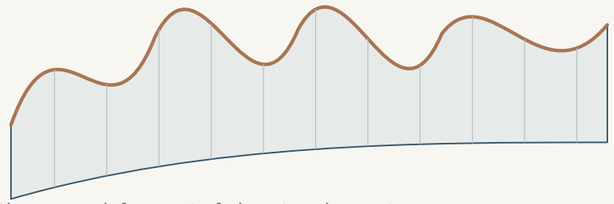
Different regions acquire different preferred lengths.

02 / Compatibility



Connected tissue cannot freely adopt every local length.

03 / Buckling



Thin tissue can deform out of plane to release stress.

Wavy leaf and petal margins are documented examples. Research links differential tissue growth to residual stress and 3D form [R1, R2].

TRANSLATING THE PRINCIPLE / WHAT IS SHARED, WHAT CHANGES

Physical concept	In living tissue	In this Grasshopper system
Preferred size	Local growth changes stress-free dimensions.	Length goals prescribe segment target lengths.
Connected material	Adjacent tissue regions must remain compatible.	A connected chain couples neighbouring segments.
Resistance to bending	Tissue thickness and stiffness resist curvature.	Angle goals bias turning; weights are design controls.
Where form can move	A leaf or petal may buckle out of its initial plane.	Points remain on a prescribed host mesh.
Spatial variation	Growth strain can vary across a tissue [R1].	Density assigns radius, length and bend strength.

A mechanical analogy, made controllable.

The project abstracts incompatible length, bending and contact into a design system. It is not a calibrated model of tissue, cell division or biological growth rate. Its 3D tests conform a curve to a host; they do not predict the host’s morphogenesis.

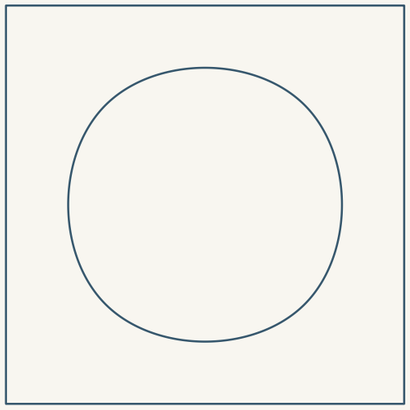
[R1] Huang et al., PNAS (2018), doi:10.1073/pnas.1811296115. [R2] Sharon et al., Nature (2002), doi:10.1038/419579a.

Conceptual diagrams and analogy retained from the completed study. Research references R1-R2 are listed on page 29.

A controllable growth system

Host geometry defines the domain. Local assignments steer the goals. Relaxation develops the curve.

01 / INITIALISE



HOST OUTLINE + EXPORTED SEED

Prepare one closed curve

Host boundary → scaled seed
Rebuild curve → pull back to host
Divide → shift points → line segments

Separate host branch

Mesh Brep supplies the constraint mesh
and the full-form field bounds.

INITIALISATION CONTRACT

One valid, nonsingular surface face.
One closed seed; fixed segment count.
Reset after geometry or control edits.

02 / ASSIGN + SOLVE

segments

SPATIAL FIELD / PYTHON

Uniform · gradient · point · curve

Evaluate the field at initial segment midpoints;
smooth cyclically and convert values into goal settings.

Initial assignments

Radius r_i / rest length ℓ_i / bend strength k_i

A Length(Line)
Expand toward rest length

B Collider
Resist local overlap

C Angle
Resist tight bending

D OnMesh
Keep particles on host mesh

BOUNCYSOLVER
Four goals evaluated together

Internal iteration updates particle positions + momentum
Assignments stay attached to their original segments.

03 / READ THE RESULT



SUPPLIED DEVELOPED GROWTH

Construct the final curve

Solver vertices feed a closed NURBS.
The display curve is downstream
of the particle-based constraints.

Pause → check → save

Sampled curvature + mesh deviation
Geometry, settings and run metadata

PARALLEL PREVIEW BRANCH

Same field function, sampled on the
full host mesh before segment smoothing.
Preview does not feed the solver.

READING THE SYSTEM Solid: geometry / goal data Dashed: host / preview branches Loop: solver iteration

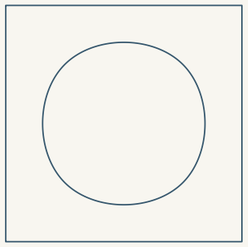
Source-derived workflow. Geometry panels are supplied exports; this document does not claim a new solver run.

From host surface to controlled growth

Prepare geometry, assign behaviour, relax the network, then inspect and capture the result.

01 / PREPARE THE GEOMETRY

Define where growth can occur.



The host supplies

a seed boundary,
a constraint mesh,
and field bounds.

SOURCE EXPORT / HOST + INITIAL SEED

SEED PATH

Build → rebuild → pull to host

Generate a host-derived closed seed; rebuild it, then pull the rebuilt curve back onto the face.

SEGMENT PATH (G)

Divide → shift → connect

Form a closed, fixed segment network.
The saved definition starts with 1,500 segments.

PARALLEL HOST PATH / MESH BREP (H)

Host mesh → OnMesh goal + field domain.
The physics mesh is separate from preview refinement.

02 / ASSIGN LOCAL BEHAVIOUR

Translate design intent into settings.

DESIGN CONTROLS (H)

Uniform · gradient · point · curve

Blend and contrast set the field effect.
Axis / bias set the gradient; reach and background shape point and guide-curve influence.

DENSITY FIELD / EMBEDDED PYTHON (P)

Sample the initial segments

Evaluate the field at segment midpoints.
Smooth around the closed network, then map each value to a local control multiplier.

THREE PER-SEGMENT SETTINGS

Rest length	Expansion target
Collision radius	Local separation
Bending strength	Resistance to folding

ASSIGNMENT LIFETIME

Values stay attached to their initial segments.
Moving particles do not resample the spatial field.

03 / RELAX THE NETWORK

Let competing goals develop the form.

KANGAROO / FOUR PARALLEL GOALS (G)

A **Length(Line)**
Seek assigned rest lengths.

B **Collider**
Separate nearby segments.

C **Angle**
Resist adjacent-line bending.

D **OnMesh** (H)
Constrain particles to the host mesh.

All goals act on the same particle system.

BOUNCYSOLVER
Update positions + momentum

Repeat internally while running

04 / INSPECT AND CAPTURE

Read the result and preserve evidence.



Developed growth

Actual supplied vector geometry.
Not a new run.

SOURCE EXPORT / DEVELOPED STATE

SOLVER VERTICES → NURBS CURVE

Construct the smooth output

The closed display curve is reconstructed from solver vertices after particle-based constraints.

PAUSE RUN → CHECK

Assess the resulting curve

Validity, closure, length and sampled diagnostics.

SAVE RUN / OPTIONAL

Keep geometry + evidence

geometry.3dm / run.json / curve_samples.csv
Archive the matching Grasshopper file separately.

READ THE BRANCHES

H + G / SHARED GEOMETRY

A single geometric reference

H: host mesh → OnMesh goal and field domain.
G: initial segments / adjacent pairs → goal geometry; segment endpoints → OnMesh particle positions.

P / FULL-FORM FIELD PREVIEW

Same field function, different sampling

Evaluate the raw field on a refined copy of the host mesh.
This happens before cyclic segment smoothing.
The preview is a reference; it never drives the solver.

E / INTERPRETING THE EVIDENCE

What the workflow establishes

The definition verifies connections, scripts and saved controls.
Checks estimate curvature and mesh deviation from 1,000 intervals.
Coverage and overlap tests are not implemented.

HOW TO READ — Follow 01–04 left to right; read each phase downward. Arrows carry data. The only feedback loop is inside the solver.

Follow the four phases left to right. Arrows carry data; the feedback loop is internal to the solver.

Inside the workflow

What is prepared once, what is repeatedly solved, and what is checked after pausing.

A / PREPARE THE NETWORK

01 / HOST VALIDATION

One supported surface face

Open patch or one supported seam direction.
Unsupported host types return a seed error.

↓

02 / HOST-DERIVED SEED

Boundary or surface-coordinate perimeter

Open patch: scale boundary around host centre.
Seamed face: construct a rounded inset perimeter.

↓

03 / REBUILD + REMAP

Rebuild first; pull back to the face

Join pulled pieces; require one valid closed curve.
The old Map to Surface path is bypassed.

↓

04 / DISCRETISE

Divide curve → shift list → connect

Fixed lines + endpoints + adjacent line pairs.
No adaptive vertex insertion in the active chain.

B / TRANSLATE THE FIELD

01 / FIELD FUNCTION

Combine attractor + axis contributions

Point / guide distances use smooth falloff.
The weighted field is clamped to [–1, 1].

↓

02 / INITIAL SAMPLING

Midpoints → cyclic smoothing

Sample main and paired line lists separately.
Neighbour weights per pass: ¼, ½, ¼.

↓

03 / CONTROL MAPPING

Field → multiplier → goal settings

Contrast raised to (blend × smoothed field).
Blend = 0 restores the scalar baseline.

↓

04 / GOAL ASSIGNMENT

Radius · rest length · bend strength

Each mapping uses its own exponent and clamp.
Attractors set parameters, not attractive forces.

C / RUN, CHECK + RECORD

01 / INITIALISE OR RESET

Start the prepared particle system

Load geometry and assigned goal settings.
Reset after changing geometry or controls.

↓

02 / RUN

Relax all four goals together

Excess target length folds as constraints compete.
30 iterations/update; momentum 0.60 (saved).

↓

03 / PAUSE + CHECK

Inspect the reconstructed NURBS

Run must be false for CHECK or SAVE.
Checks read the curve; they never modify it.

↓

04 / SAVE SNAPSHOT

Record geometry, settings and metrics

3DM: final curve, host, mesh, seed, influences.
JSON: settings / metrics. CSV: curve samples.

Why preparation matters

Pulling after rebuilding restores surface placement.
Constraints act on a discretised network; the final smooth curve needs its own downstream checks.

Why the preview can differ

Preview samples mesh vertices before smoothing.
Solver assignments move with the original segments.
A world-space field is not continuously re-applied.

What a saved run can support

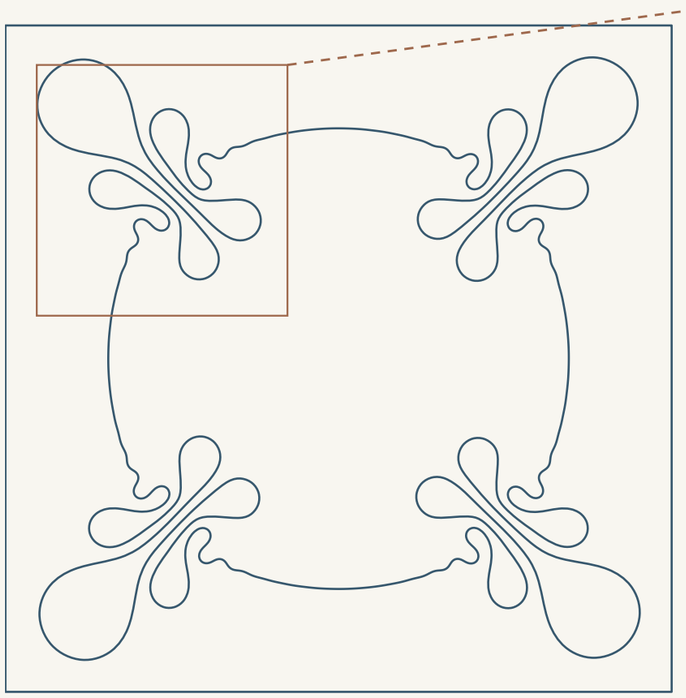
Closure and length; sampled bend radius / deviation.
No automated coverage or overlap certification.
Saved sliders are not verified for every supplied export.

Saved controls describe a file snapshot. The current and archived snapshots are distinguished on page 22.

Anatomy of controlled growth

A fixed network balances expansion, local separation, bending resistance and a shared host constraint.

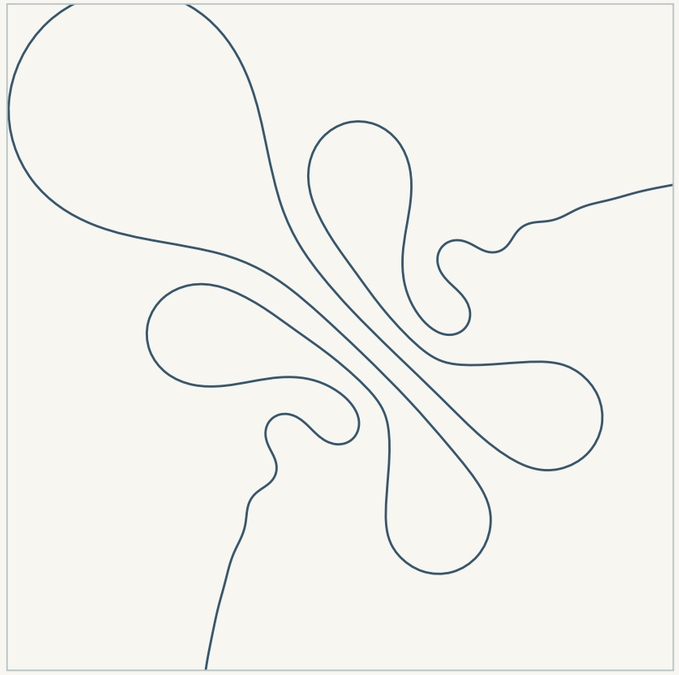
01 / GEOMETRY AS EVIDENCE



EXPORTED EMERGENT FOLDING

Actual source curves, retained in full.
This drawing is an output state,
not a plot of solver particles or forces.

02 / LOCAL STRUCTURE



Enlarged window into the same vector paths.
More available length can form folds as goals compete.
Collision and bending goals influence spacing and curvature.

03 / FOUR COUPLED GOALS

A Expansion

Length goals seek prescribed rest lengths.
Net expansion requires target total length
to exceed the initial total length.

B Separation

Collider acts on the segment network.
The assigned radius controls local clearance
but does not certify an intersection-free result.

C Bending

Angle goals resist changes in direction.
Lower assigned stiffness permits tighter folds;
it is not an exact loop-diameter target.

D Conformity

OnMesh constrains particles to the host mesh.
The final smooth curve is constructed afterward;
its mesh deviation is checked separately.

04 / DENSITY BECOMES THREE LOCAL SETTINGS

$$d_i = C^{\beta\, \bar{f}_i}$$

C: contrast · β: blend
$\bar{f}_i$: smoothed initial field value
β = 0 gives the scalar baseline.

Spacing

$$r_i = r_0\ \mathrm{clamp}(d_i^{-s},\ 0.3,\ 3)$$

Dense assignments reduce radius.

s: spacing contrast

Expansion

$$\ell_i = \ell_0\ \mathrm{clamp}(d_i^{g},\ 0.65,\ 1.5)$$

Packing boost adjusts rest length.

g: local packing / expansion

Bending

$$k_i = k_0\ \mathrm{clamp}(j_i^{-2q},\ 0.12,\ 6)$$

$j_i = \sqrt{(d_i\, d'_i)}$, using paired lines.

q: loop-size contrast; d'_i: paired assignment

Implementation-derived equations. Geometry illustrates the result; no measured force or clearance field is implied.

The mechanics of a fold

Excess target length is accommodated through competing geometric requirements.

OBSERVED GEOMETRY / STATE 04



One curve. Four competing requirements.

The form emerges from coupled constraints.
No single goal specifies the final pattern.
This crop retains the original exported Béziers.

EXPLANATORY SCHEMATICS / NOT MEASURED FORCE VECTORS

01 / Extension

LENGTH(LINE)

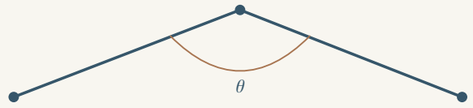


$e\ell = \ell - \ell^*$

If $\ell < \ell^*$, the goal favours extension. Other goals may prevent the target from being reached.

02 / Bending

ANGLE

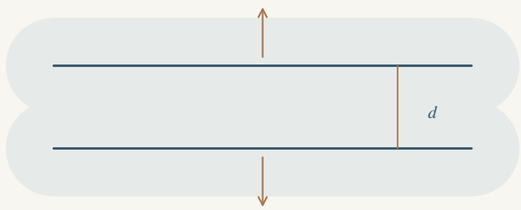


$e\theta = \theta - \theta^*$

The angle goal resists departures from its target. Lower weight permits tighter turns under competing goals.

03 / Exclusion

COLLIDER

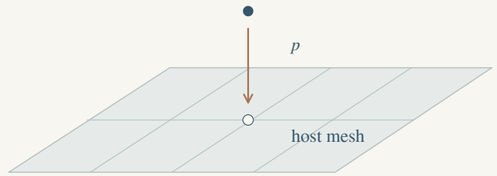


$\delta = max(0,\ r_i + r_j - d_{ij})$

Thickened segments resist overlap. Radii set an exclusion scale; strength controls the influence of the goal.

04 / Confinement

ONMESH



$e_m = dist(p,\ M)$

Points are pulled to the host mesh. The host is prescribed: this system does not grow the surface itself.

Symbols describe geometric residuals, not the exact solver update.
Kangaroo balances weighted goals with momentum and damping.
Recorded states are numerical relaxation states, not biological time.

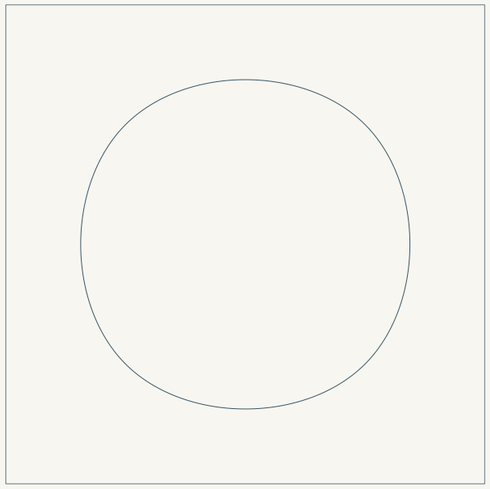
WHY FOLDS EMERGE

Extension competes with confinement, bending resistance and contact; deformation accommodates the mismatch.

The equations are geometric residuals, not the internal Kangaroo update. Numerical states are not biological time.

Evolution of growth

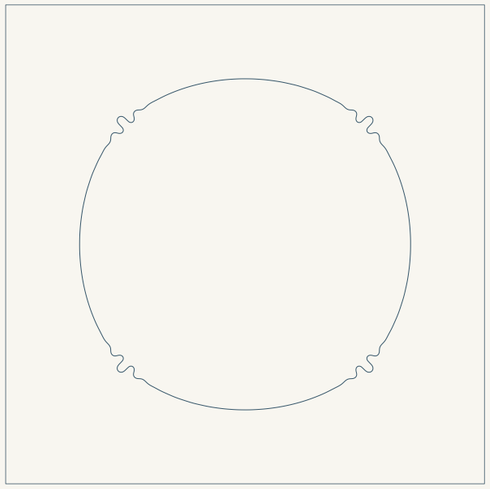
Seven recorded states reveal the transition from a simple closed curve to a folded pattern.



00 / Initial seed

A smooth closed curve establishes the initial condition.

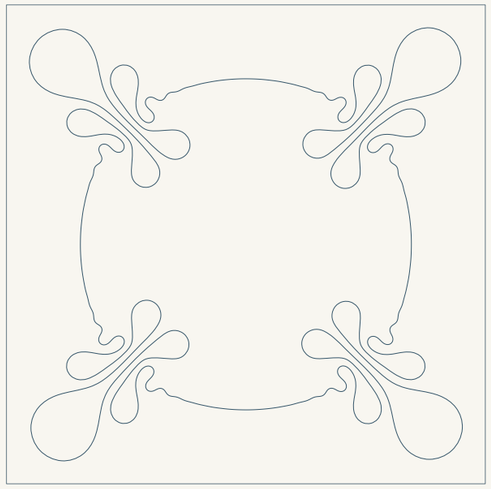
L / L₀ 1.00



01 / First folds

Small deformations appear in four regions of the seed.

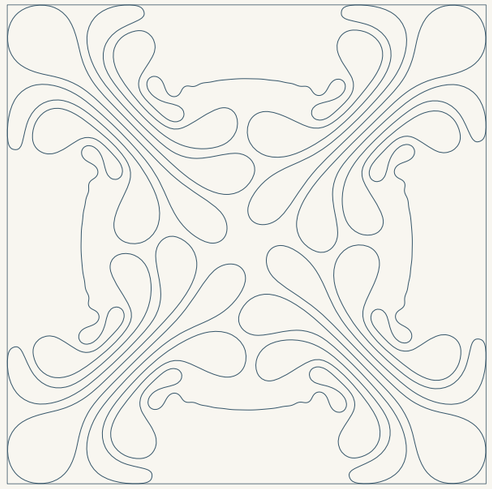
L / L₀ 1.11



02 / Emergent folding

Distinct lobes extend towards the corners of the domain.

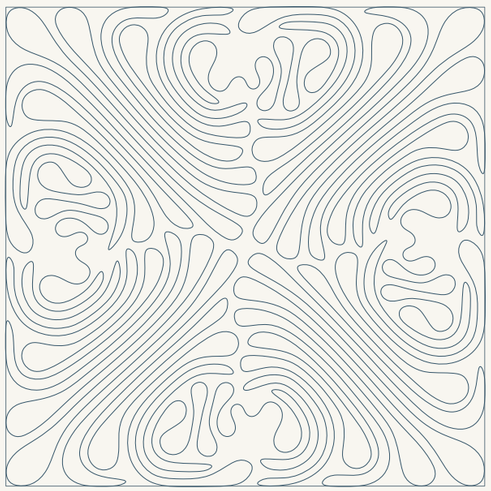
L / L₀ 4.37



03 / Expanding folds

Larger folds spread across the available square.

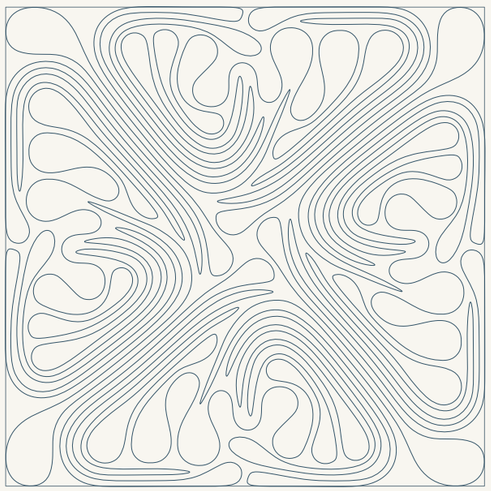
L / L₀ 11.15



04 / Progressive growth

Successive folds form a denser, folded spatial pattern.

L / L₀ 21.69



05 / Domain occupation

The curve occupies the domain with pronounced local bands.

L / L₀ 24.39



06 / Continued relaxation

The longer-run state redistributes the pattern across the square.

L / L₀ 19.77

Reading the sequence

Growth first produces folds; later states show continued geometric rearrangement. The last export has a shorter curve than state 05 despite its longer recorded run.

ONE DOMAIN, SEVEN STATES

All square boundaries are identical. Every state uses the same drawing scale and preserves its exported curve.

L / L₀

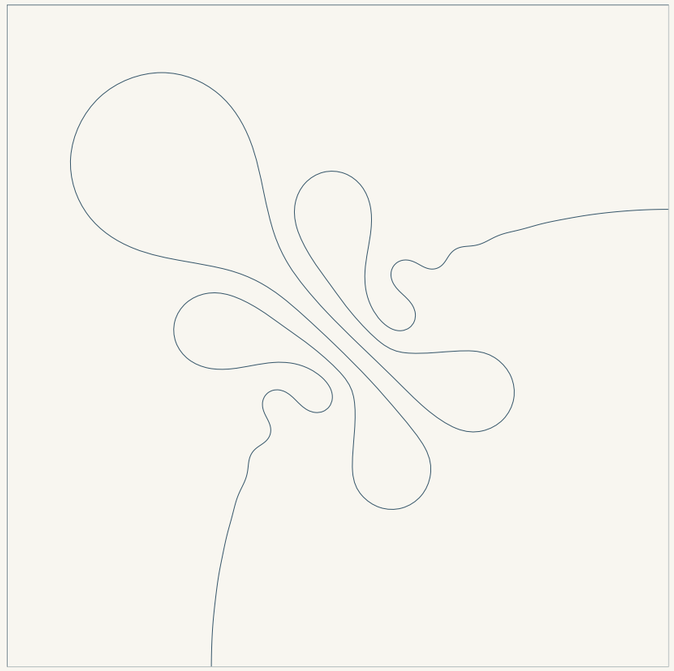
Exported curve length relative to the seed. A geometric measure, not elapsed time, solver energy or percentage coverage.

Recorded states are not equal time intervals. Length ratios are measured from the supplied cubic Bezier exports.

How the curve finds its form

Matched details connect observed fold emergence, accumulation and redistribution to the solver goals.

02 / Fold emergence



One lobe develops into a corner-facing fold.

04 / Fold accumulation



Neighbouring folds pack into curved bands.

06 / Pattern redistribution



The later state rearranges the local pattern.



Matched upper-left quadrants. Original curves are clipped and enlarged without reconstruction.

THE COMPUTATIONAL MECHANISM

Prepare the seed

Host-derived curve → rebuild → pull to surface. Divide Curve + Shift List + Line establish the segment chain before relaxation.

Density assignments

Initial segment samples set local radius, target length and bending strength. Assignments travel with the segments.

Length(Line)

Target lengths drive segment expansion.

Collider

Thickened segments resist local overlap.

Angle

Bending goals influence the shape of folds.

OnMesh

Particles are constrained to the host mesh.

Relax and reconstruct

BouncySolver balances the connected goals with momentum across repeated iterations. A periodic NURBS curve forms the output.

Iteration changes the geometry

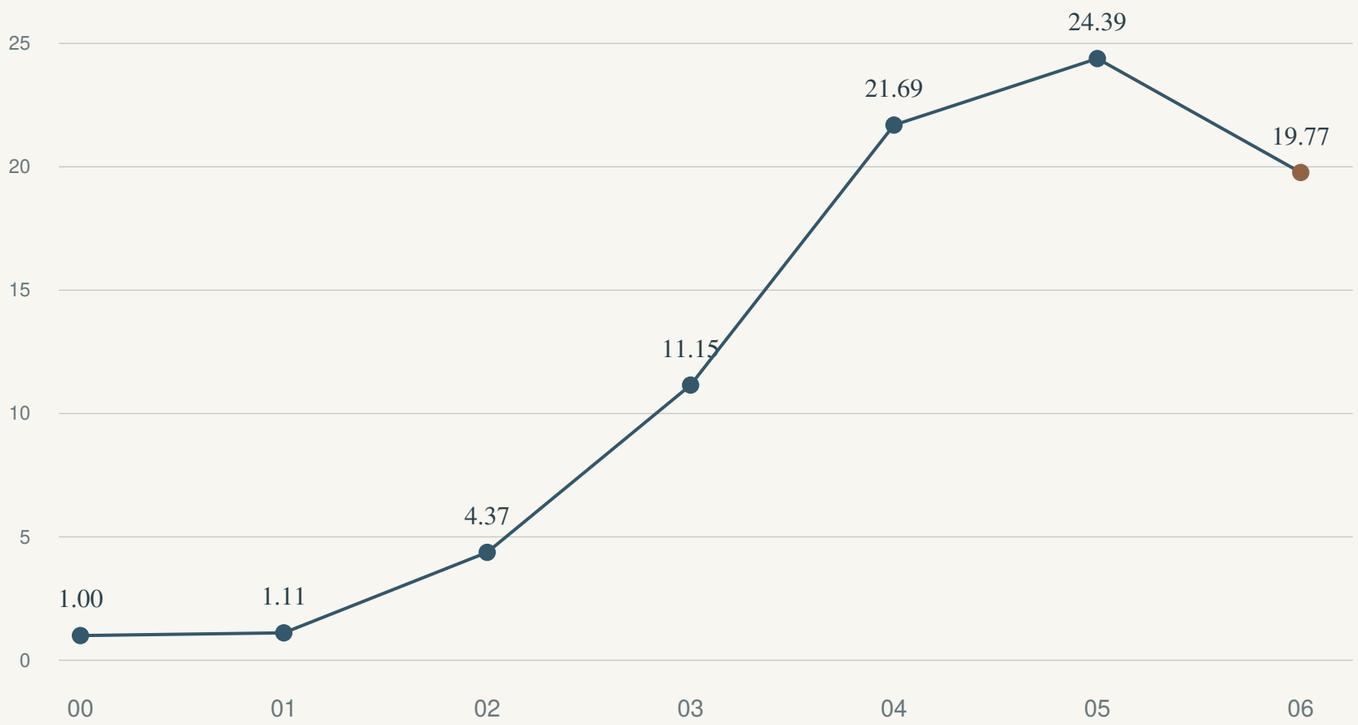
The supplied chain pre-divides the seed. It does not add new vertices each iteration.

Source curves are clipped and enlarged without reconstruction. The diagrams do not isolate the contribution of individual goals.

Later does not necessarily mean longer

An export-based reading of the seven states adds a quantitative check to the visual sequence.

EXPORTED CURVE LENGTH / SEED LENGTH



RECORDED STATE / EQUAL SPACING DOES NOT REPRESENT TIME

18.94%

shorter in state 06 than state 05

The later export records geometric rearrangement. Continued solver updates do not guarantee monotonically increasing curve length.

WHAT THE MEASURE ESTABLISHES

Length is computed from the exported curves. It does not establish elapsed time, domain coverage, convergence or a more uniform final density.

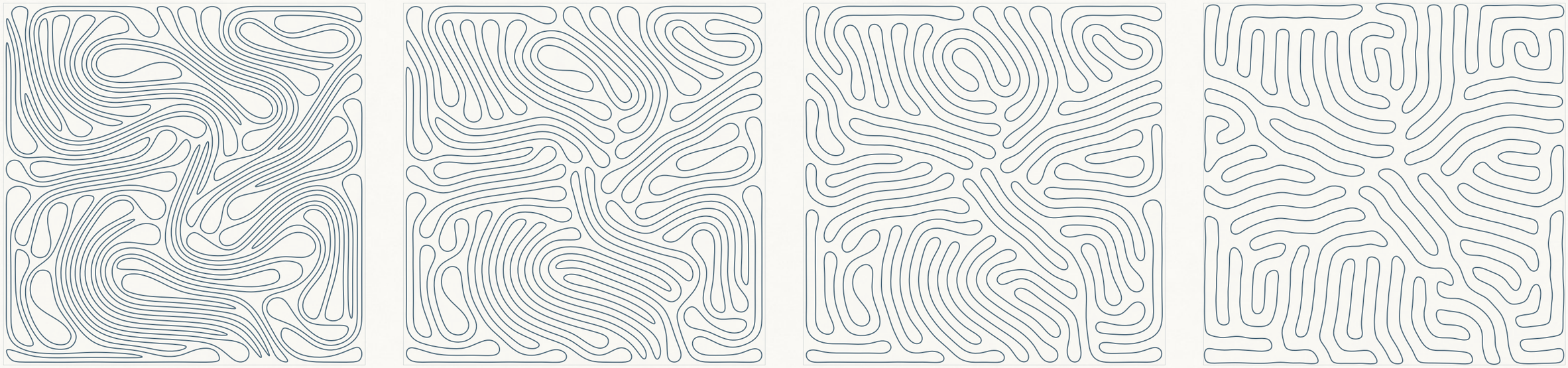
FULL MEASUREMENT RECORD / EXPORT-COORDINATE UNITS

STATE 00	STATE 01	STATE 02	STATE 03	STATE 04	STATE 05	STATE 06
931.36	1,033.76	4,072.87	10,387.53	20,202.93	22,713.69	18,412.83
1,500 cubic segments	1,500 cubic segments	1,500 cubic segments	1,500 cubic segments	1,500 cubic segments	1,500 cubic segments	1,500 cubic segments

Method: 32-point quadrature of the supplied cubic Beziers. Identical exported square boundaries. Ratios are dimensionless.

One parameter, four spatial characters

Increasing collision radius changes the observed spacing and folding pattern across a shared square study.



01 / RADIUS 1.0

02 / RADIUS 1.5

03 / RADIUS 2.0

04 / RADIUS 3.0

01 / RADIUS 1.0

Tighter local packing

02 / RADIUS 1.5

More open separation

03 / RADIUS 2.0

Broader folded bands

04 / RADIUS 3.0

Wider exclusion scale

A useful design control

The radius sets the scale of the collision goal. These exports show the resulting morphological range; the input radius is not a measured clearance certificate for the final smooth curve.

All four finished vector studies retained. Radius order: 1.0, 1.5, 2.0, 3.0. No physical unit or collision-free guarantee is inferred.

Turning a field into behaviour

A bounded translation from spatial intent to three local mechanical parameters.

IMPLEMENTATION / EXACT PARAMETER MAPPING FROM THE EMBEDDED SCRIPT

Sample once. Assign. Relax.

The field is sampled at initial segment midpoints.
Cyclic smoothing reduces jumps around the closed chain.
Assignments travel with the segments during relaxation.

$$D_i = C^{b\,f_i}$$

$f_i \in [-1, 1]$ · C = contrast · b = blend

Attractor distance and an axis gradient define the input field.
An attractor modifies the assignments; it is not a force pulling
the evolving curve toward a point. Reset after changing inputs.

$$r_i / r_0 = clamp(D_i^{-s},\ 0.3,\ 3.0)$$

Spacing contrast s: smaller radii permit closer packing.

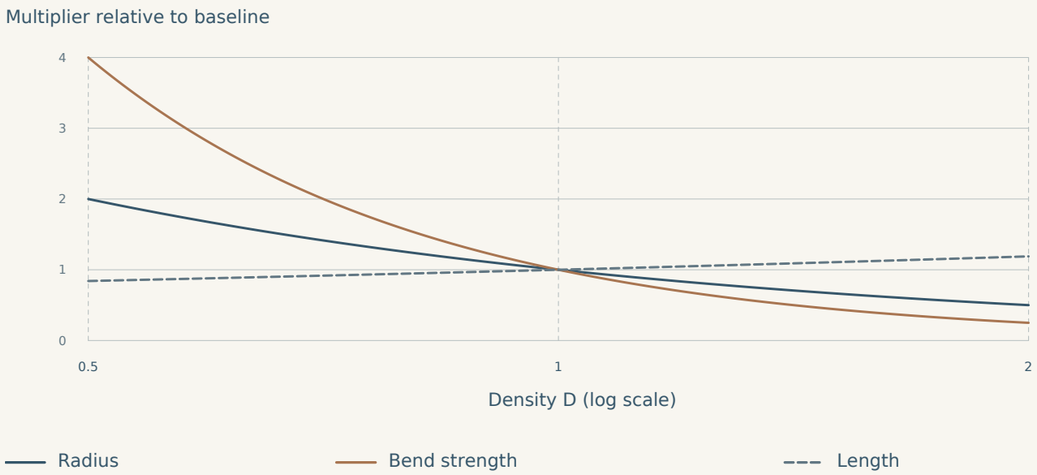
$$\ell_i^* / \ell_0 = clamp(D_i^{g},\ 0.65,\ 1.5)$$

Growth boost g: optional increase in target length.

$$B_j / B_0 = clamp(\hat{D}_j^{-2q},\ 0.12,\ 6.0)$$

Loop contrast q: lower strength allows tighter turning.
$\hat{D}_i = \sqrt{(D_i\ D_{paired})}$ uses both segments at the angle goal.

ANALYTICAL RESPONSE / ILLUSTRATIVE INPUTS, NOT MEASURED RUN SETTINGS



Density D	r / r0	ℓ* / ℓ0	B / B0
0.5	2.00	0.84	4.00
1.0	1.00	1.00	1.00
2.0	0.50	1.19	0.25

Example: s = 1, q = 1, g = 0.25; adjacent segments share D.
If g = 0, target length stays unchanged as density varies.

A control law is not an outcome guarantee.

Radius is not measured curve clearance; bending strength
is not a specified loop diameter. The response also depends
on target lengths, the host, discretization and solver state.

Export evidence: $L_{05} / L_0 = 24.39$; $L_{06} / L_0 = 19.77$.
The later curve is 18.94% shorter. More solver updates
cannot be read as monotonically increasing curve length.

VALIDATION TARGETS / smooth-curve clearance · host deviation · goal residuals · repeatability across resolution

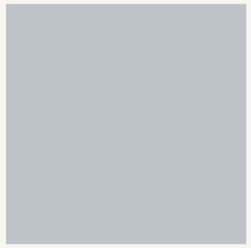
The analytical example is not a measured run. D1 denotes the archived definition; the current file contains the same four embedded scripts.

Spatial density gradients

A constant field and two directional variations within the same square domain.

01 / UNIFORM

Constant field



FIELD



GROWTH / BASELINE DISTRIBUTION

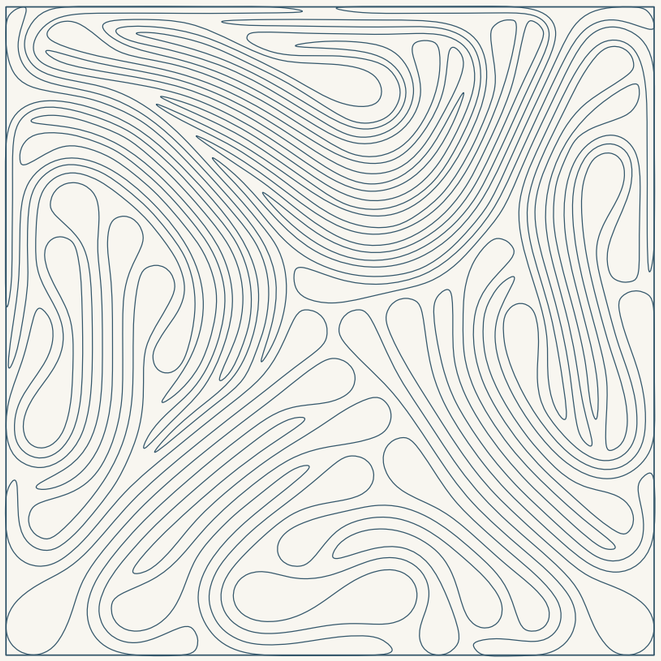
A single field value across the domain.

02 / LOW INTENSITY

Vertical gradient



FIELD



GROWTH / GRADUAL DIFFERENTIATION

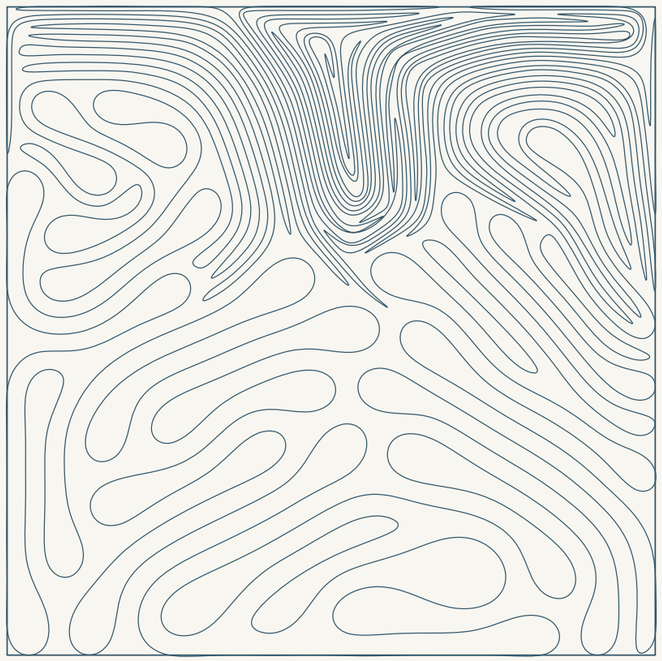
A restrained transition from top to bottom.

03 / HIGH INTENSITY

Vertical gradient



FIELD



GROWTH / STRONGER DIFFERENTIATION

A wider visible contrast across the field.

READING THE STUDY

Field previews retain their exported colours. Growth outputs share the same scale and lineweight.

Original field previews above; corresponding source curves below. Field colours are qualitative; no numeric scale is inferred.

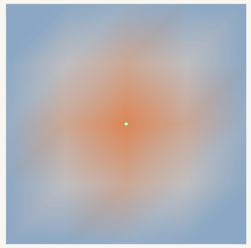
Original field previews retain their colours; corresponding growth curves remain vector geometry. Colours are qualitative, without a numeric scale.

Point attractor placement

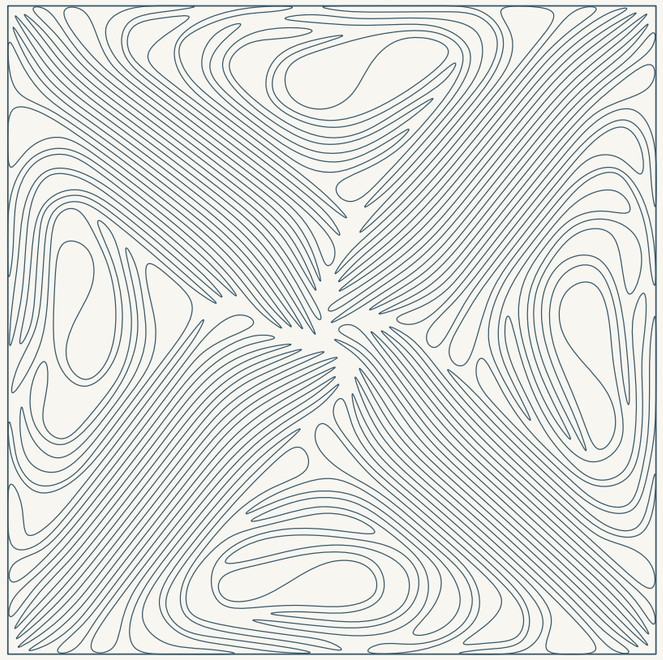
Centre, left-edge midpoint and upper-left corner fields redistribute local assignments.

01 / CENTRE

Interior point



FIELD



GROWTH / INTERIOR INFLUENCE

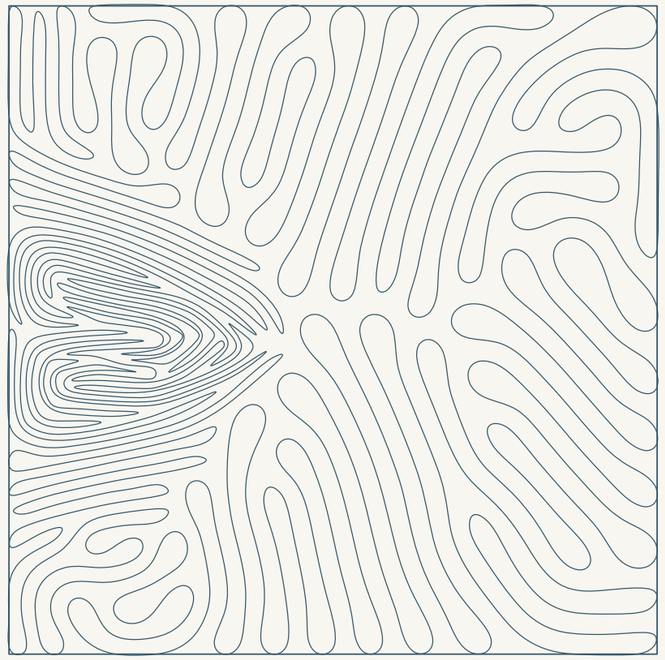
The field is concentrated within the square.

02 / LEFT EDGE

Boundary midpoint



FIELD



GROWTH / EDGE INFLUENCE

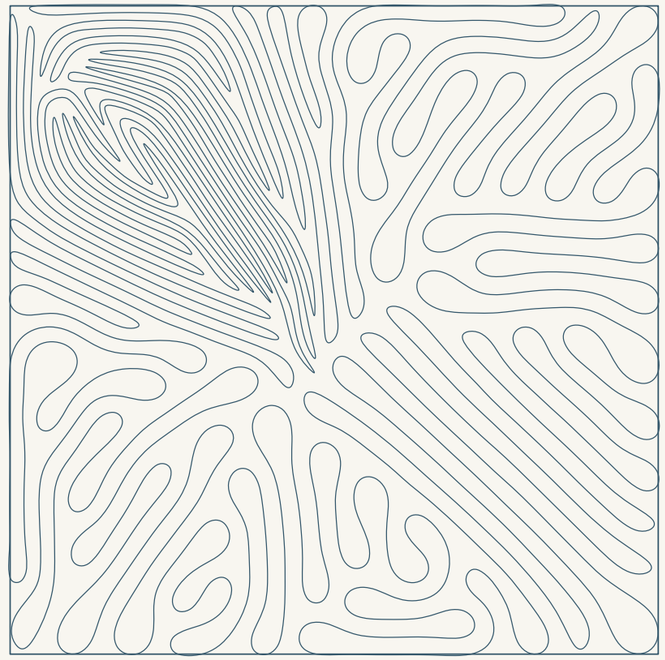
The field meets the centre of the left edge.

03 / UPPER-LEFT CORNER

Boundary corner



FIELD



GROWTH / CORNER INFLUENCE

The field is concentrated at a corner.

READING THE STUDY

Field previews retain their exported colours. Growth outputs share the same scale and lineweight.

Original field previews above; corresponding source curves below. Field colours are qualitative; no numeric scale is inferred.

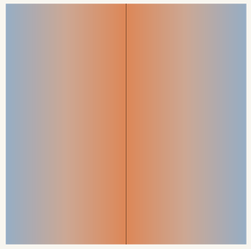
Original field previews retain their colours; corresponding growth curves remain vector geometry. Colours are qualitative, without a numeric scale.

Curve attractor paths

Vertical, diagonal and freeform guides organise the field along continuous paths.

01 / VERTICAL

Central straight guide



FIELD

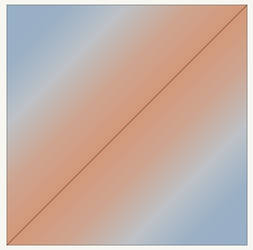


GROWTH / AXIAL FIELD

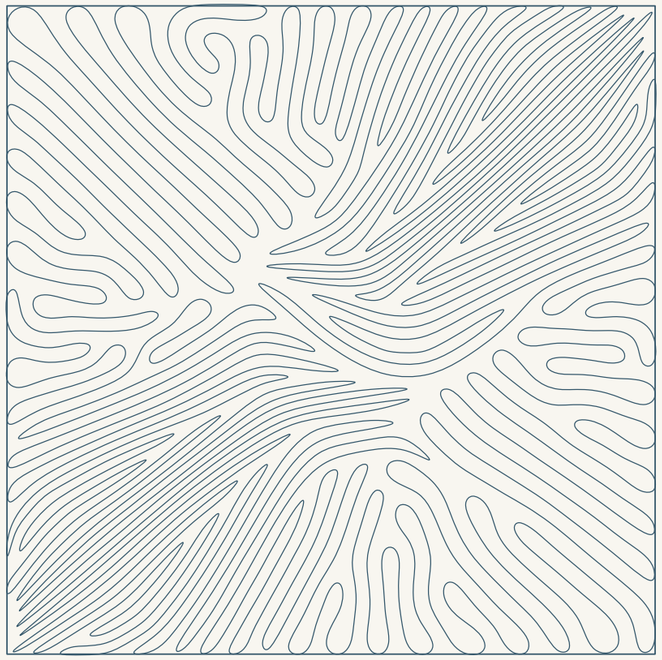
A vertical band passes through the centre.

02 / DIAGONAL

Corner-to-corner guide



FIELD

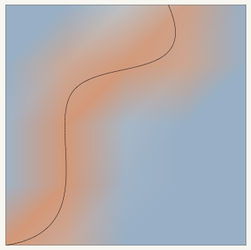


GROWTH / OBLIQUE FIELD

The band spans opposite corners.

03 / FREEFORM

Curved guide



FIELD



GROWTH / CURVED FIELD

The band follows the supplied curved path.

READING THE STUDY

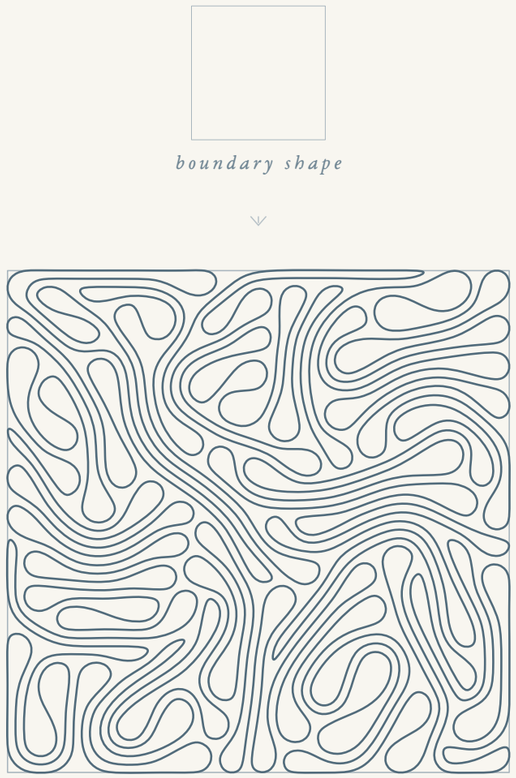
Field previews retain their exported colours. Growth outputs share the same scale and lineweight.

Original field previews above; corresponding source curves below. Field colours are qualitative; no numeric scale is inferred.

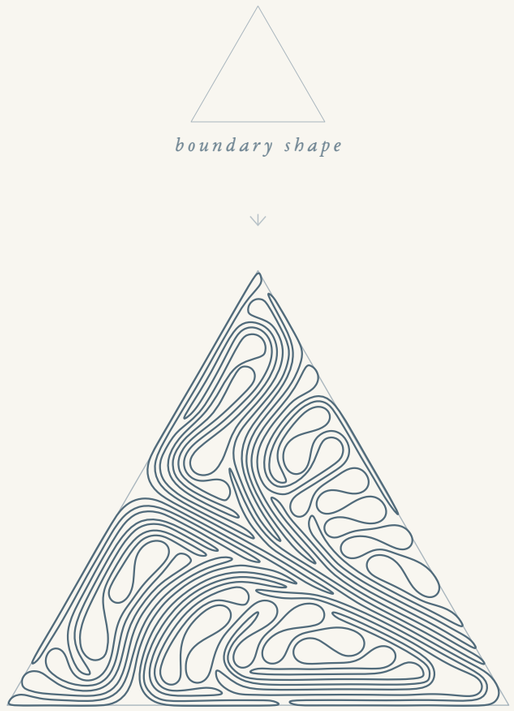
Original field previews retain their colours; corresponding growth curves remain vector geometry. Colours are qualitative, without a numeric scale.

Four boundaries, one growth approach

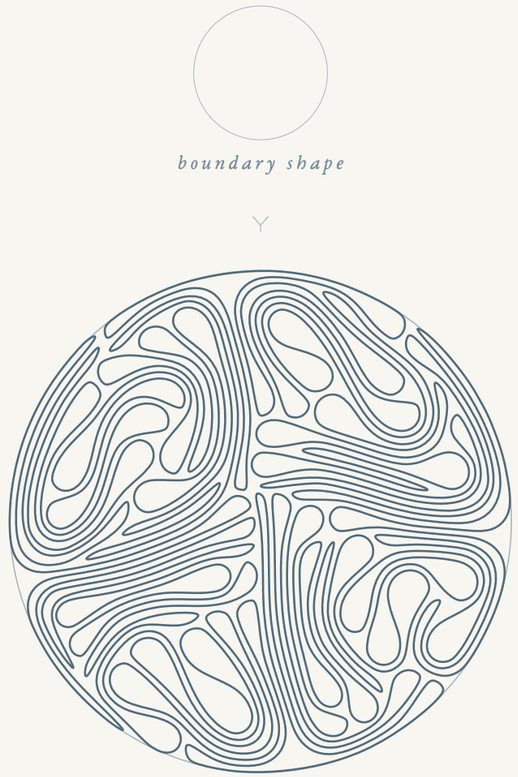
Square, triangle, circle and freeform studies compare adaptation to different planar domains.



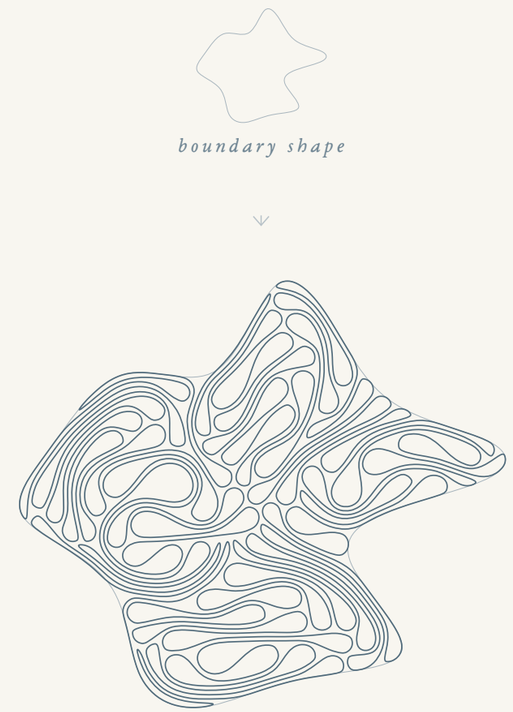
01 / SQUARE



02 / TRIANGLE



03 / CIRCLE



04 / FREEFORM

01 / DOMAIN

Prescribe the boundary

Each outline defines the spatial constraint for its corresponding developed curve.

02 / OBSERVATION

Read the adaptation

The finished studies show the curve responding to four distinct host outlines.

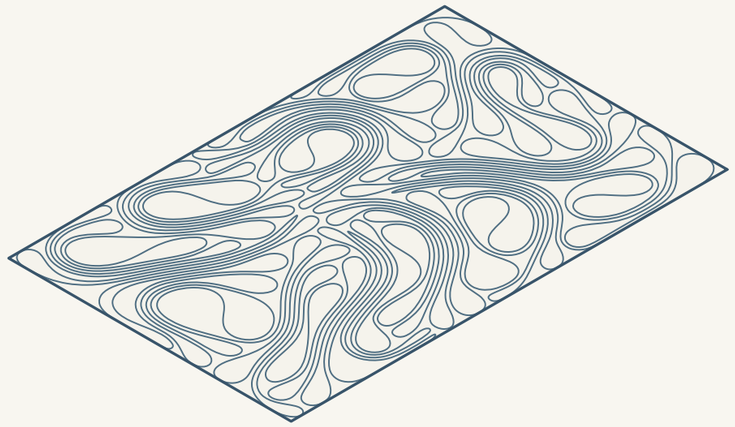
03 / SCOPE

Keep the claim specific

These examples demonstrate the tested domains; they do not prove every possible 2D shape.

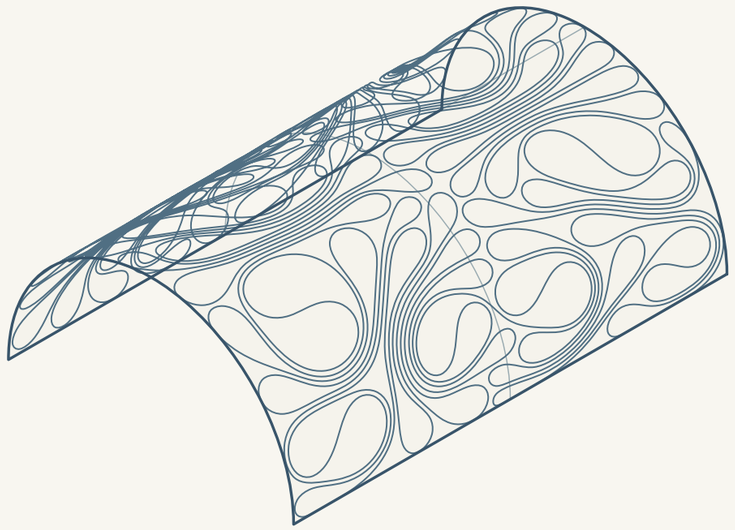
From planar growth to spatial form

One growth system is represented on flat, curved and twisted hosts.



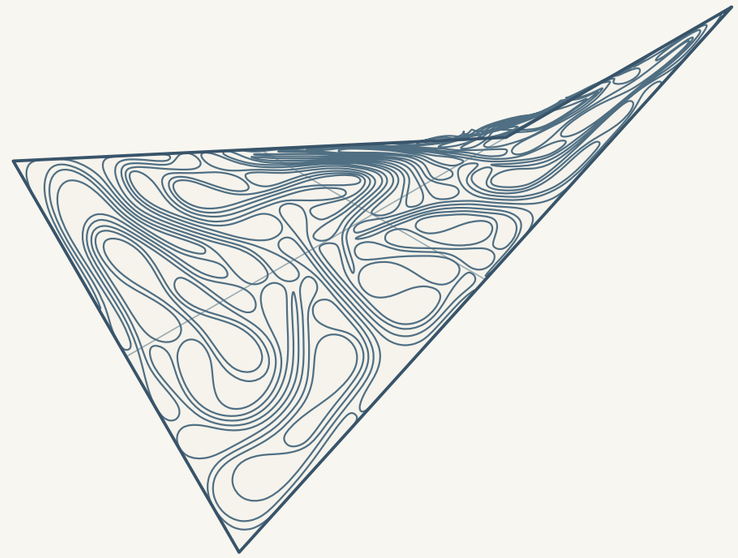
01 / FLAT

planar host



02 / CURVED

bent surface



03 / TWISTED

torsional surface

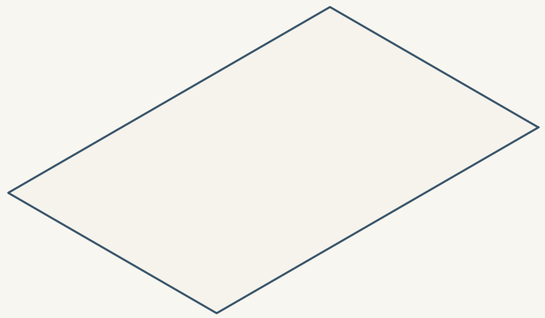
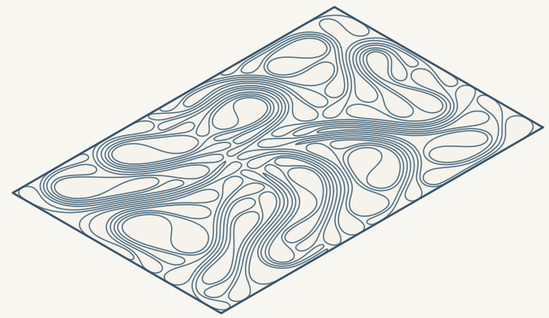
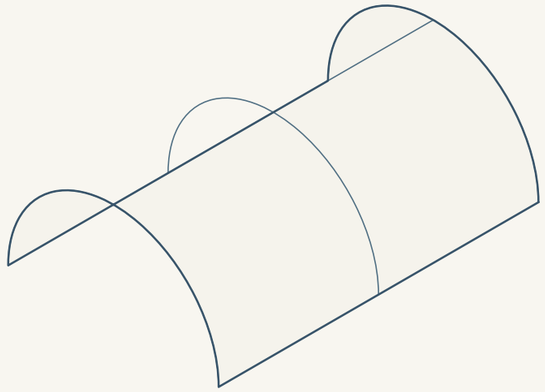
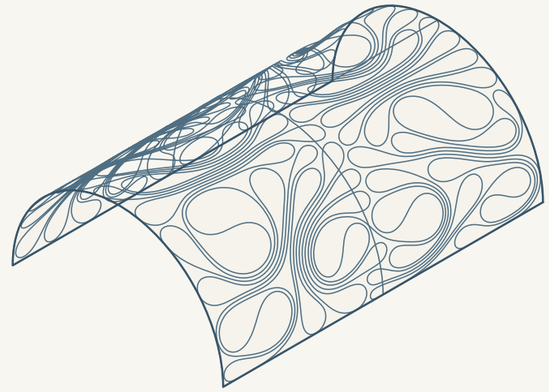
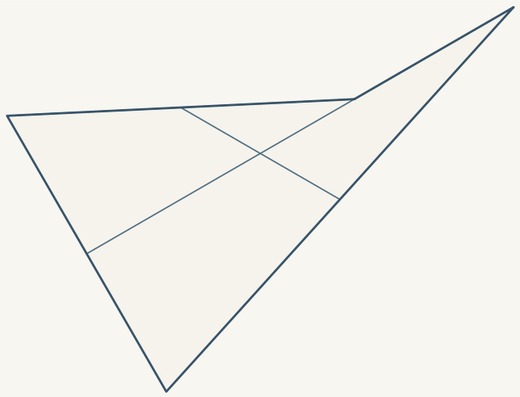
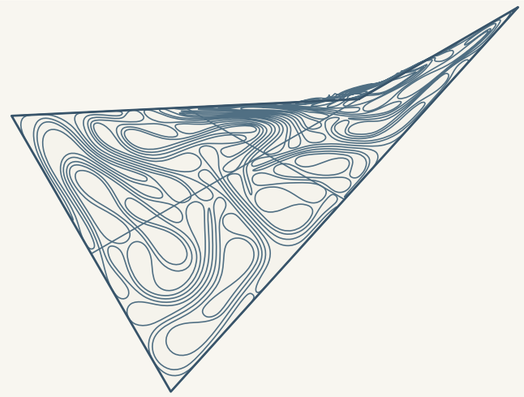
Change the host. Retain the system.

Planar, bending and torsional conditions show the curve adapting to prescribed three-dimensional geometry. The host supplies the spatial constraint; the solver does not generate the host surface itself.

Original Rhino vector exports retained. These are geometric demonstrations, without a reported curve-to-host tolerance.

Surface adaptation / anatomy

Original host geometry beside its corresponding growth projection.

	A / HOST GEOMETRY *projected host and original surface edges*	B / CONFORMED GROWTH *source path mapped to each three-dimensional condition*
01 / FLAT *planar host*		
02 / CURVED *bent surface*		
03 / TWISTED *torsional surface*		

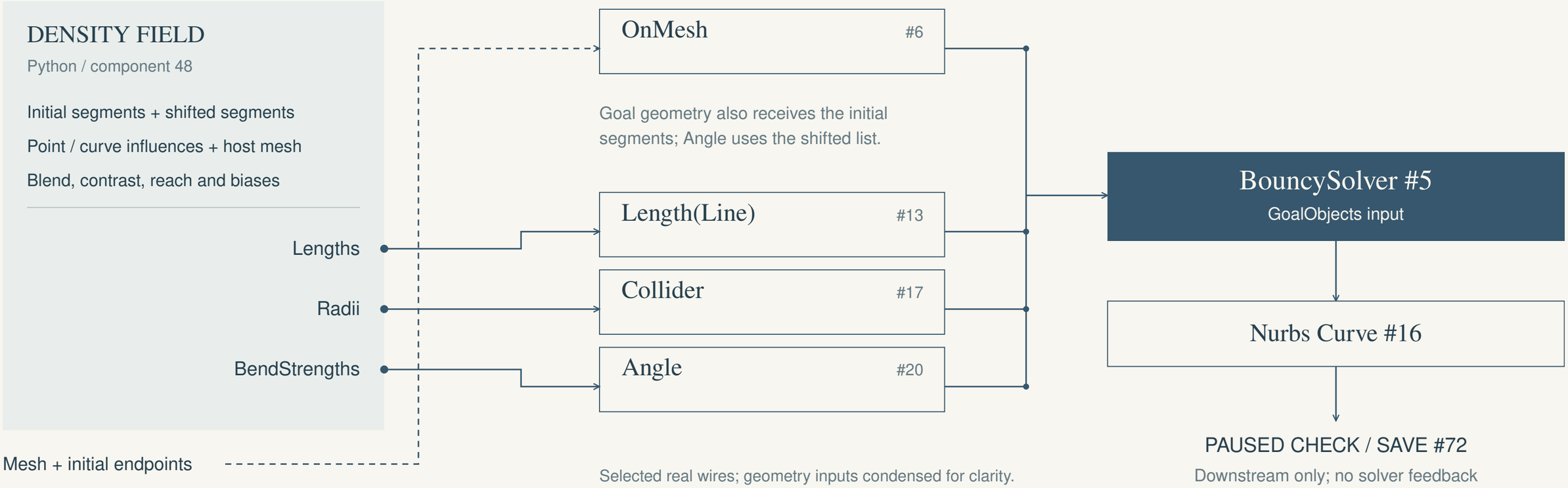
Source: Rhinoceros + Illustrator. Original curve control points are retained; the projected views are not newly simulated results.

From definition to evidence

Traceable components, explicit controls and a separate verification branch make the system inspectable.

01 / IMPLEMENTED DENSITY-TO-SOLVER CONNECTIONS

PORT NAMES FROM THE SAVED DEFINITION



Selected real wires; geometry inputs condensed for clarity.

02 / ARCHIVED CONTROL STATE

Seed segments / scale	1500 / 0.50
Rest length / collision radius	10.000 / 1.127
Density blend / contrast	0.00 / 2.00
Bend / expansion / collision strength	3000 / 10 / 200
Momentum / iterations per update	0.60 / 30

Saved values are not verified settings for every supplied export.

03 / ENGINEERING DECISIONS

Repair seed placement

Rebuild first, then PullToBrepFace before division.

Keep the growth network fixed

Density modifies goal settings; no adaptive insertion.

Separate diagnostics from simulation

Paused sampling + export never alter the solver state.

04 / EVIDENCE BOUNDARY

Verified from the definition: component connections, scripts, saved values and host reference.

Checks sample 1000 intervals. Coverage and overlaps are not tested.

Native Rhino execution was not run during this documentation audit.

This finished board records the archived study snapshot. Page 22 compares it with the current uploaded definition.

Same scripts. Different saved controls.

The current uploaded definition was inspected alongside the definition archived with the growth sequence.

CONTROL	ARCHIVED STUDY FILE [D1]	CURRENT UPLOADED FILE [D2]
Seed segments / seed scale	1500 / 0.50	**1500 / 0.50**
Rest length / collision radius	10.000 / 1.127	**10.000 / 1.000**
Density blend / contrast	0.00 / 2.00	**0.65 / 2.00**
Gradient bias / axis	0.00 / Z	**1.00 / Z**
Bend / expansion / collision strength	3000 / 10 / 200	**3000 / 10 / 200**
Momentum / iterations per update	0.60 / 30	**0.60 / 30**
Spacing / loop contrast	1.00 / 1.50	**1.00 / 1.50**
Local packing / smoothing passes	0.50 / 1	**0.50 / 1**
Attractor reach / bias / open background	0.21 / 1.00 / 0.50	**0.21 / 1.00 / 0.50**

VERIFIED IN THIS COMPILATION

All four embedded Python scripts are identical between D1 and D2: density field, paused checks/export, host-derived seed and rebuild-to-host remapping.

HOW TO INTERPRET THE FILE STATES

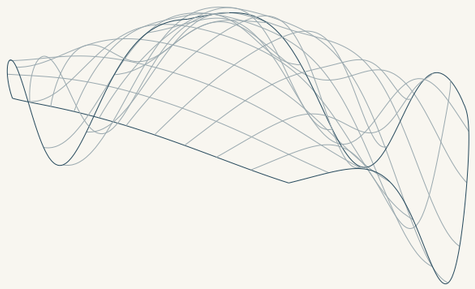
These values are saved file states, not reconstructed settings for every image. Study-specific captions retain their own provenance. Native Rhino/Kangaroo execution was not performed for this compilation.

D1 SHA-256: 1d0316fb822eaf62cec887da254b20bda3d67b2a80485d678e6bdc0dfe27b078

D2 SHA-256: 209cf06041652b9c7d65fd03783fac51d09a63c8ebc3be3fcce02d9955fa6c8b

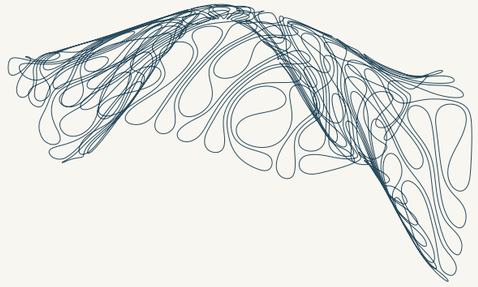
COVE / from surface to pavilion

A continuous growth curve follows the rounded canopy, then acquires volume.



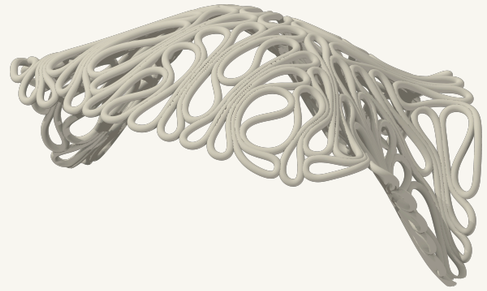
01 / HOST SURFACE

Rounded canopy / spatial constraint



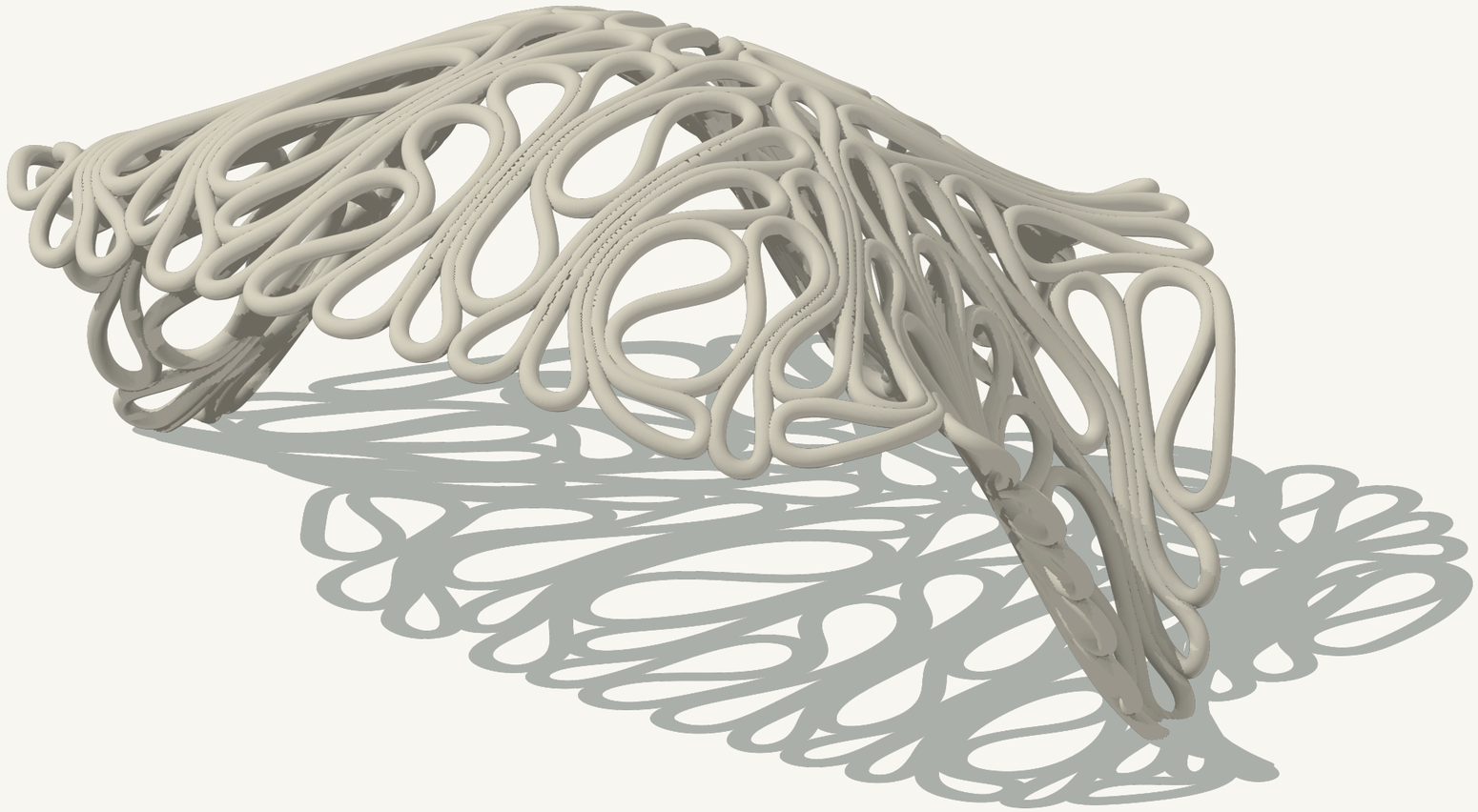
02 / GROWTH CURVE

Centreline recovered from the supplied sweep



03 / VOLUMETRIC FORM

Supplied tubular growth / original geometry



LIGHT, CURVATURE & CONTINUITY

Directional light reveals the growth geometry and its projected shadow on the supplied ground plane.

DIGITAL DESIGN STUDY

Supplied model-derived development plate. The ground-plane shadow makes curvature and continuity legible.

A canopy read through its shadow

The aerial view makes the continuous loops and open canopy silhouette legible.



Supplied conceptual architectural visualisation. Context, people and material appearance are illustrative.

Under the growth

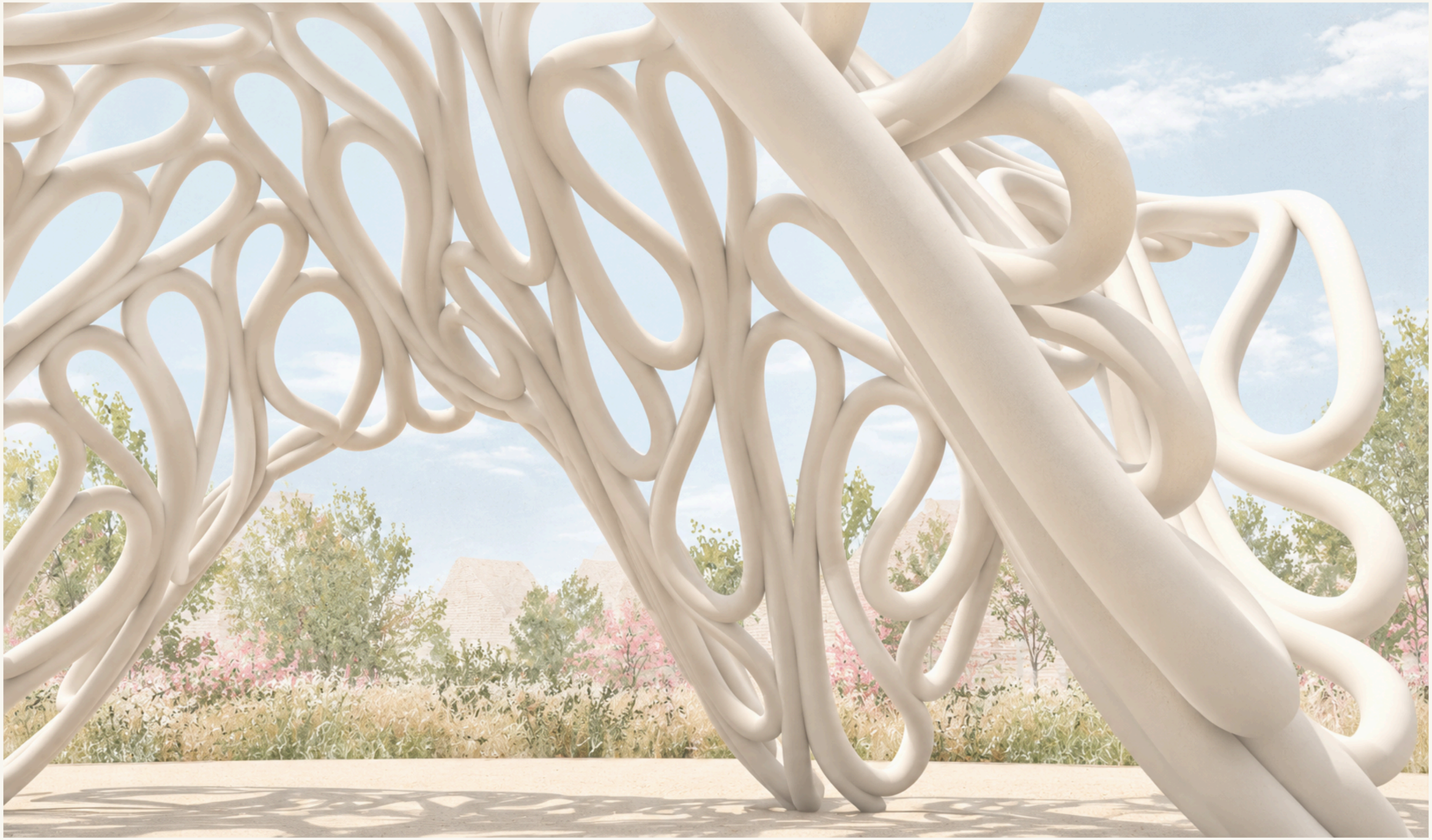
An interior viewpoint translates the geometric study into an inhabitable spatial proposition.



Supplied conceptual architectural visualisation. The image communicates atmosphere rather than verified construction detail.

Continuity, curvature and light

A close view connects the tubular interpretation to the underlying language of folds and loops.



Supplied conceptual architectural visualisation. Model geometry is documented on page 23; rendered joints are not fabrication specifications.

What the studies establish

The value of the project lies in the connection between controllable inputs, visible behaviour and traceable evidence.

07

Recorded growth states

One seed develops folds and later rearranges. Exported length rises to 24.39 times the seed at state 05, then falls to 19.77 times at state 06.

Evolution / pp. 10-12

04

Collision-radius cases

Radius values 1.0, 1.5, 2.0 and 3.0 show distinct spacing and folding characters across the square study.

Local control / p. 13

09

Spatial density cases

Uniform, two gradients, three point fields and three guide-curve fields expose global and local modes of control.

Density / pp. 15-17

04 + 03

Boundary and surface tests

Four planar outlines and three host-surface conditions show the method adapting to the supplied geometries.

Conformance / pp. 18-20

The transferable contribution

A workflow that separates geometry, controls, solver behaviour and verification, then communicates their relationships through measurable and visual evidence.

A precise boundary around the result

The completed work supports a digital design study. The next tests are defined by the remaining uncertainties.

ESTABLISHED	NOT YET ESTABLISHED	A TARGETED NEXT TEST
Implementation is inspectable.	A settled solver state or convergence.	Record goal residuals and maximum particle displacement across updates.
Collider is part of the goal system.	Guaranteed clearance of the smooth curve.	Test self-intersections and minimum non-adjacent curve distance with a stated tolerance.
Particles are constrained to a host mesh.	Exact smooth-curve conformity to CAD.	Measure maximum and RMS curve-to-host distance, including trimmed boundaries.
Fields assign local mechanical settings.	Measured final density matching the field.	Integrate curve length within equal spatial cells and compare the distribution with the intended field.
Seven source states share one boundary.	Resolution-independent outcomes.	Repeat identical settings at several division counts; compare geometry statistics and stability.
A pavilion application is visualised.	Structural or manufacturing feasibility.	Specify material, joints, supports and fabrication process, then test those requirements separately.

Existing paused checks sample 1,000 intervals for curve diagnostics. They do not implement coverage or overlap certification; the tests above are specified future work.

An evidence trail through the project

Finished sections are preserved in full substance; duplicate exports are consolidated into a single reading sequence.

RESEARCH REFERENCES

R1 Huang, C. et al. (2018). Differential growth and shape formation in plant organs. PNAS 115(49), 12359-12364.
https://doi.org/10.1073/pnas.1811296115

R2 Sharon, E. et al. (2002). Buckling cascades in free sheets. Nature 419, 579.
https://doi.org/10.1038/419579a

PROJECT SOURCES

D1 Growth-sequence archived definition, seven AI exports, Growth_Measurements.csv and Technical_Notes.md.

D2 Current Kangaroo_Refined_Mapped_Seed.gh; binary archive and embedded scripts inspected for this compilation.

D3 OriginalProjectPresentation.pdf and OriginalProjectWriteUp.pdf, Cameron Hendey, ARC3201 / 2024.

D4 Finished study PDFs, COVE development plate, pavilion model and four supplied contextual renders.

FINISHED-SECTION COVERAGE

Computational systems / 3 pages	05, 08, 21
Complete workflow / 2 pages	06-07
Growth package / all 5 boards	04, 09-11, 14
Collision-radius comparison	13
Density studies / all 9 cases	15-17
2D boundary comparison / all 4 shapes	18
3D comparison + surface anatomy	19-20
COVE form development	23
All four final renders	01, 24-26

PRODUCTION NOTES

Analytical drawings are embedded as original PDF vector artwork. Geometry is placed using uniform transforms; curve coordinates and control points are not redrawn. Field previews and architectural visualisations remain their supplied raster images.

Earlier STRIA draft metrics are not assigned to the finished studies. The original fabrication aim is retained as context, with the digital scope stated explicitly.

Compiled October 2026. Reproduction package includes the assembly script, used source plates, measurements, fonts and placement manifest.