Render the Possibilities
SIGGRAPH2016

Modeling Plant Life in Computer Graphics

Introduction

Siggraph 2016 Course

Sören Pirk, Bedrich Benes, Takashi Ijiri, Yangyan Li, Oliver Deussen, Baoquan Chen, Radomír Měch

Course Summary

An introduction to plant modeling

and

recent advances in plant modeling in computer graphics.

Course Motivation

Recent years have seen a lot of progress in vegetation modeling

We focus on the following three areas

1) Procedural and biological modeling

2) Reconstruction and inverse procedural modeling

3) User-assisted models

Requirements

- The course is 1.5 hours long
- No previous knowledge of biology is required
- Requires basics of basic algebra and calculus
- Knowledge about geometric modeling is a plus

Presenters






- Bedrich Benes — Purdue University, USA
- Oliver Deussen — University of Konstanz, Germany
- Sören Pirk — Stanford University, USA
- Baoquan Chen — Shandong University, China
- Radomír Měch — Adobe Systems, Inc., USA
- Takashi Ijiri — Ritsumeikan University, Japan
- Yangyan Li — Stanford University, USA

Modeling Plant Life in Computer Graphics

Overview

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Plants in Computer Graphics

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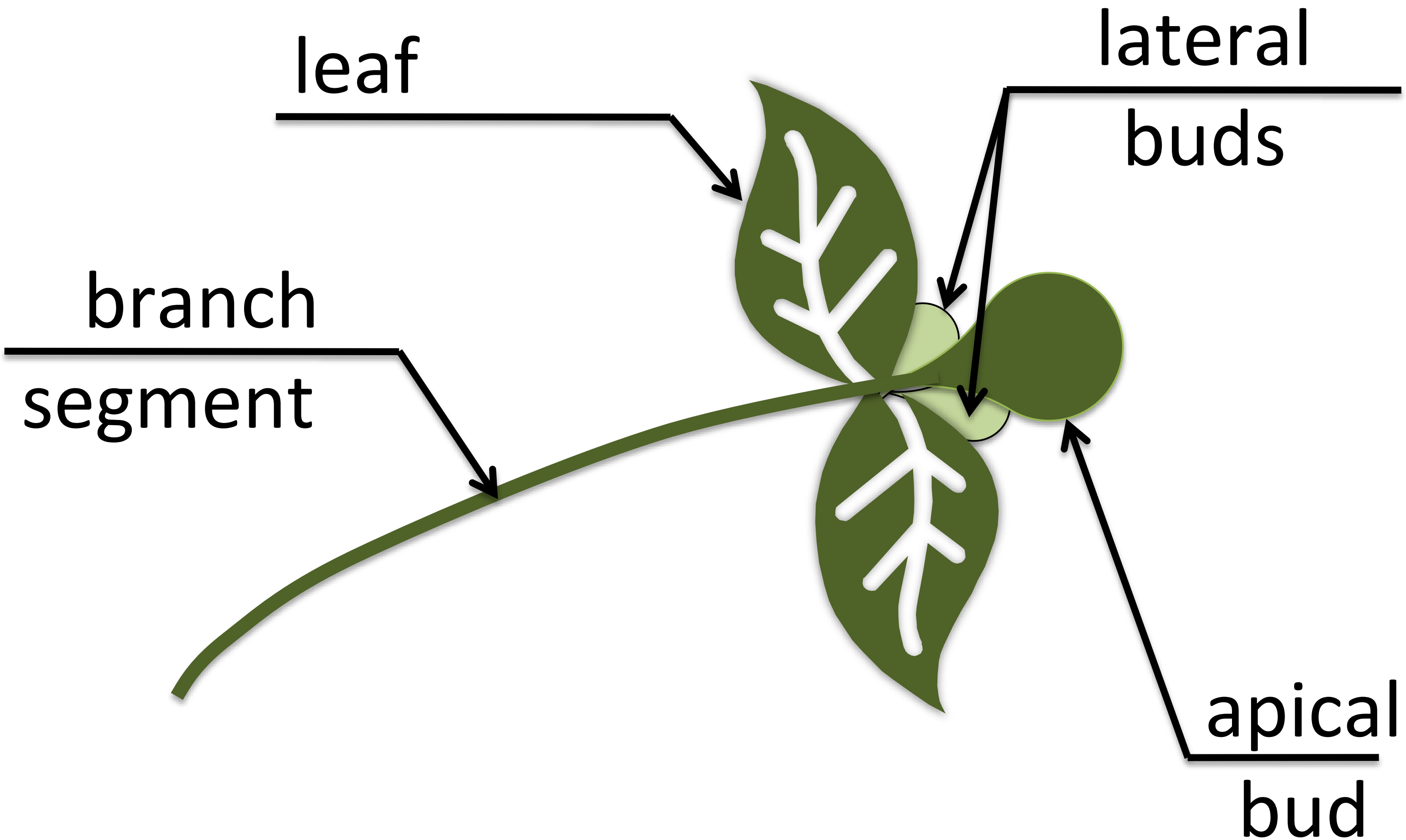
- Biologically-based simulations
- Plant is a modular system – basic elements (leaves, internodes, etc.)
- Ecosystems consider entire plant communities (a plant is a module)
- Plant geometry is the result of **interaction of the modules**

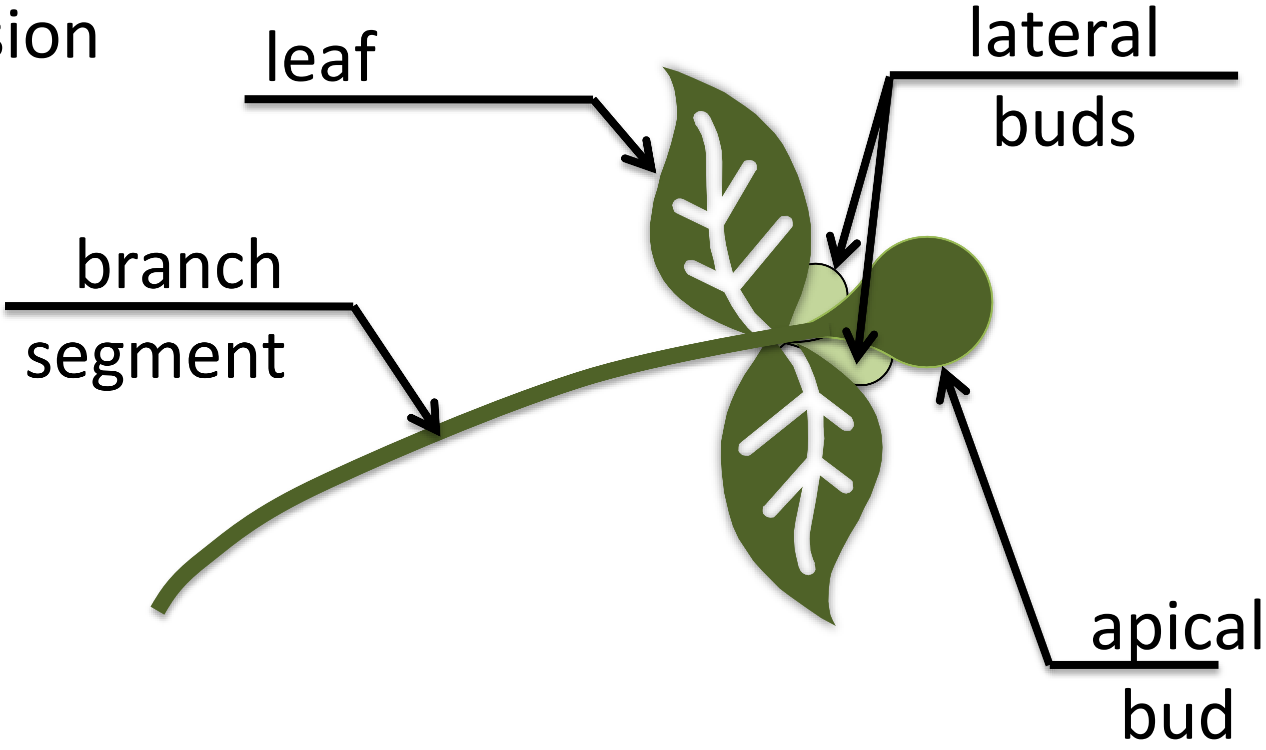
Plant Modules



Plant Growth

- Growth is biologically-based
- Uses plant modules to control the growth
- Primary growth – apex extension

- Apical bud
- Lateral buds
  - Initially dormant
  - Activated after some time



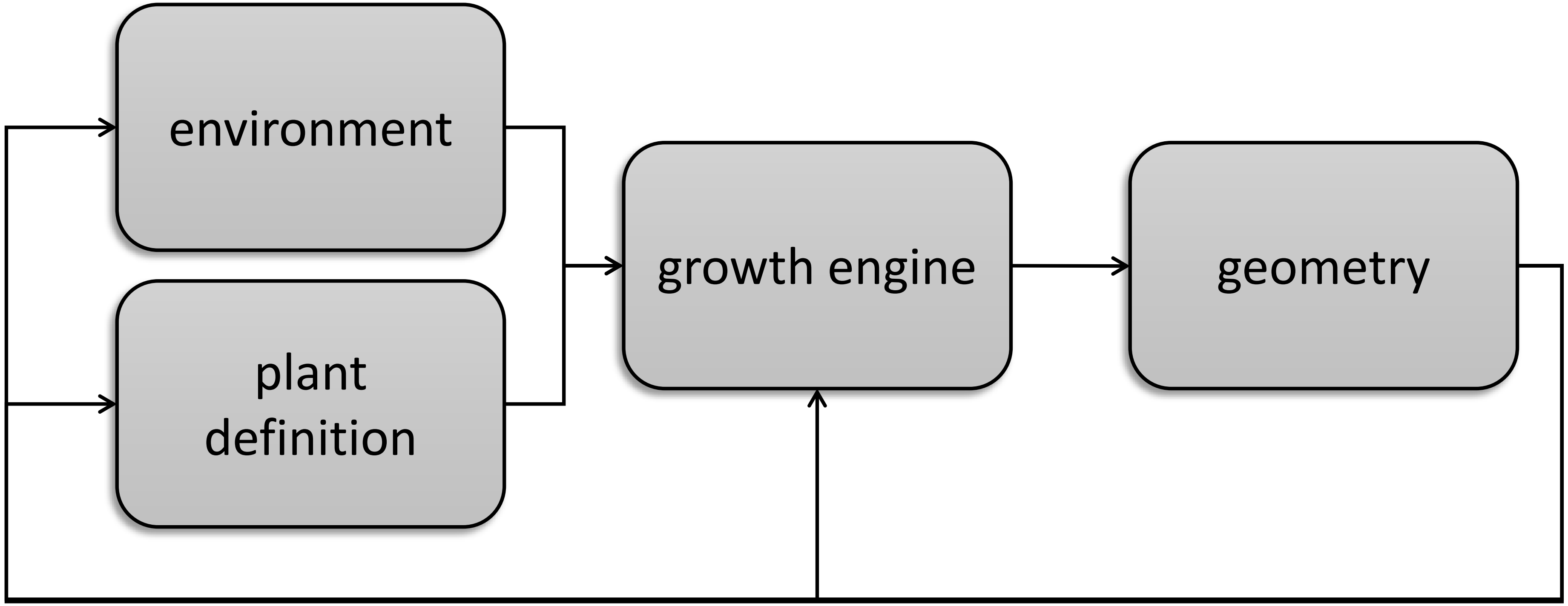
Plant Growth

- Secondary growth (cambial growth)

- Branch is getting thicker

- Annual rings formation

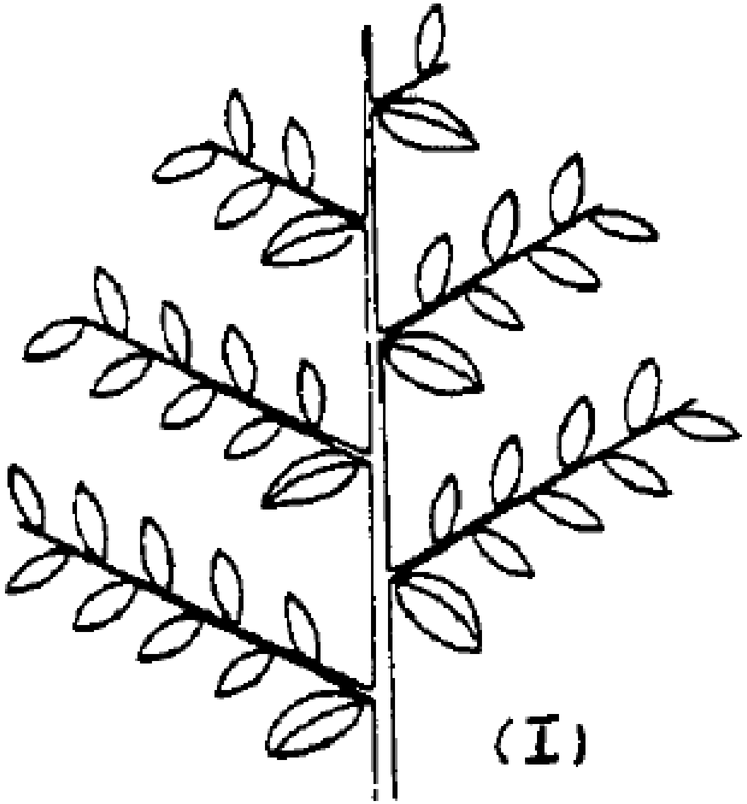
Generic Plant Modeling System



Plant Definition

- Ramification (branching)
- Biological model
- Bud lifespan
- Plant sensitivity to external impetus

Ramification



Continuous

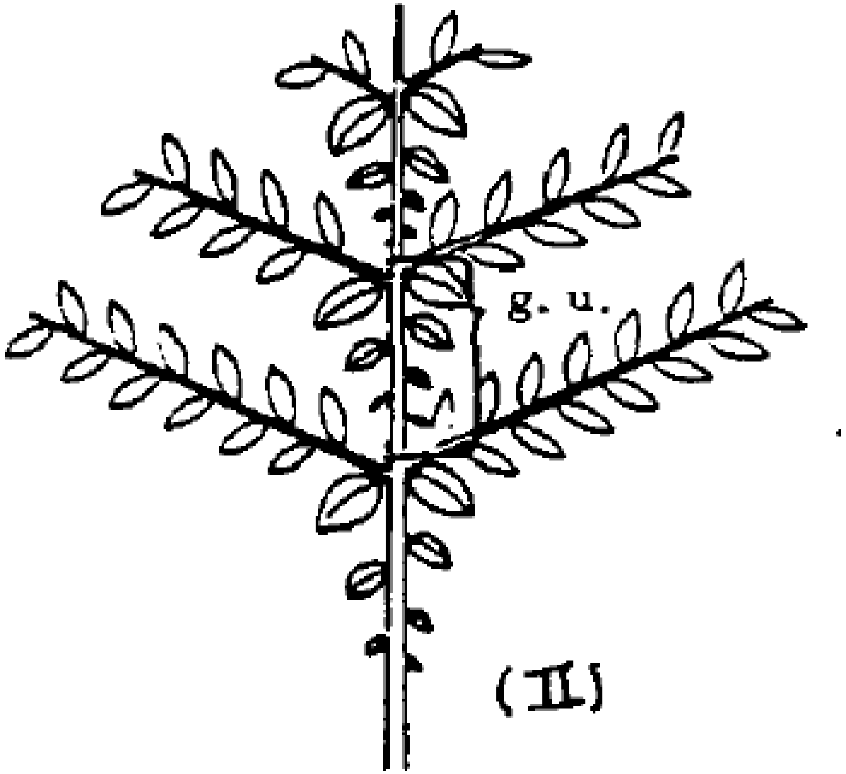


Image from (de Reffye et al 1988)

Rhythmic

Axis (branch) order

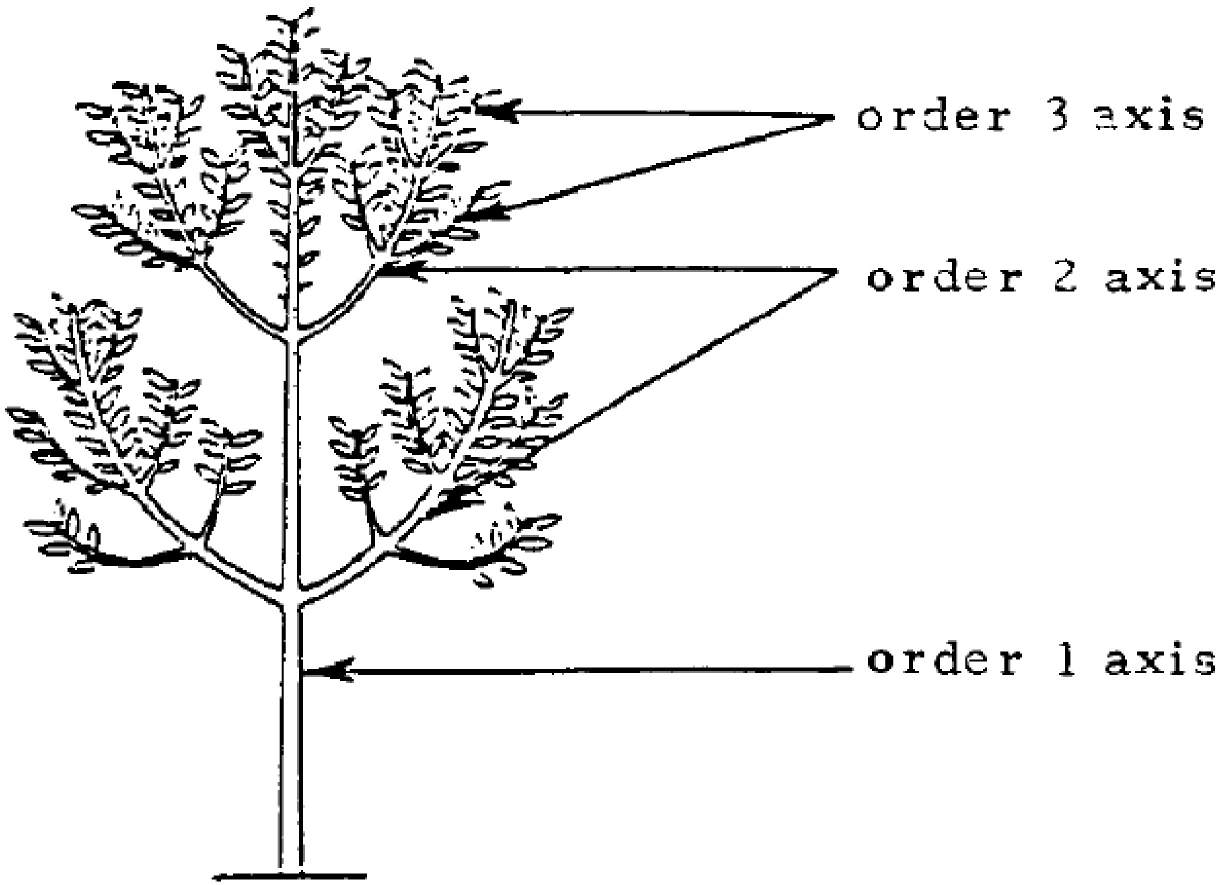
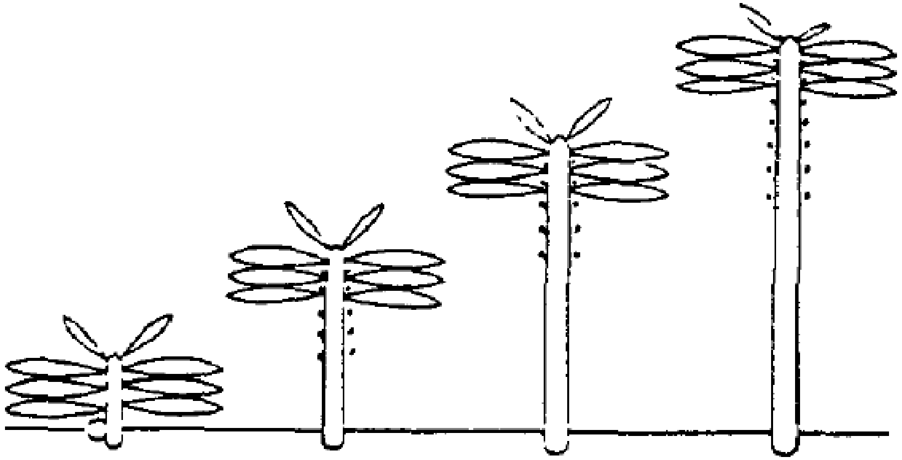
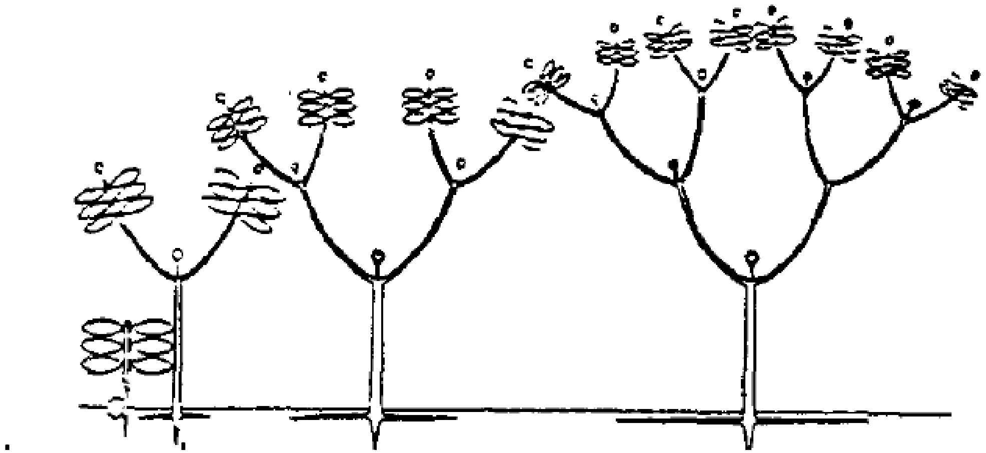


Image from (de Reffye et al 1988)

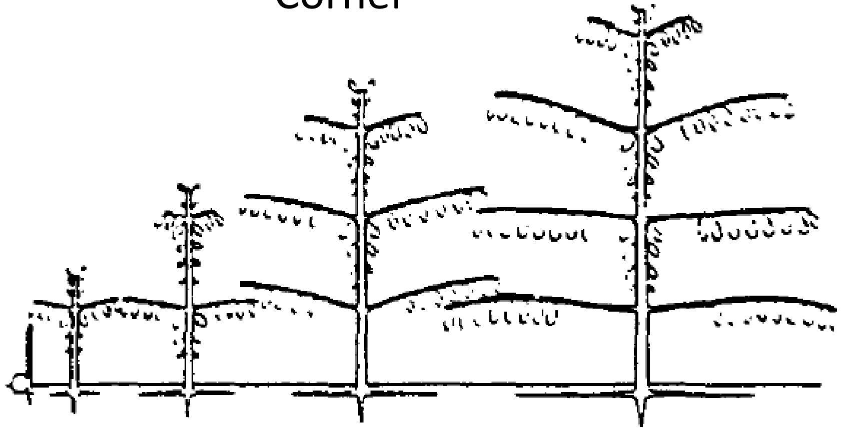
Biological Model



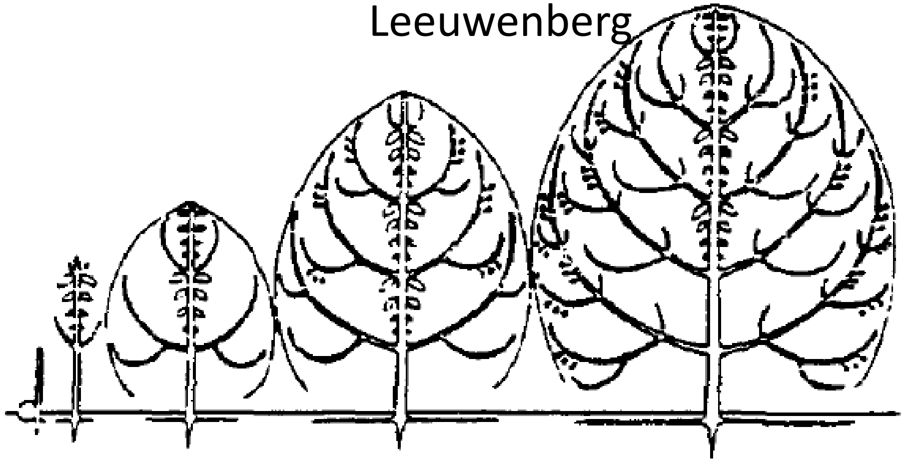
Corner



Leeuwenberg



Massart



Rauh

Images from (de Reffye et al 1988)

Light and Phototropism

- plant growth is driven by buds (“plant engines”)
- each bud evaluates its illumination
- determines the brightest spot (bending)
- % of illuminated buds on a branch determines its fate

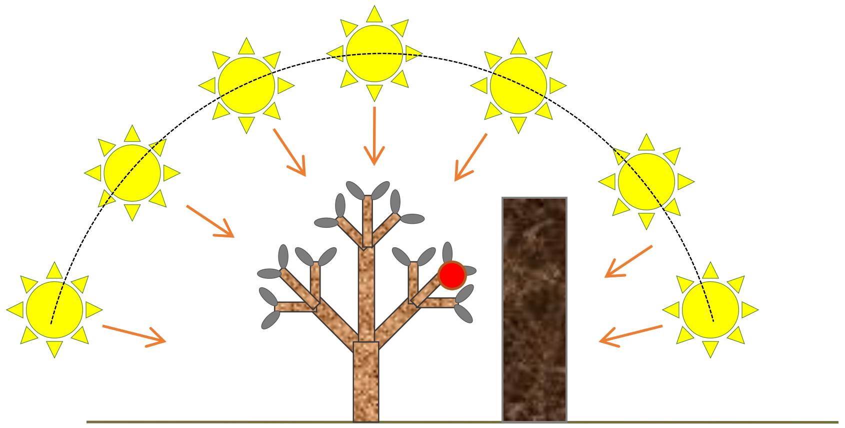
Illumination

- Phototropism
  - Branches tend to grow toward the light
  - Calculate the total illumination on a bud *i*

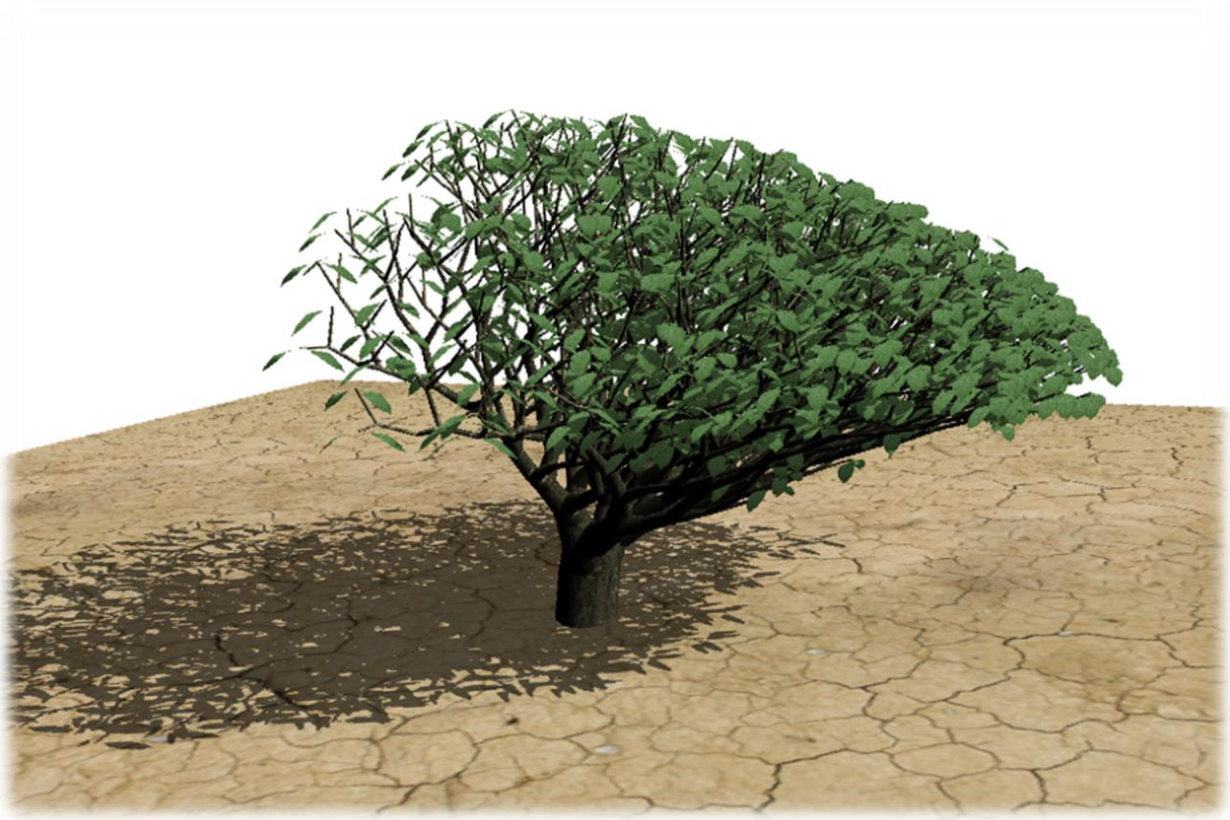
$$E_i = n_i / m$$

    - n_i – no. of positive samples
    - m – no. of all samples

  - Find the brightest spot
    - Bend the direction

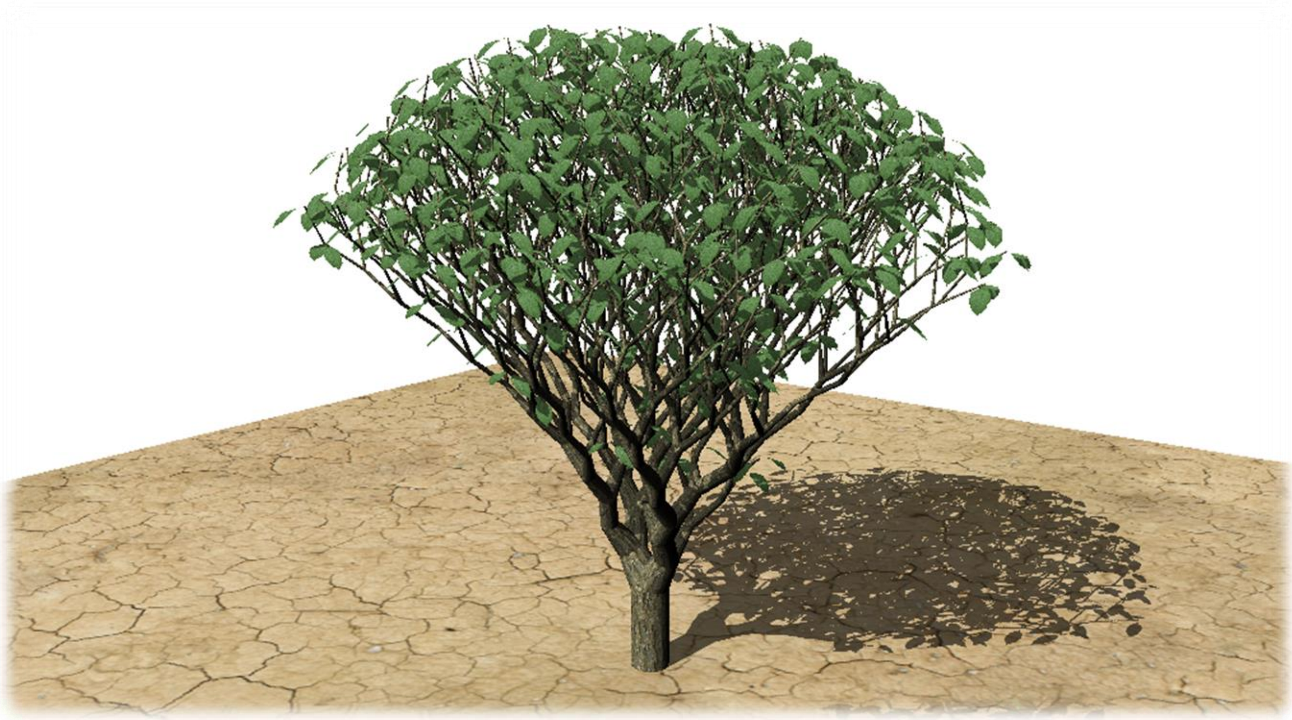


Light and Phototropism



Gravity

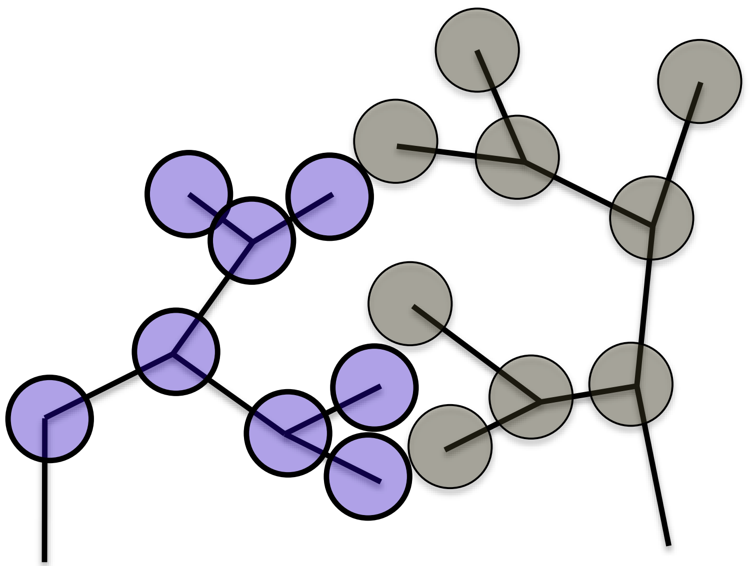
- Gravitropism
  - Branches tend to grow against gravity



Competition for Resources

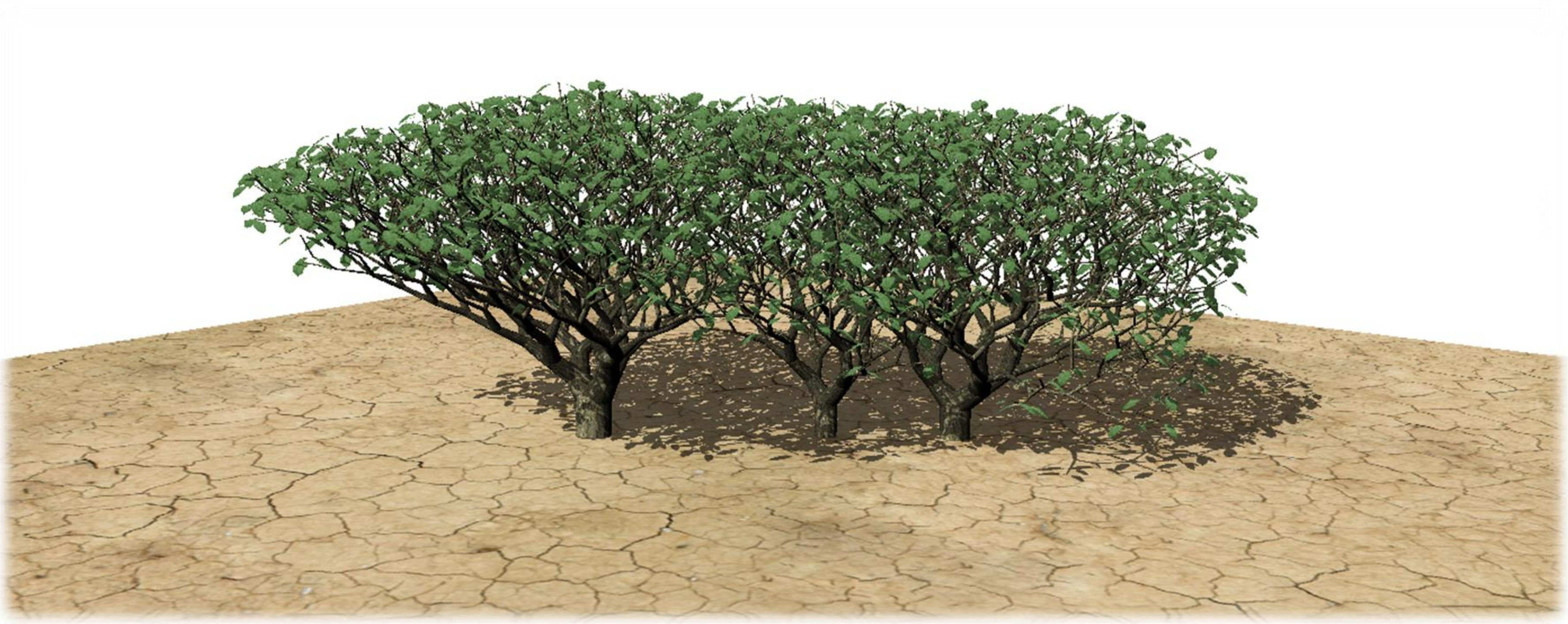
- Branches tend to avoid each other

- Honda model [Honda67]
  - A buds has a sphere of interest
  - Two spheres cannot overlap
  - If two spheres collide – do something



Competition for Resources

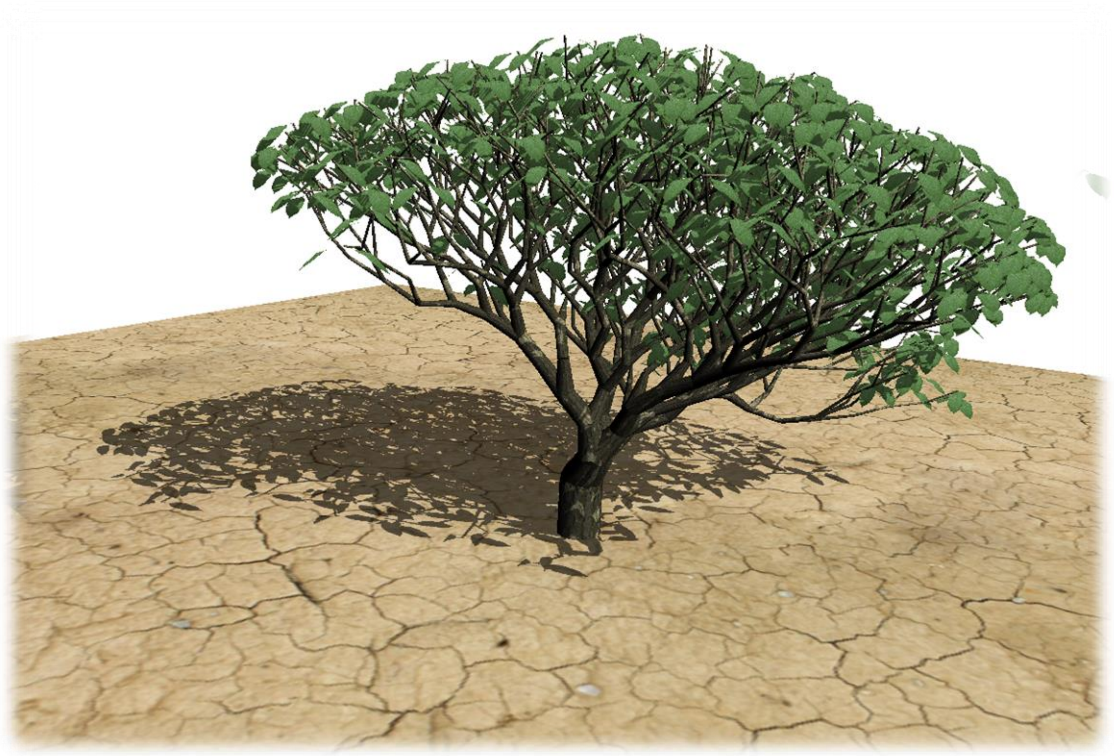
- a small ecosystem fighting for space on bud level



Competition for Resources

Competition for Space

- Branches compete for space



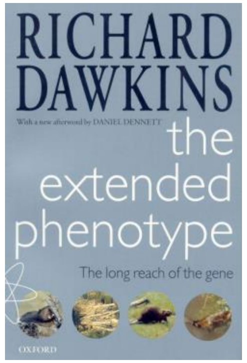
Competition for Resources

- at the level of an ecosystem

image from
Palubicki, W., Horel, K., Longay, S., Runions, A., Lane, B., Měch, R., and Prusinkiewicz, P., (2009) Self-organizing tree models for image synthesis. ACM Trans. Graph. 28, 3, Article 58 (July 2009), 10 pages.

Ecosystems

- A module, so far, was a part of a plant
- An entire plant can be thought of as a module
- Plants compete for resources (Extended Phenotype – Dawkins)
- Result of the competition are ecosystems



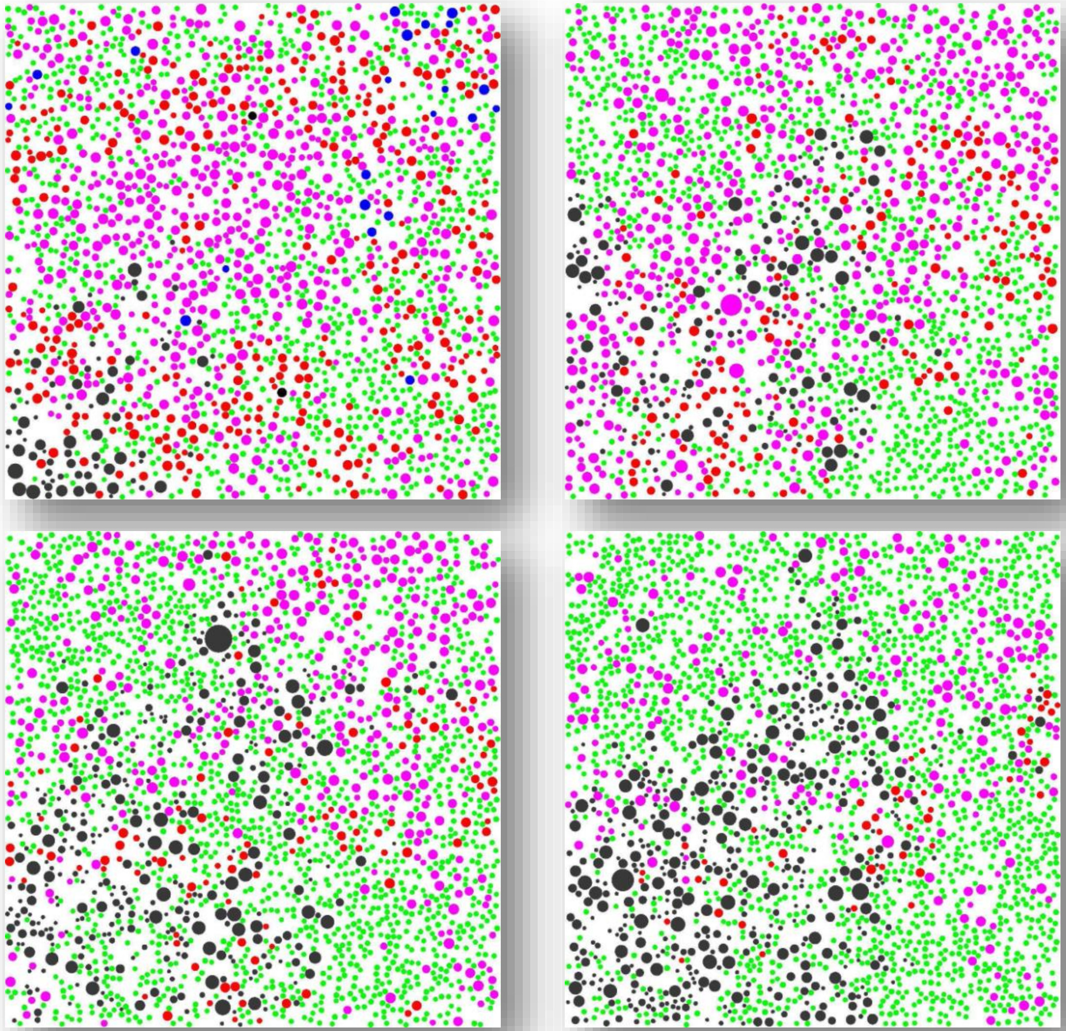
Ecosystems

25 years

75 years

100 years

125 years



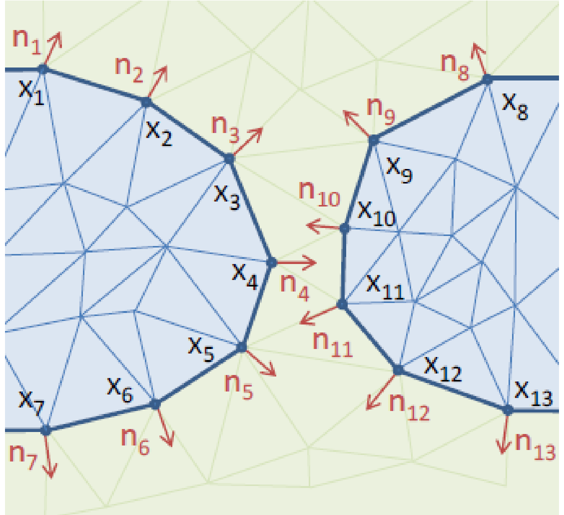
Urban Ecosystems

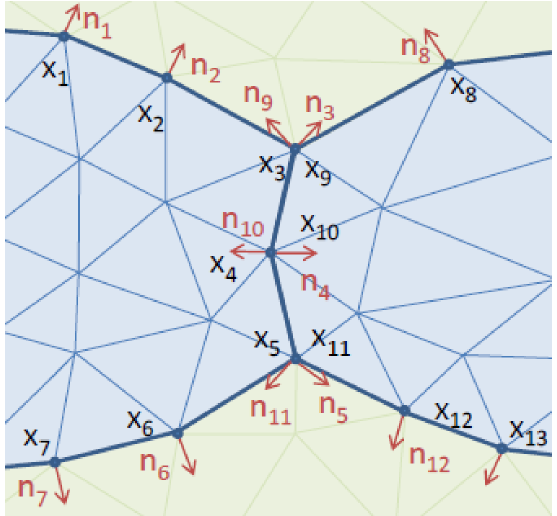
Cambial (Secondary) Growth

Kratt, J., Spicker, M., Guayaquil, A., Fiser, M., Pirk, S., Deussen, O., Hart, J.C., and Benes, B., (2015) Woodification: User-Controlled Cambial Growth Modeling in Computer Graphics Forum (Proceedings of Eurographics 2015), 33 (2), 361-372 (DOI=10.1111/cgf.12566)

Cambial (Secondary) Growth

- Uses deformable simplicial complexes
- Propagate vertices based on growth function
- Detection of collisions and self-intersections
- Adds cracks





Cambial (Secondary) Growth

Used References

- Benes, B., Andrysco, N., and Stava, O., (2009) *Interactive Modeling of Virtual Ecosystems*, in EG Workshop on Natural Phenomena, pp. 9-16
- Benes, B., Massih, M-A., Jarvis, P., Aliaga, D.G., and Vanegas, C., (2011) *Urban Ecosystem Design*, in Proceedings of I3D, pp: 167-174
- de Reffye, P.; Edelin, C.; Françon, J.; Jaeger, M. & Puech, C. (2988) *Plant models faithful to botanical structure and development,* in SIGGRAPH Computer Graphics, ACM, 1988, 22, 151-158
- Palubicki, W., Horel, K., Longay, S., Runions, A., Lane, B., Měch, R., and Prusinkiewicz, P., (2009) *Self-organizing tree models for image synthesis*. ACM Trans. Graph. 28, 3, Article 58 (July 2009), 10 pages.
- Kratt, J., Spicker, M., Guayaquil, A., Fiser, M., Pirk, S., Deussen, O., Hart, J.C., and Benes, B., (2015) Woodification: User-Controlled Cambial Growth Modeling in Computer Graphics Forum (Proceedings of Eurographics 2015), 33 (2), 361-372 (DOI=10.1111/cgf.12566)

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Environmental Response

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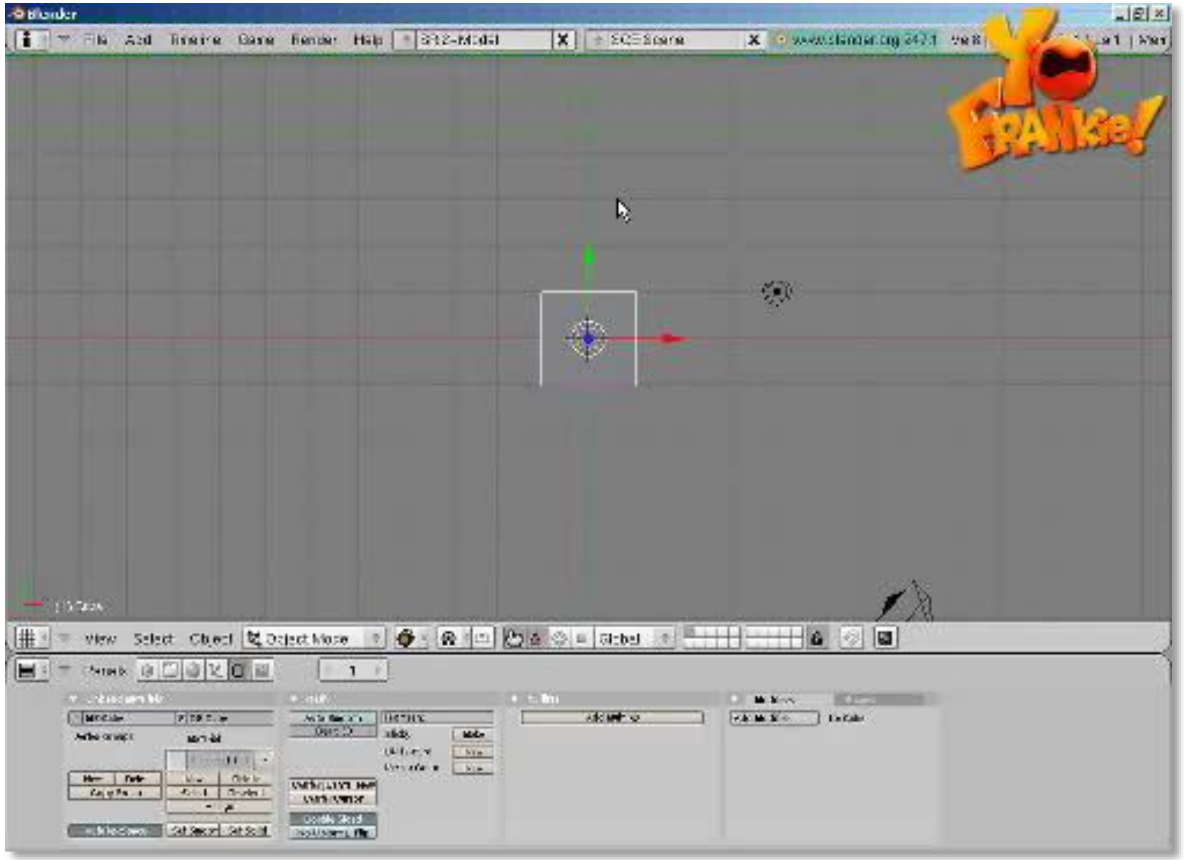
Overview

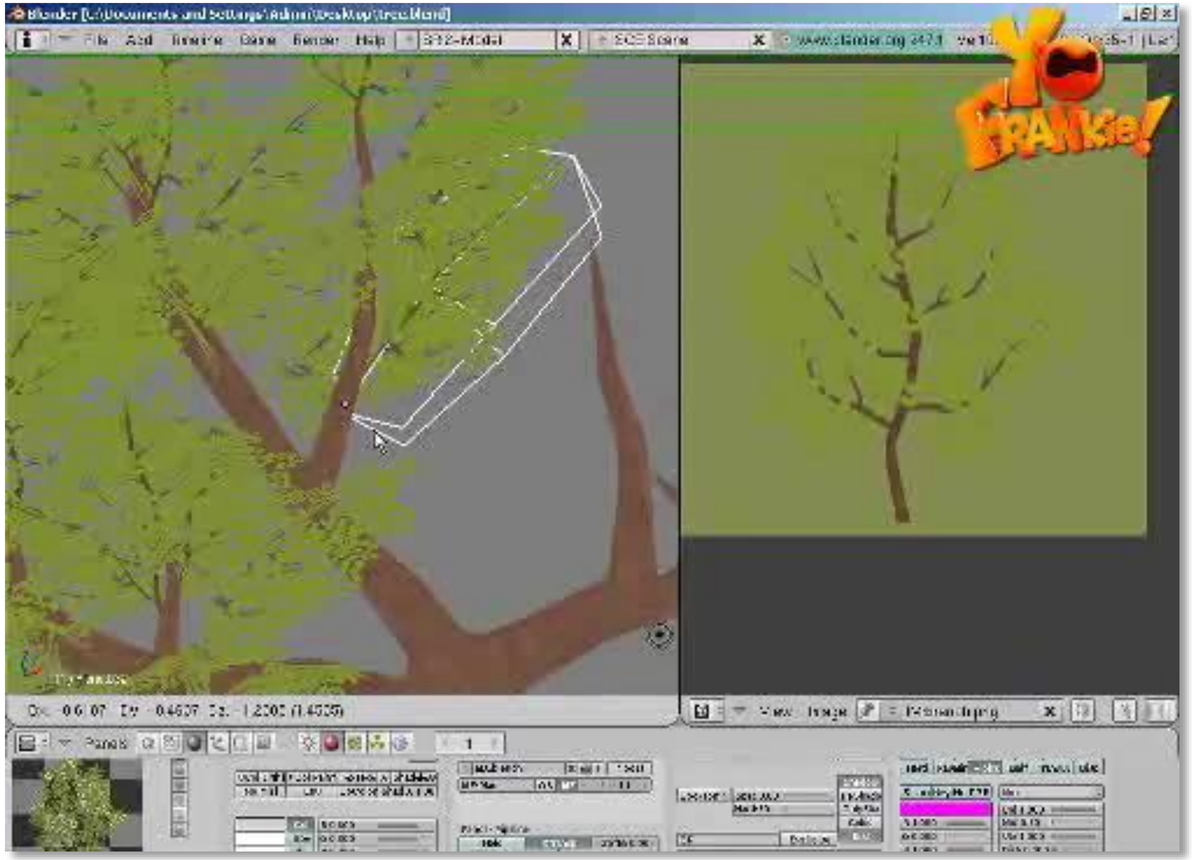
Environmental response [20 minutes]

- Real-time sensitivity of tree models **(Pirk)**
- Capturing growth response **(Pirk)**
- Physics response to wind **(Pirk)**

Tree models are static

3D Tree Modeling





Pablo Vazquez - http://vimeo.com/2956756

Plastic Trees: Interactive Self-Adapting Botanical Tree Models

Pirk, S., Stava, O., Kratt, J., Said, M. A. M., Neubert, B., Mech, R., Benes, B., Deussen, O.
Plastic trees: interactive self-adapting botanical tree models.
ACM Trans. on Graph. 31, 4, 50:1–50:10, 2012.

Environment Aware Trees

Automatic modification of 3D tree models

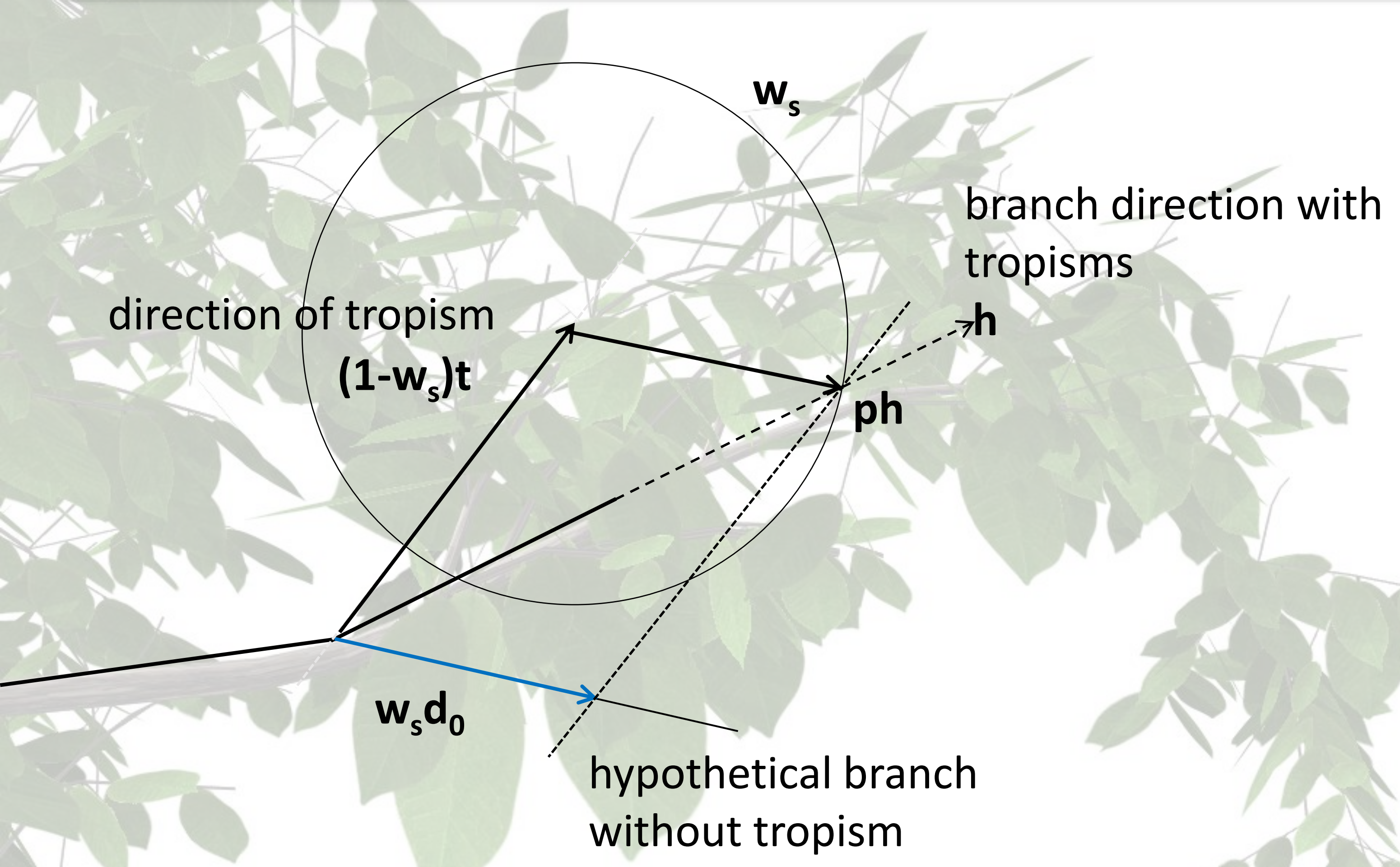
Skeletal Graph

Skeletal Graph

- Branch Age
- Growth Rate

Tree Analysis - Tropisms

Inverse Tropism



Backward modeling to estimate influence of tropisms to the original model

→ **allows to apply tropisms triggered by the new environment**

Dynamic Interaction - Bending

New Direction

combination of tropisms

$$\vec{h} = w_s \vec{d}_0 + (1 - w_s) \frac{\sum w_\tau \vec{t}_\tau}{\sum w_\tau}$$

new direction

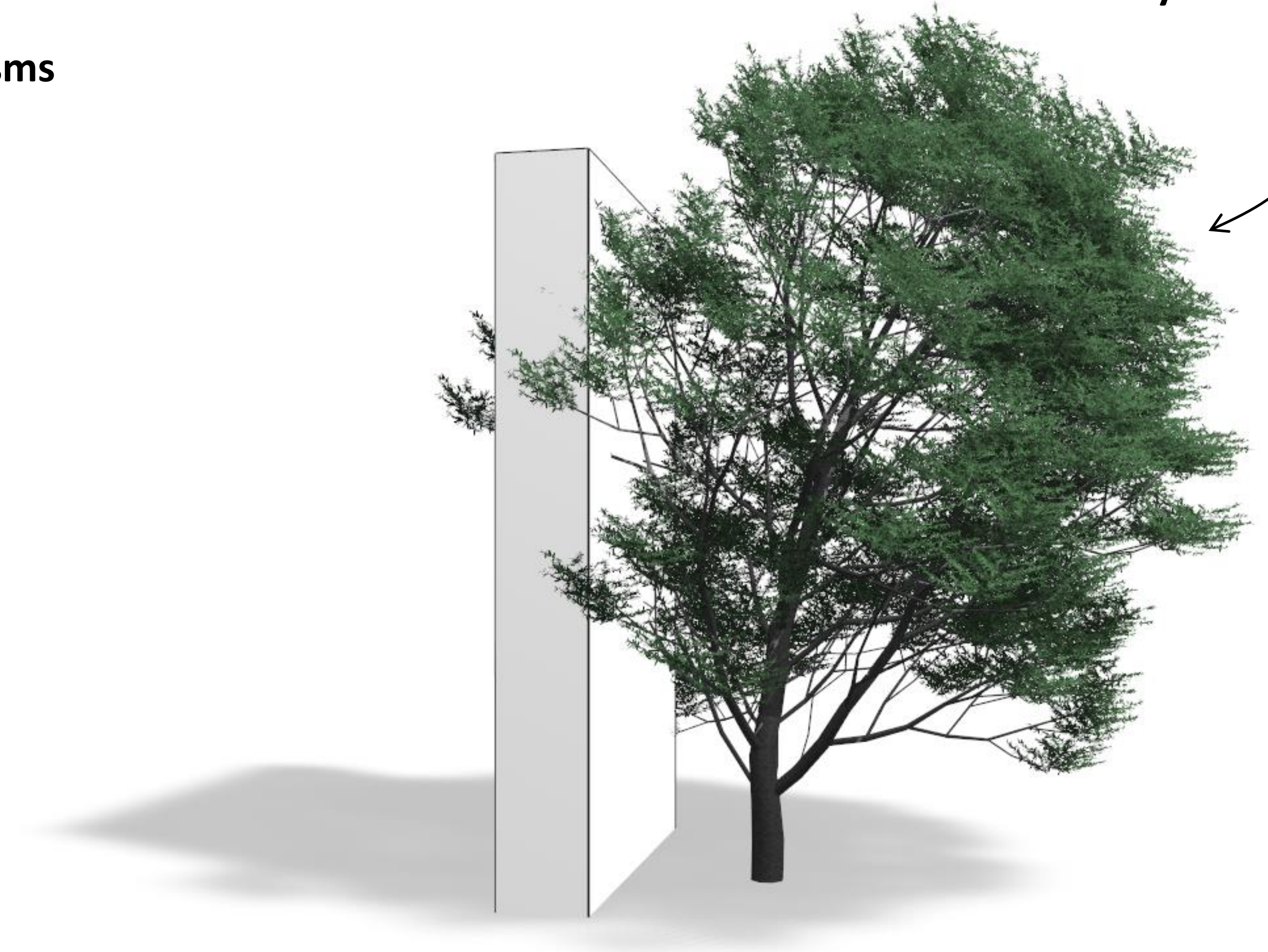
start weight

weights of tropisms

normalized direction

Transformations represent changes in the tree growth.

only bending



Dynamic Interaction - Pruning

Approach similar to **[Palubicki et al. 2009]**

Amount of Light received by the leaf-cluster.

normalized amount of light

$$\varphi_{t_s} = \sum_{c \in C_s} 2\pi {r_c}^2 i_c$$

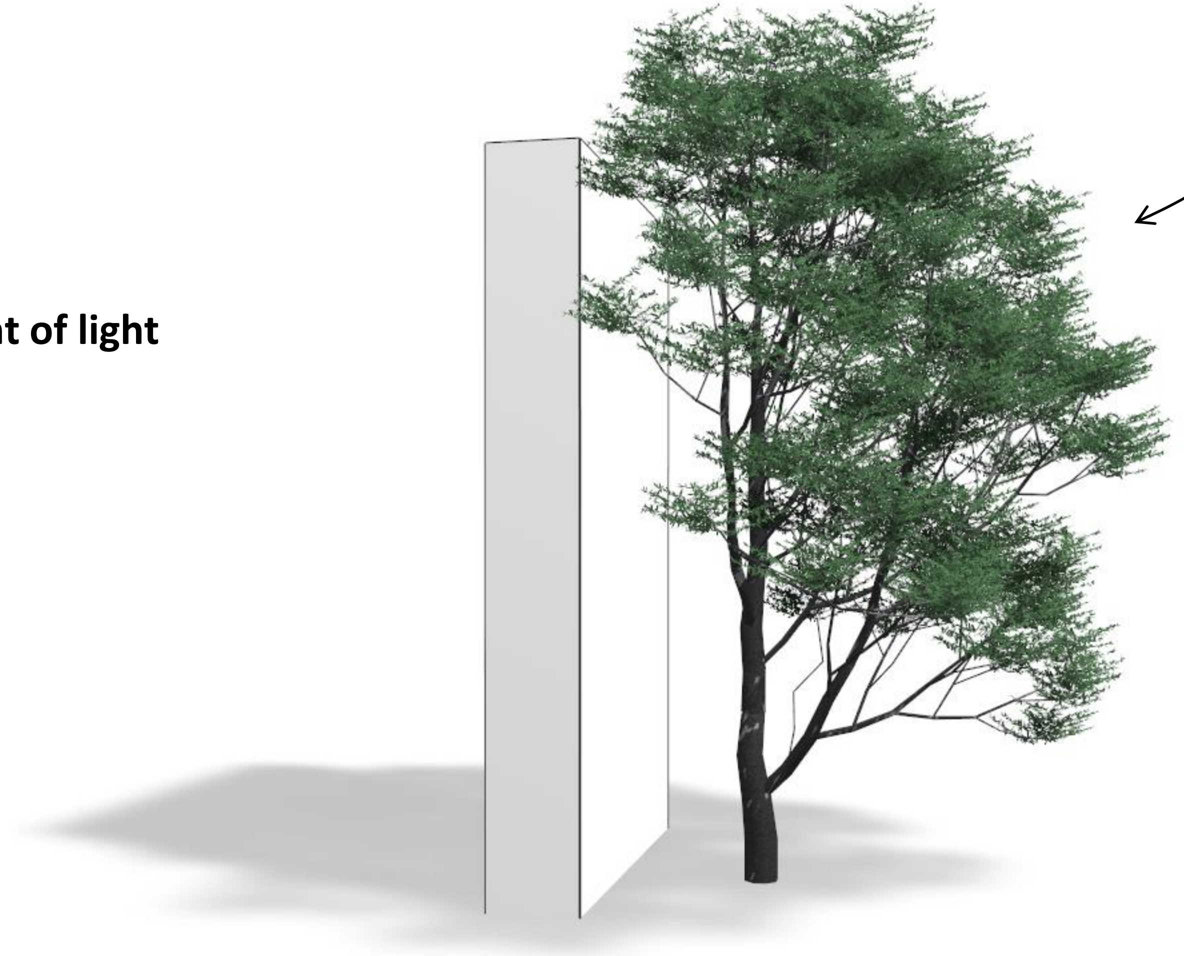
radius of a given cluster

amount of resources (light)

l_t: sum of distances

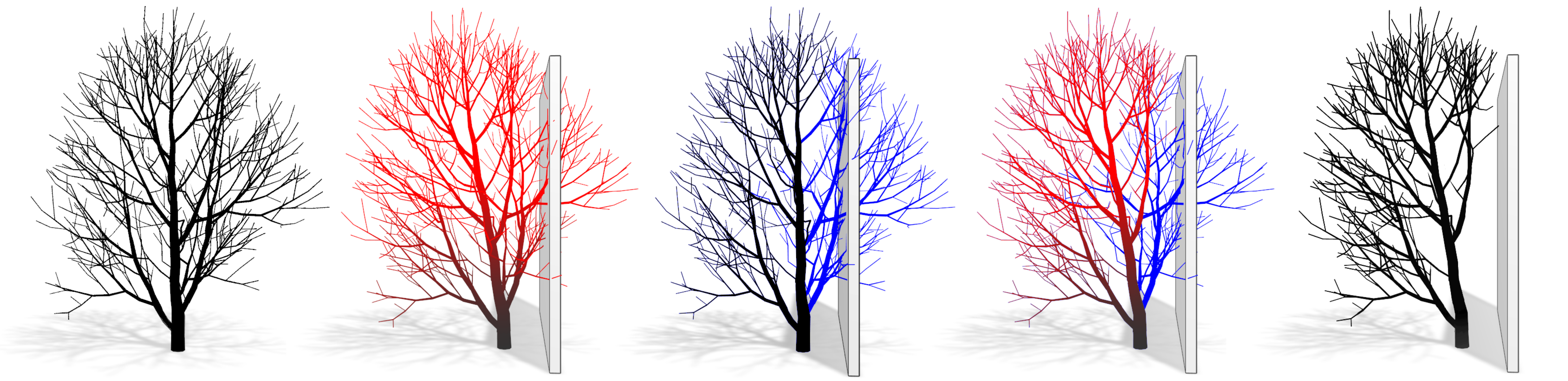
Branch is pruned when ratio $\varphi_{t_s}/l_t < thres$

only pruning

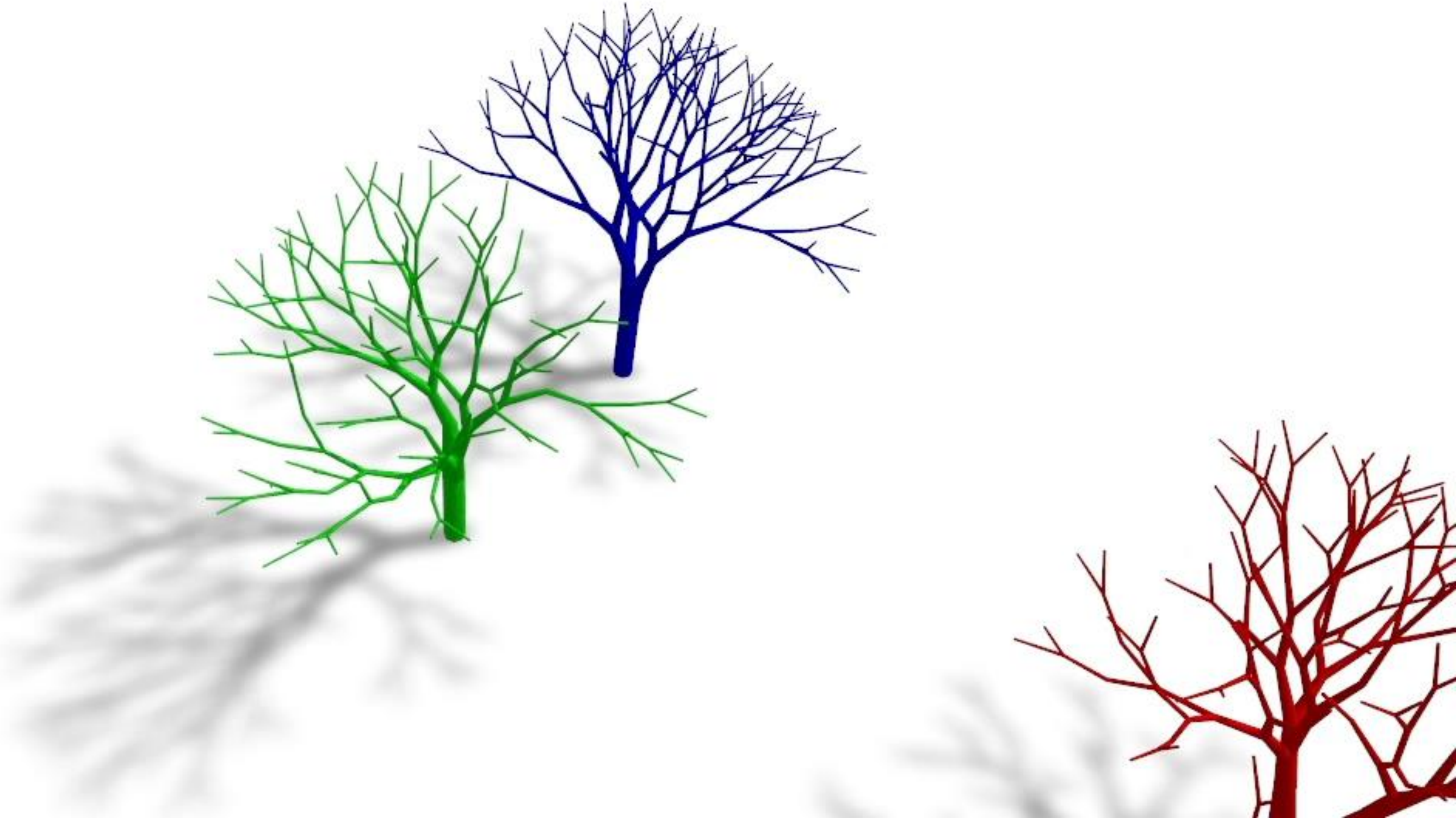


Tree/Obstacle Interaction

Original Model Bending Pruning Bending + Pruning Result



Tree/Tree-Interaction



Bending/Pruning Result

Tree/Tree-Interaction

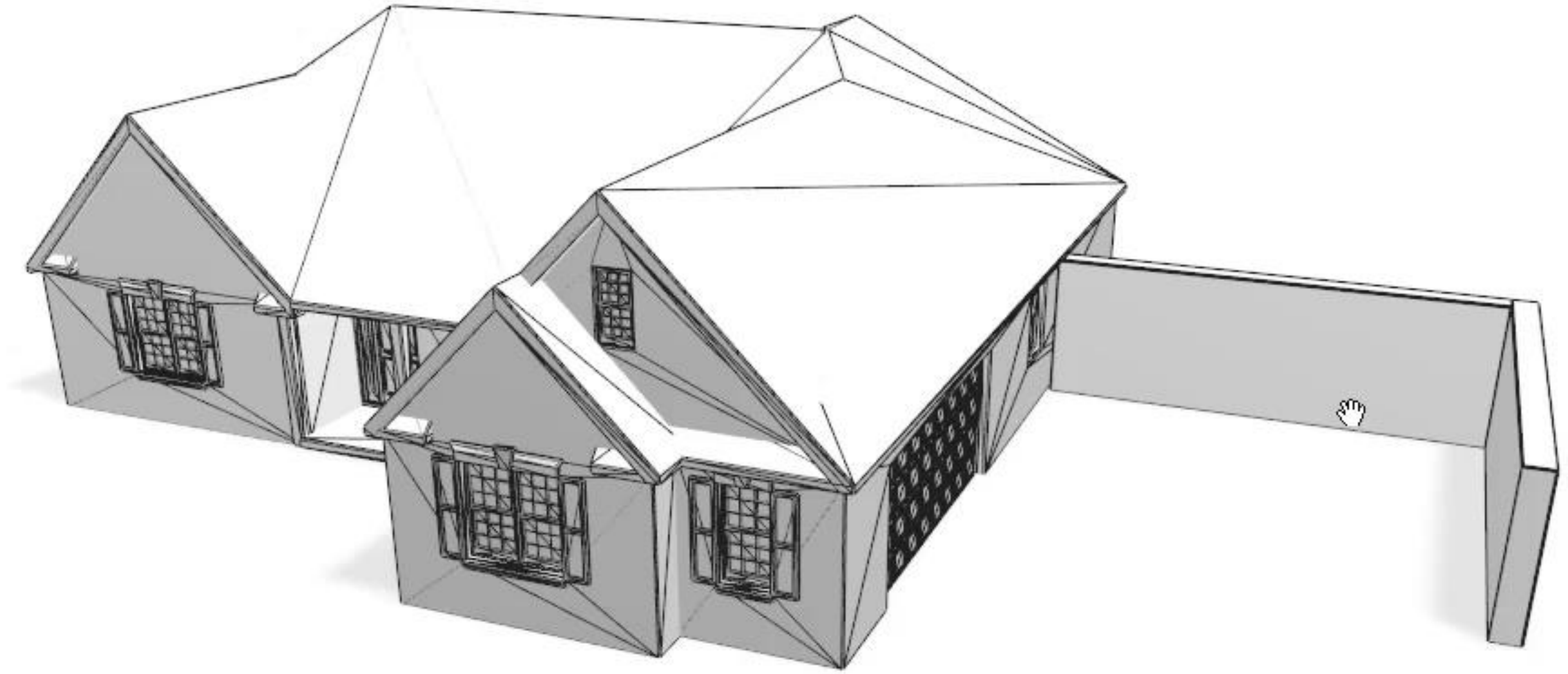
Static Models

Bending and Pruning

Strong Pruning

Exaggerated Bending

Editing



Capturing and Animating the Morphogenesis of Polygonal Tree Models

Pirk, S., Niese, T., Deussen, O., Neubert, B.
Capturing and animating the morphogenesis of polygonal tree models.
ACM Trans. on Graph. 31, 6, 169:1–169:10, 2012.


The Upthink Lab - http://vimeo.com/24487172

Continuous Animations of Growth

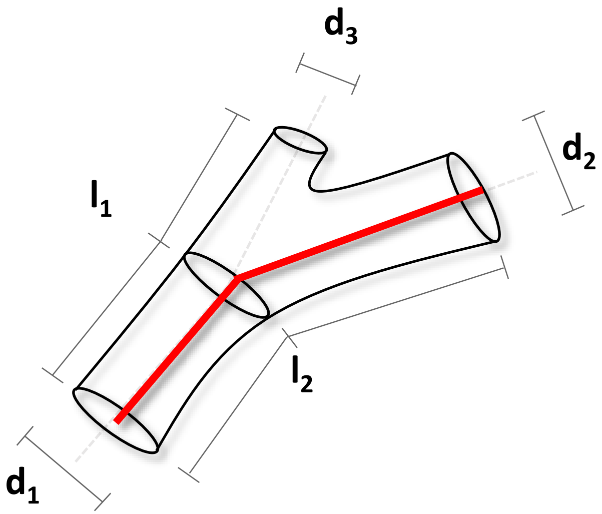
[Pirk et al. 2012b]

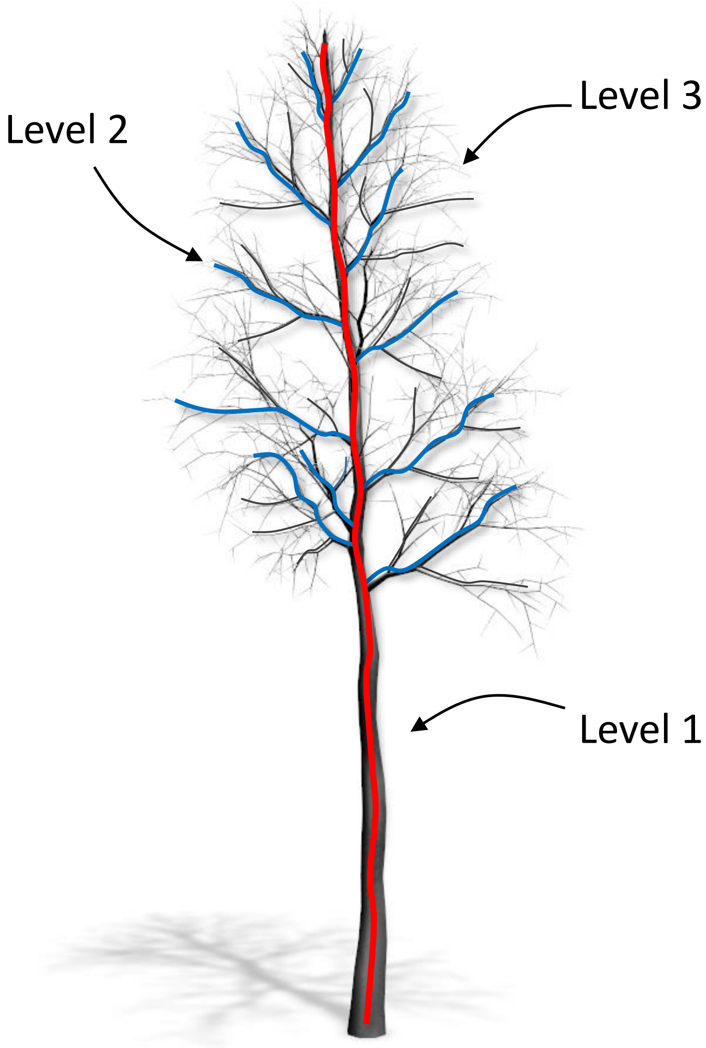
Gravelius Order

Ordering method for identifying hierarchies.

Determine main trunk based on angle between branches.

Also considering length and thickness of a branch.





Pipe Model Theory


[Shinozaki et al. 1964]

Plant forms emerge from vascular systems.

Assembly of leaf units connecting the leaves to the root.

Provides us with branch radii.

Angle/Radii Interpolation

Angle Interpolation

Current Angle

Initial Angle

$$\vartheta_\alpha = \frac{\alpha_i - \alpha_{init}}{\Delta t}$$

Angular Velocity

Duration

Radii Interpolation

Power Law of Branching

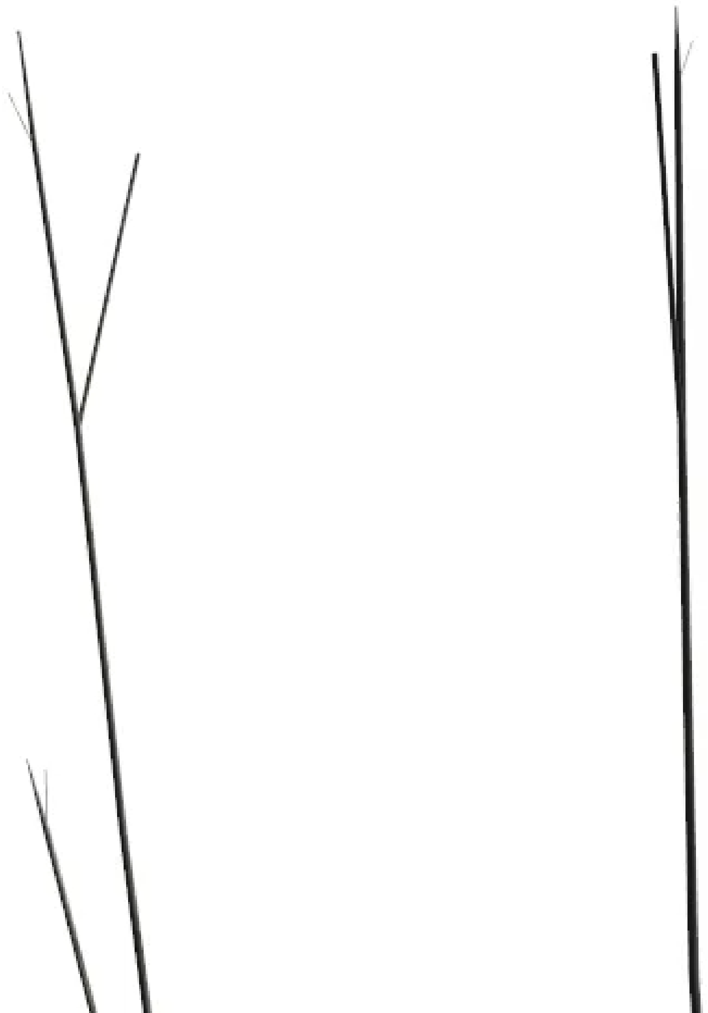
Child Radii

$$r_p = \left(\frac{\sum {r_i}^u}{b^p}\right)^{\frac{1}{u}}$$

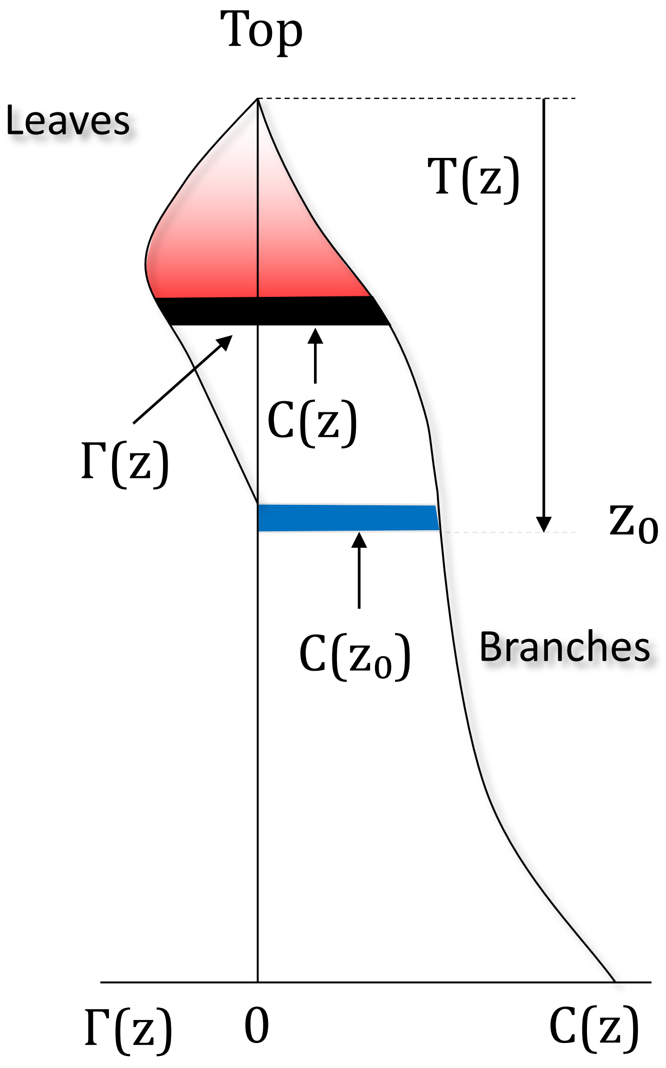
Current Radius

Original Model Coefficient

Angle/Radii Interpolation



Profile Diagram



Similar Among Plant Communities.

Represents vertical distribution of leaves.

Distribution of leaves needs to be consistent.

→ Tells us were geometry is missing.

→ How to measure densities?

[Chiba 1990, Chiba 1991]

Measuring Densities

Stratified Clipping (STC)

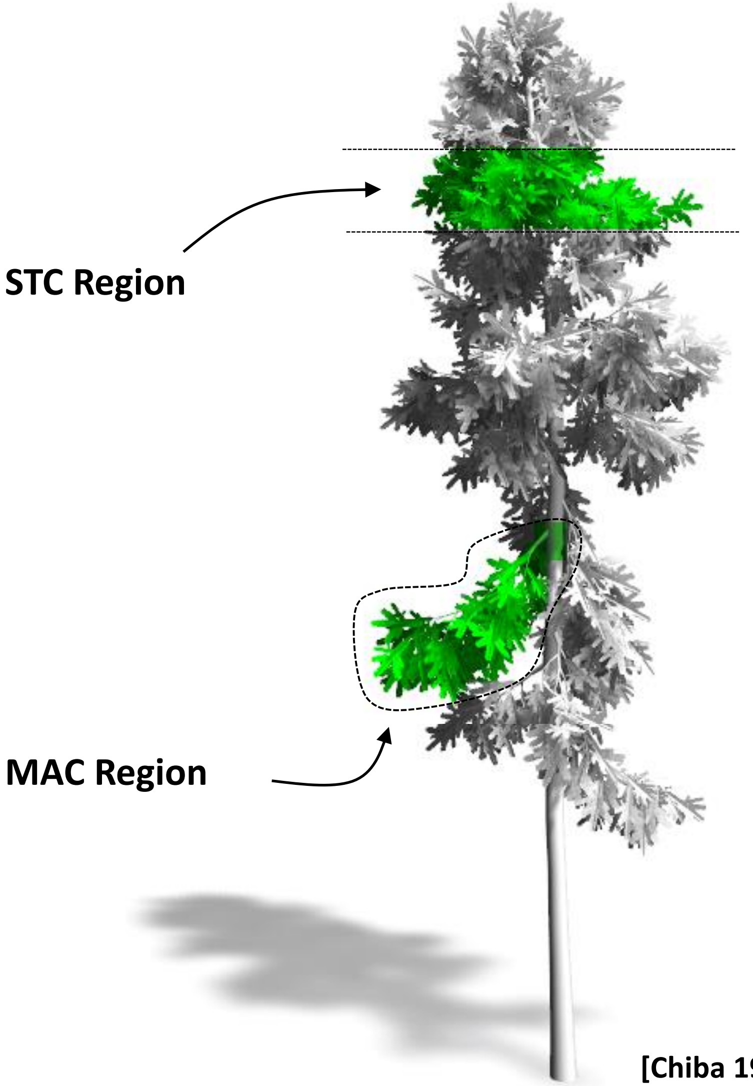
Vertical range of the tree is selected.

All branches and leaves in this region are used for measuring biomass.

Main Axis Cutting (MAC)

Part of the main axis is selected.

All branches and leaves attached to this part are used for measuring biomass.

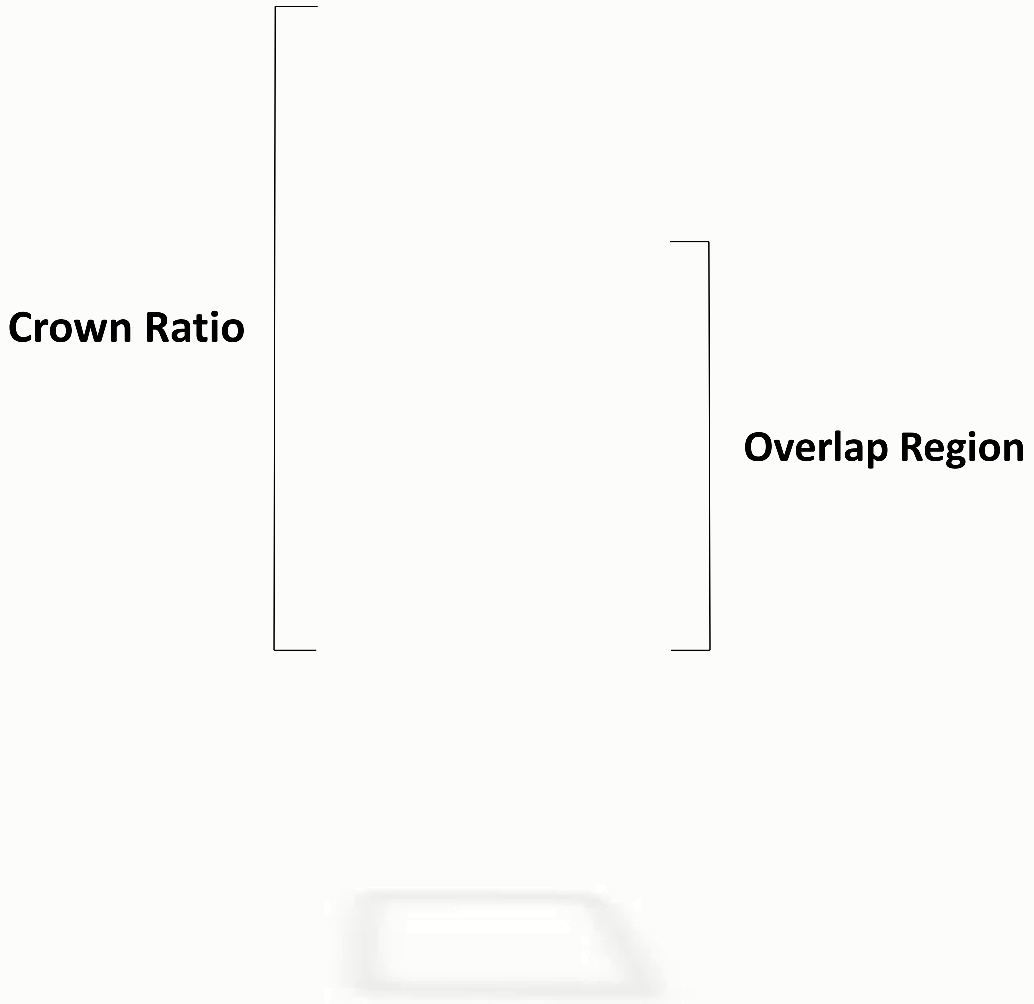


[Chiba 1990, Chiba 1991]

Crown Ratio

Add geometry where no information was available in the original model.

Remove geometry during animation to maintain plausibility and to eventually reach the input.



Growth-based Editing

Individual Growth
of Branches

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Windy Trees: Modeling Stress Response for Developmental Tree Models

Pirk, S., Niese, T., Hädrich, T., Benes, B., and Deussen. O.
Windy trees: computing stress response for developmental tree models.
ACM Trans. Graph. 33, 6, Article 204 ,11 pages, 2014.

Tree/Wind Interaction

Wind as Developmental Factor

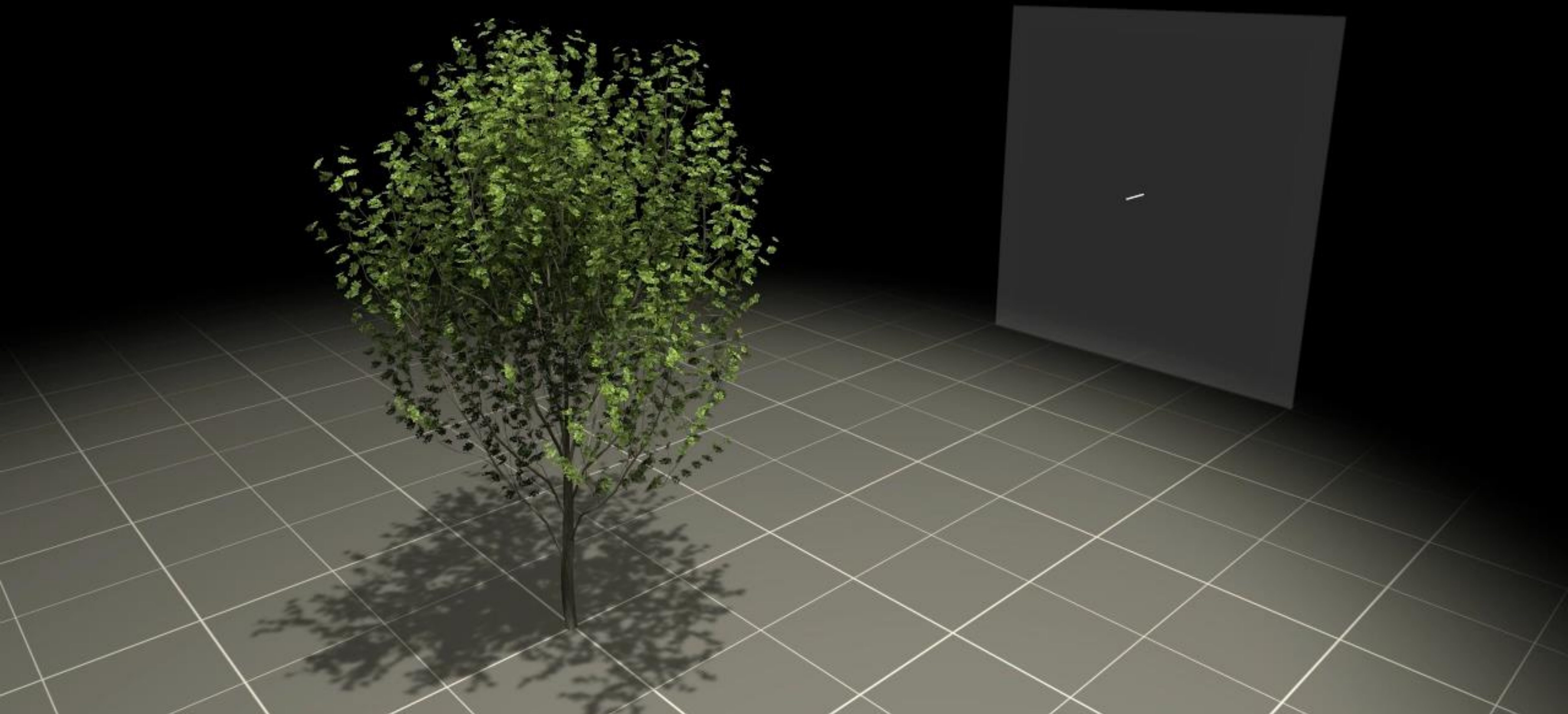
Alex Bamford

Rich Price

Walberth Mascarenha

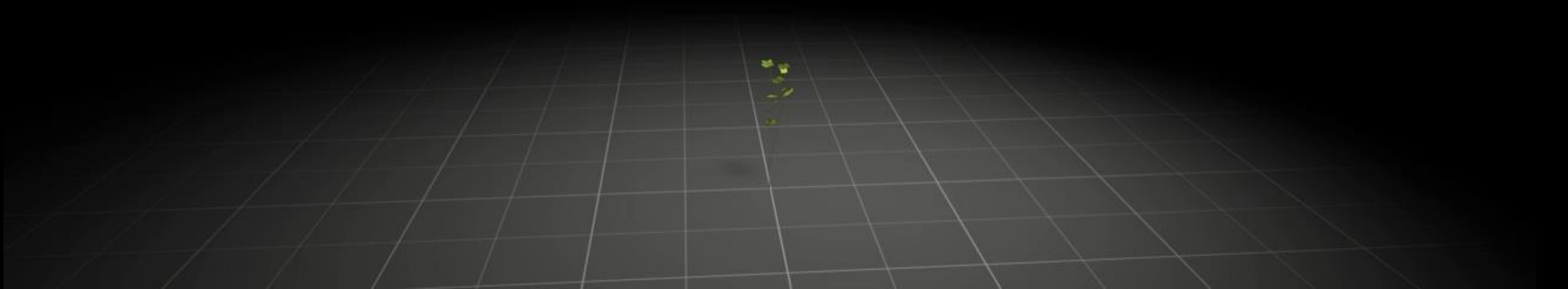
Fedderica Gentile

Windy Trees

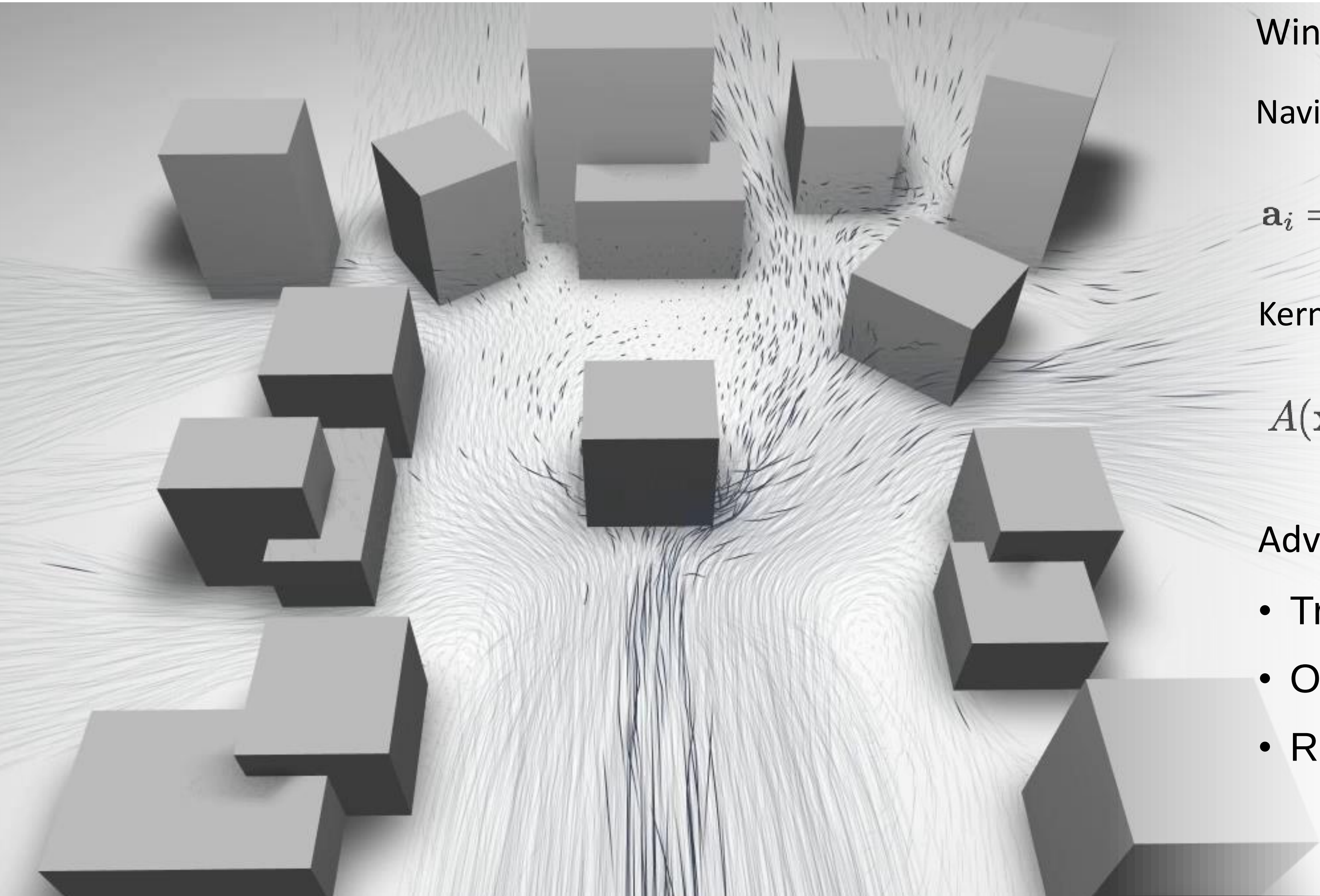


Growth Model

- Pipe Model Theory
- Gravelius Order
- Branching Angles
- Branch Radii
- Growth Rate



Smoothed Particle Hydrodynamics (SPH)



Wind Simulation

Navier Stokes - Acceleration

$$\mathbf{a}_i = \frac{d\mathbf{v}_i}{dt} = \frac{-\nabla p + \mu \nabla^2 \mathbf{v} + \rho \mathbf{g}}{\rho_i}$$

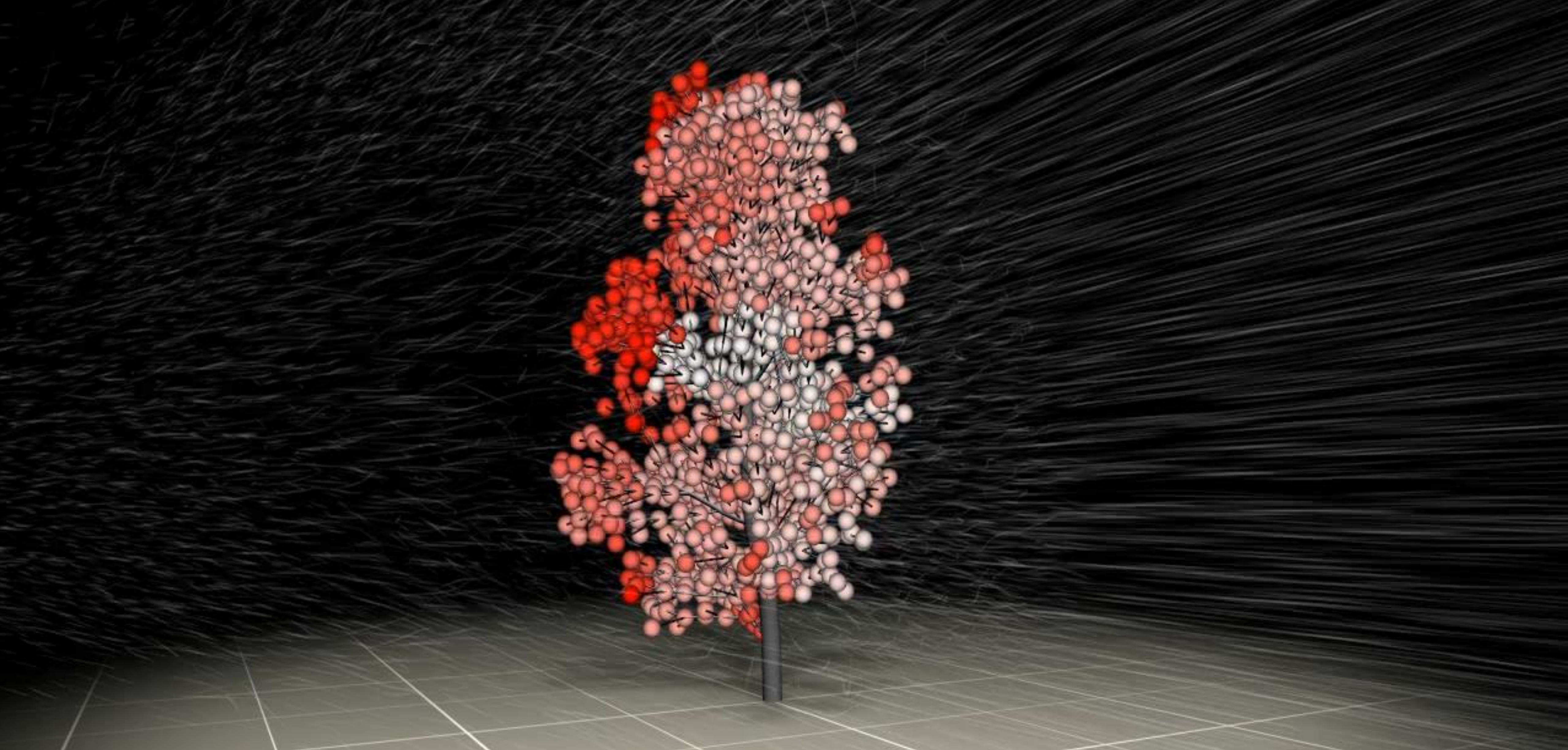
Kernel Smoothing Function

$$A(\mathbf{x}) = \sum_{j=1}^{N} \frac{m_j}{\rho_j} A_j \; W(\mathbf{x} - \mathbf{x}_j, h)$$

Advantages

- Tracking of individual collisions
- Occlusion handling (wind shadow)
- Real-time simulation

Sensor Particles



Two-Way Coupling

Force Model for Branches

Torque

$$N = I\frac{d\omega}{dt}$$

Moment of Inertia (rod)

$$I = \frac{mr^2}{3}$$

$$F_W = S_b \sigma \nu$$

Wind Force

$$D = -(\hat{\omega} \times \hat{e})\mu\omega|\omega|$$

Damping Force

$$\boldsymbol{F} = \boldsymbol{F_w} + \boldsymbol{R} + \boldsymbol{D} + \boldsymbol{P} + \boldsymbol{L}$$

Restoration Force

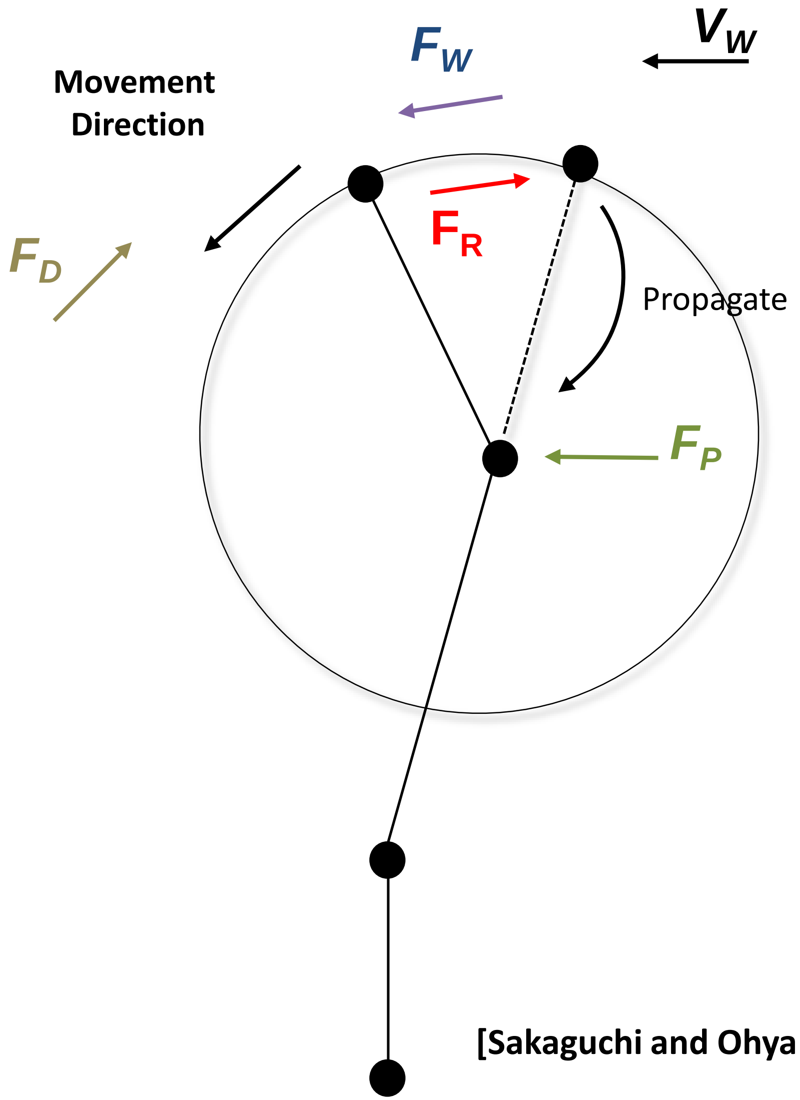
$$R = d_r k \alpha$$

Propagation Force

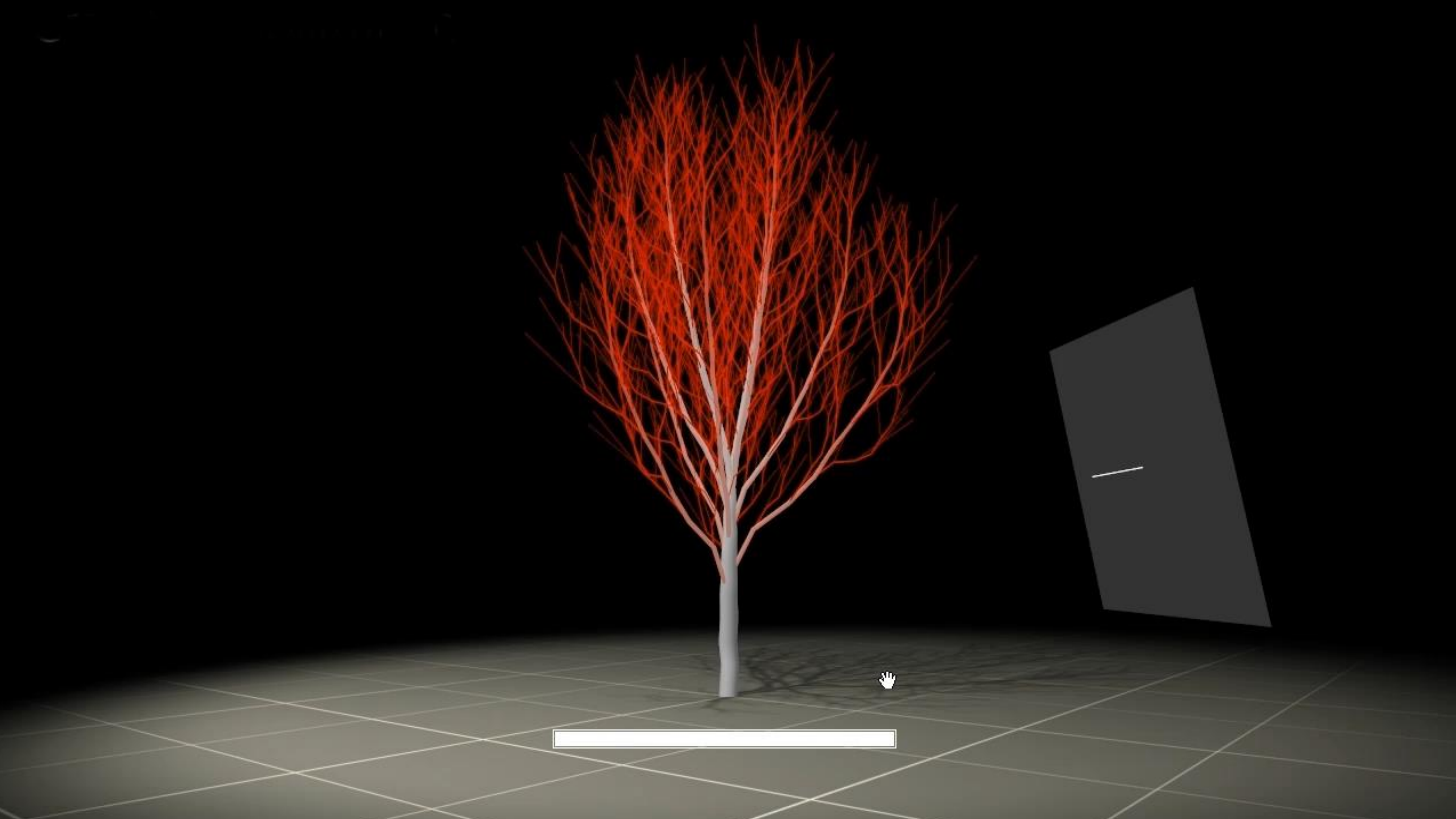
$$P_{i-1} = -\sum k_i F_{Ri}$$

Leaf Force

$$L = S_l \sigma \nu c$$



[Sakaguchi and Ohya 1999]



Breaking of Branches

- Branch breaks when the acting forces exceed a certain level of stress
- Wood is a highly inhomogeneous material
- Approximating Young's Modulus and Hook's law

Young's Modulus Coefficient

Bending Moment

Stress

$$\sigma = \frac{4cM}{3\pi r^2}$$

Branch Radius

Stress (Young's Modulus)

$$\sigma_{max} = d^3 p$$

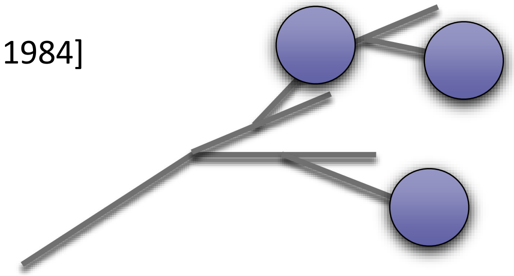
Material Property

Branch Thickness

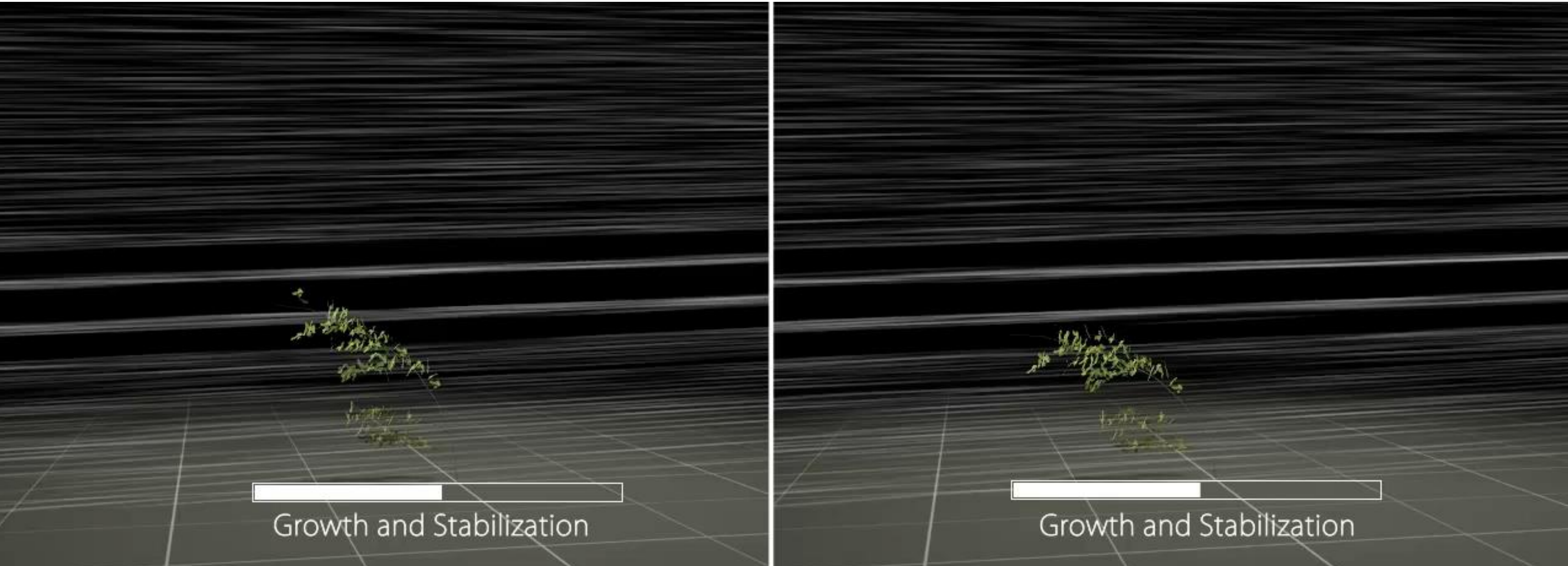
Bud Abrasion and Drying

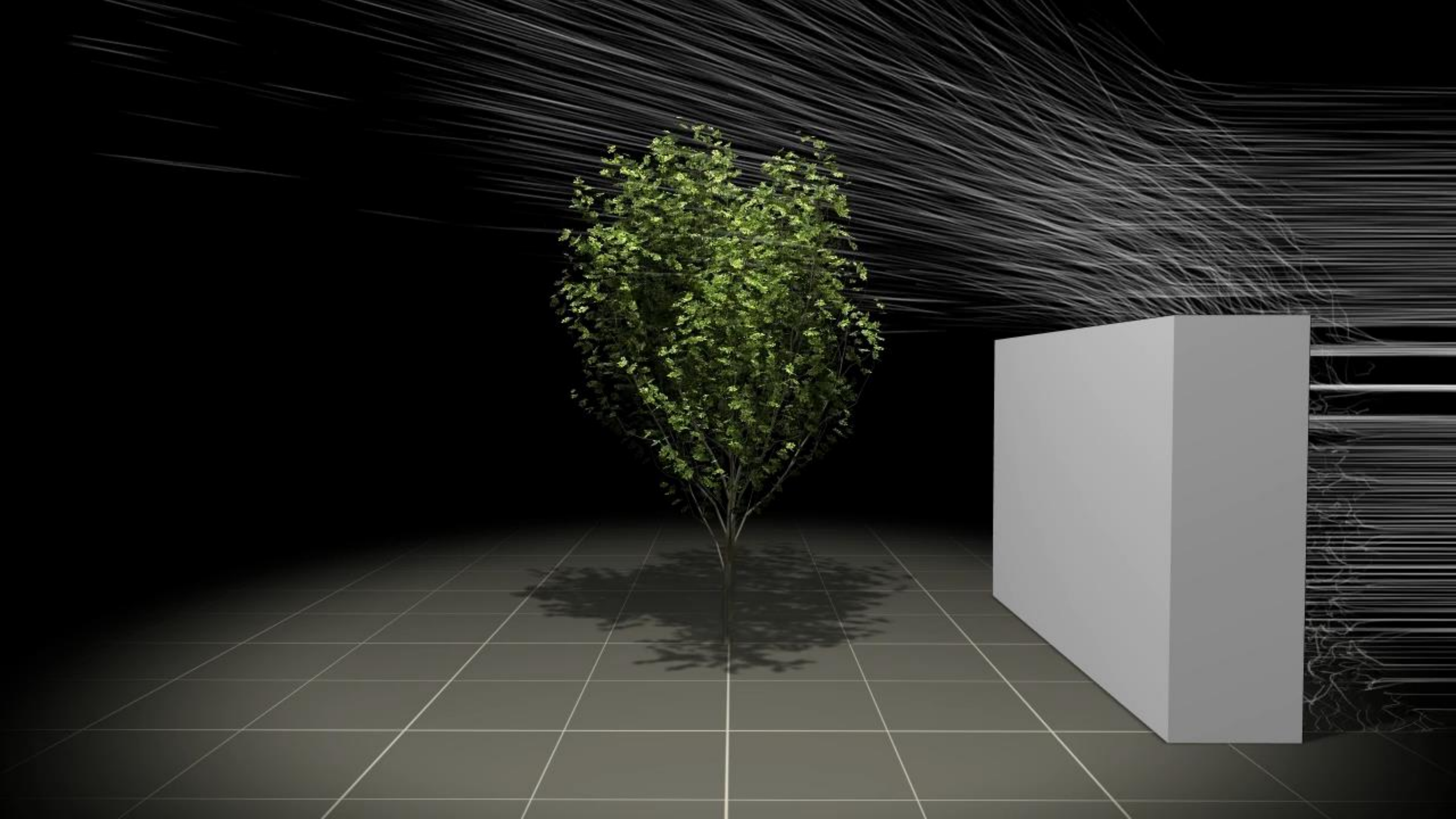
- Wind dries out or abrades buds
- Detect particles and neighboring branches
- User-defined threshold to terminate buds

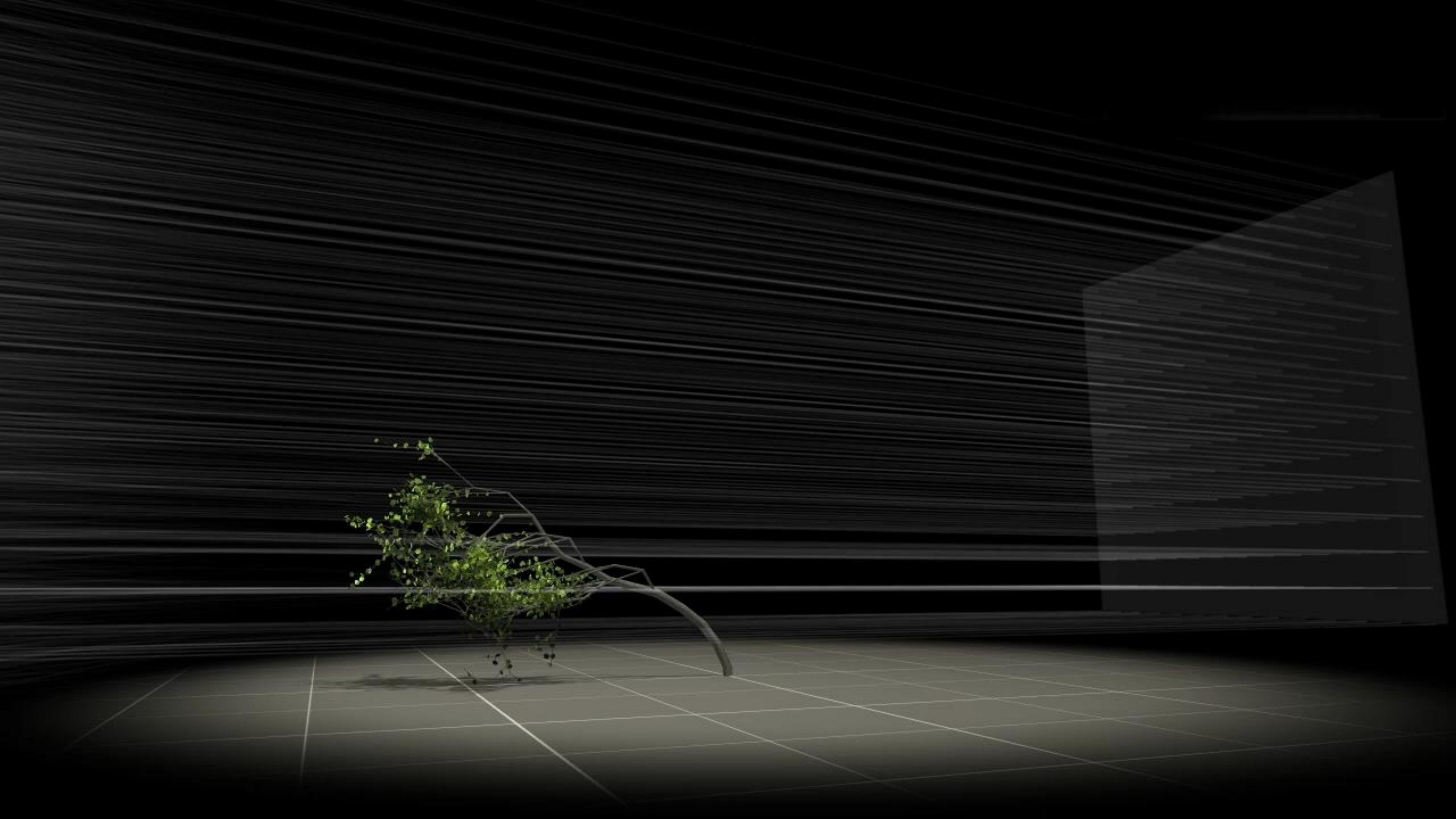
[Putz and Parker 1984]

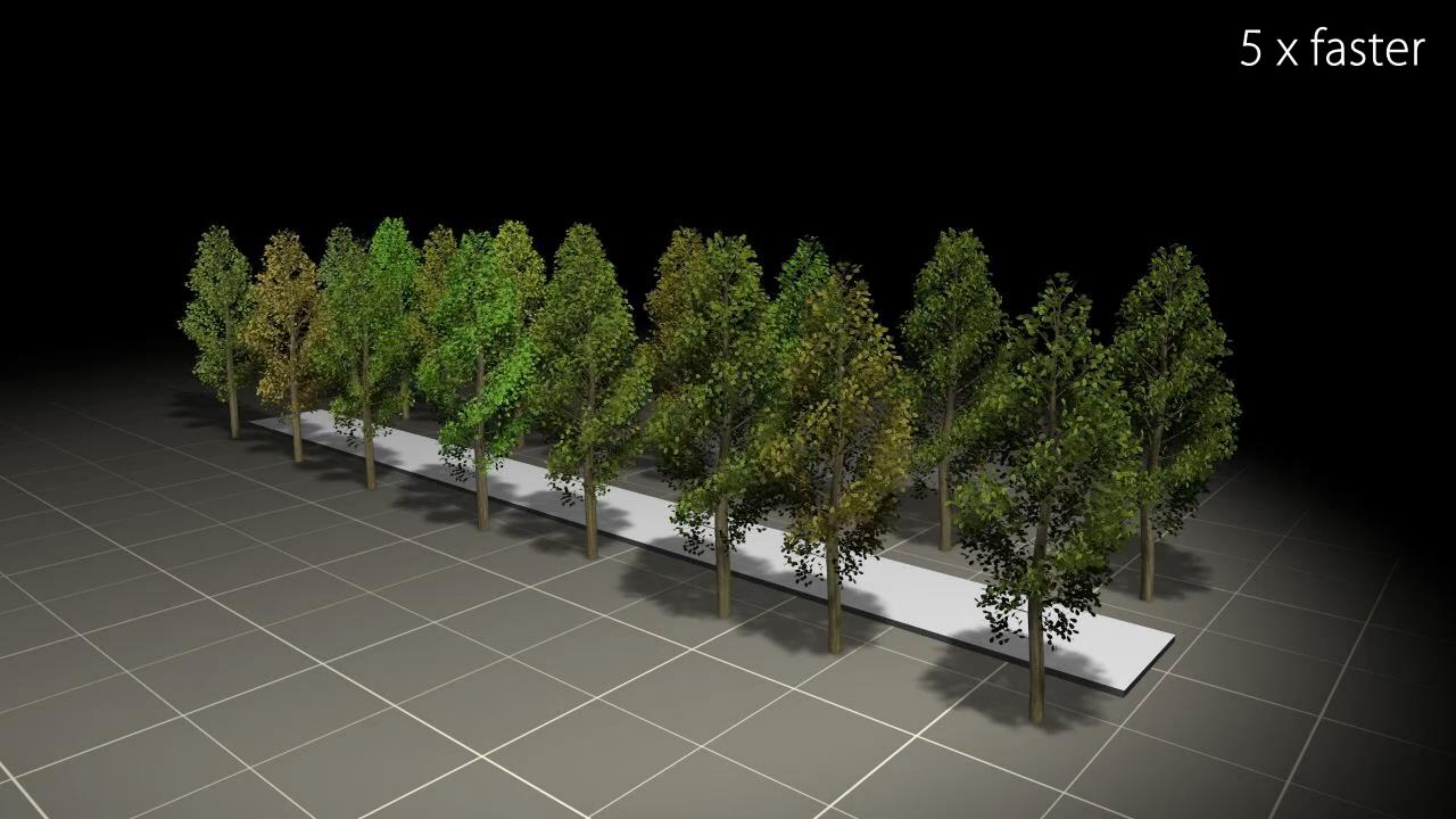


Off On








5 x faster

Modeling Plant Life in Computer Graphics

Reconstruction and Inverse Procedural Modeling

Siggraph 2016 Course

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Overview

Reconstruction and Inverse Procedural Modeling [30 minutes]

- From CT scans, flowers **(Ijiri)**
- From point sets **(Pirk, Chen)**
- Inverse Procedural Modeling **(Mech, Benes)**

Flower Modeling via X-ray Computed Tomography

- Takashi Ijiri, Shin Yoshizawa, Hideo Yokota, Takeo Igarashi. **Flower Modeling via X-ray Computed Tomography**, ACM Trans. Graph. Volume 33, Issue 4, Article No. 48, July 2014.

Background

Flower and plant modeling is important topic in CG

- CG Scene design / Simulation / Electric encyclopedia

Flower modeling is difficult

Many free-form components

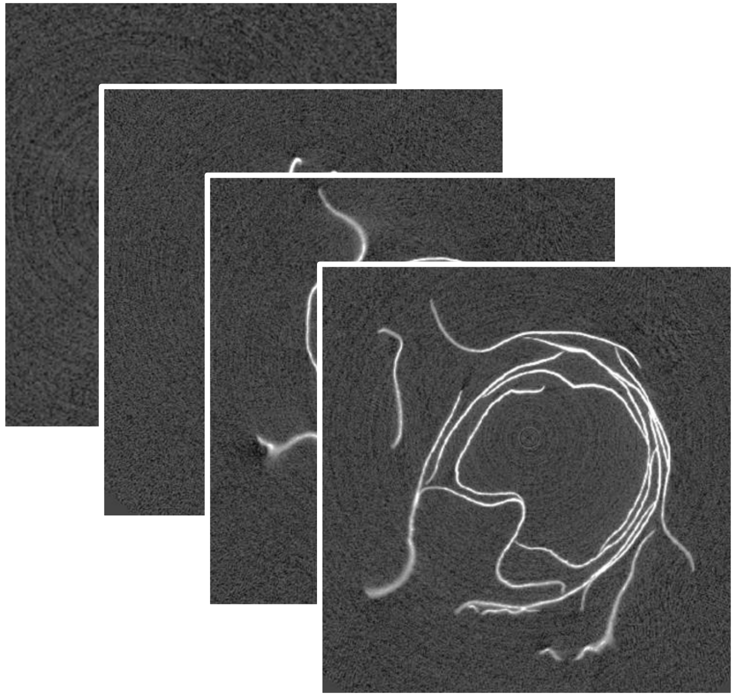
Occluded structure

Goal- Reconstruct complicated and realistic flowers

Approach- Use X-ray CT

Fix a sample
on a tube

Scan the sample by industrial CT
Matsusada precision: *μRay8700*

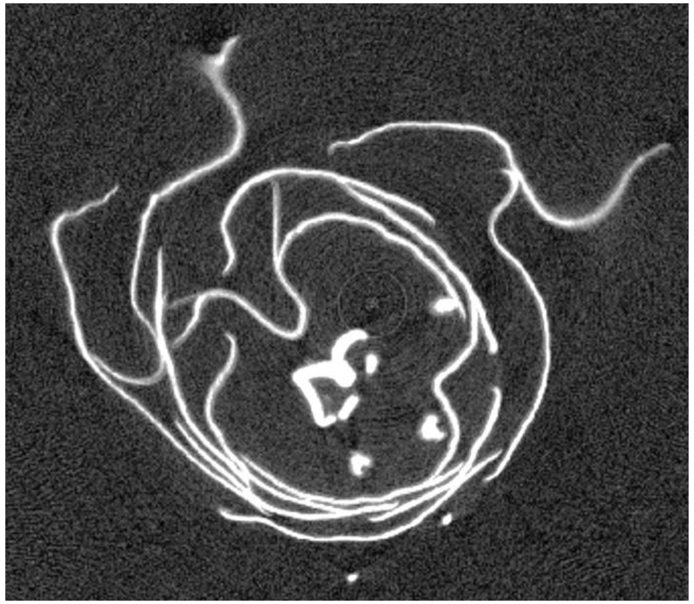


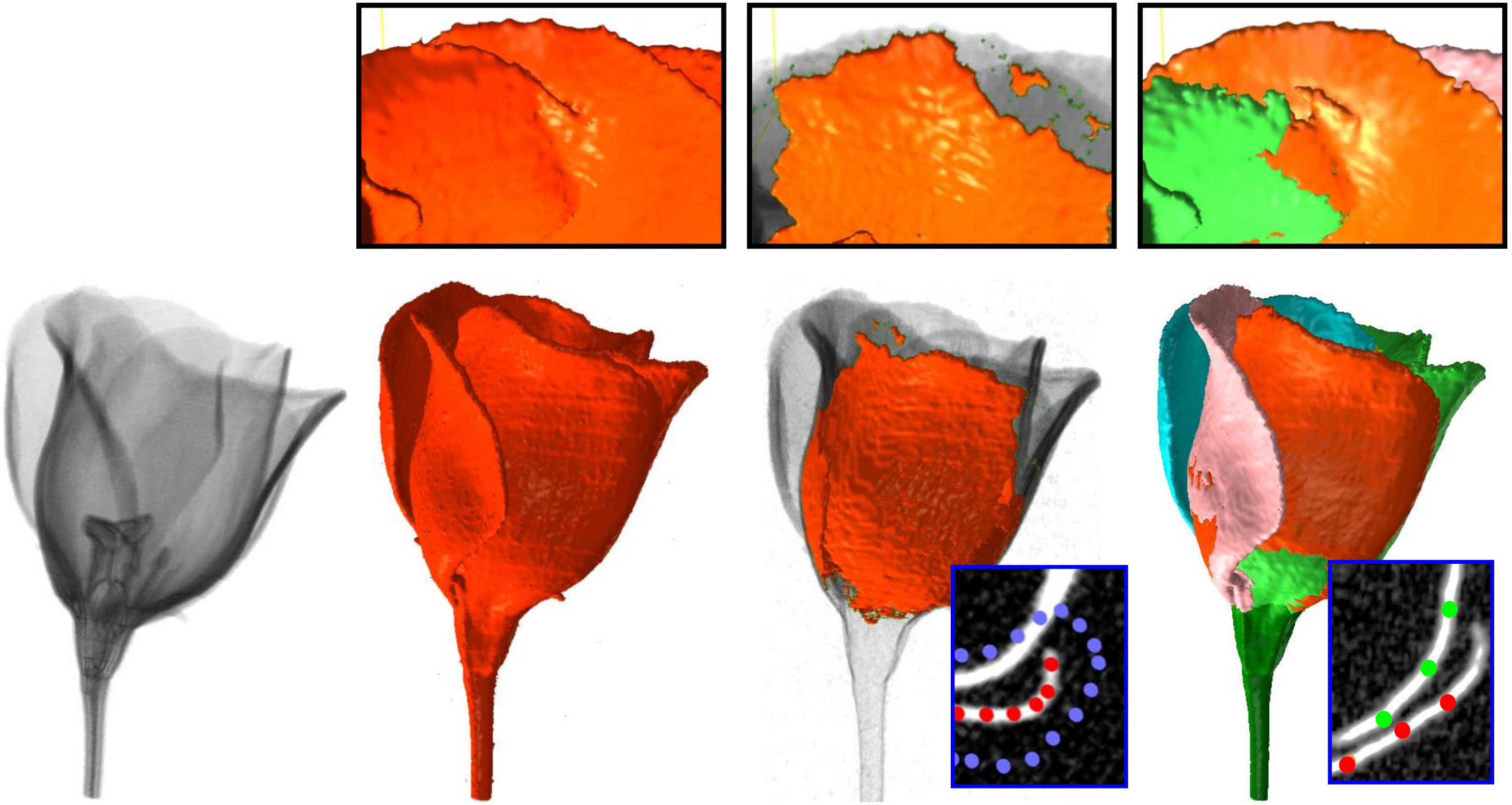
Obtain occlusion-free
flower CT volume image

Challenge – Segment volume into flower components

Flower components

- Thin shapes
- Similar CT intensity
- Contact one another



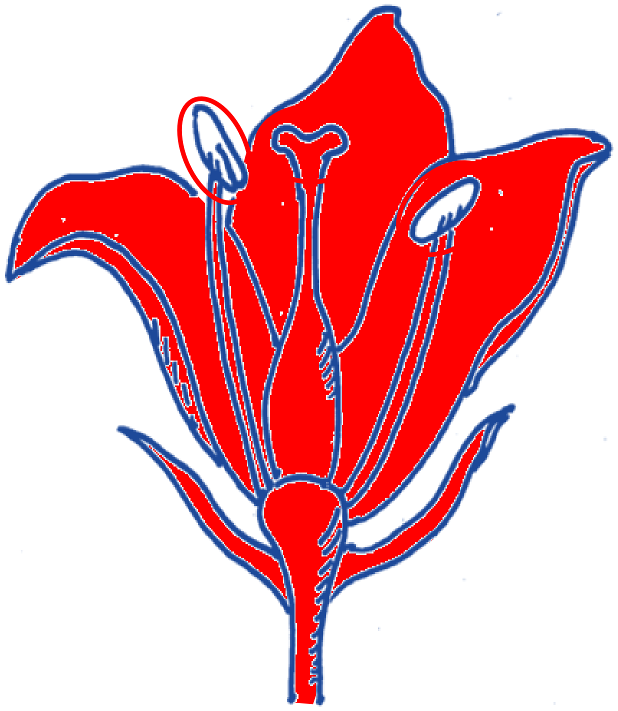


Iso surface [Lorensen et al 1987]

Graph Cut [Boykov et al 2001]

Region Grow [Adms 1994]

Key idea – Approximate flower components with simple **primitives**



Pistils

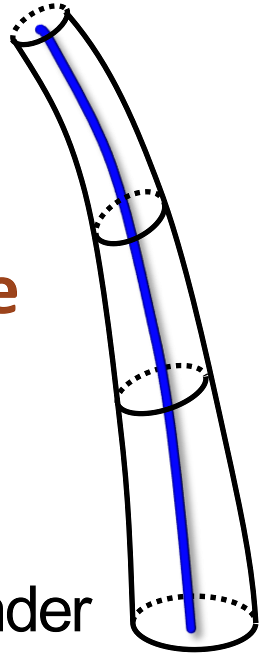
Stamens

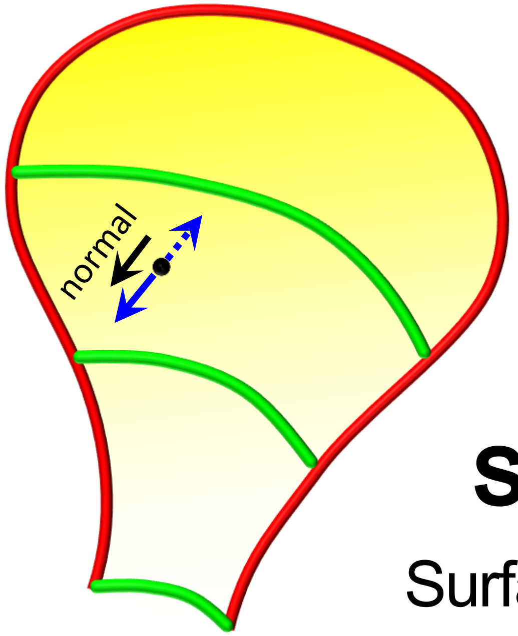
Receptacle

Stem

shaft

Curved cylinder radius varies along axis





Petals

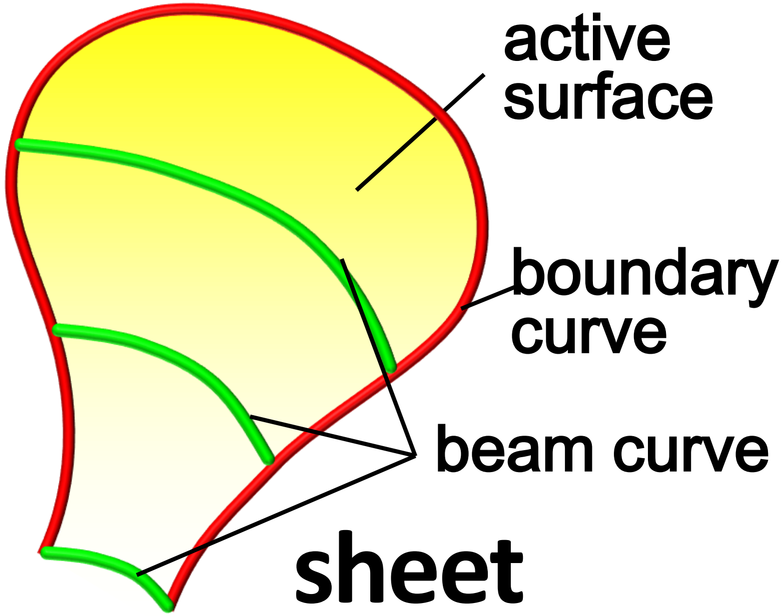
Sepals

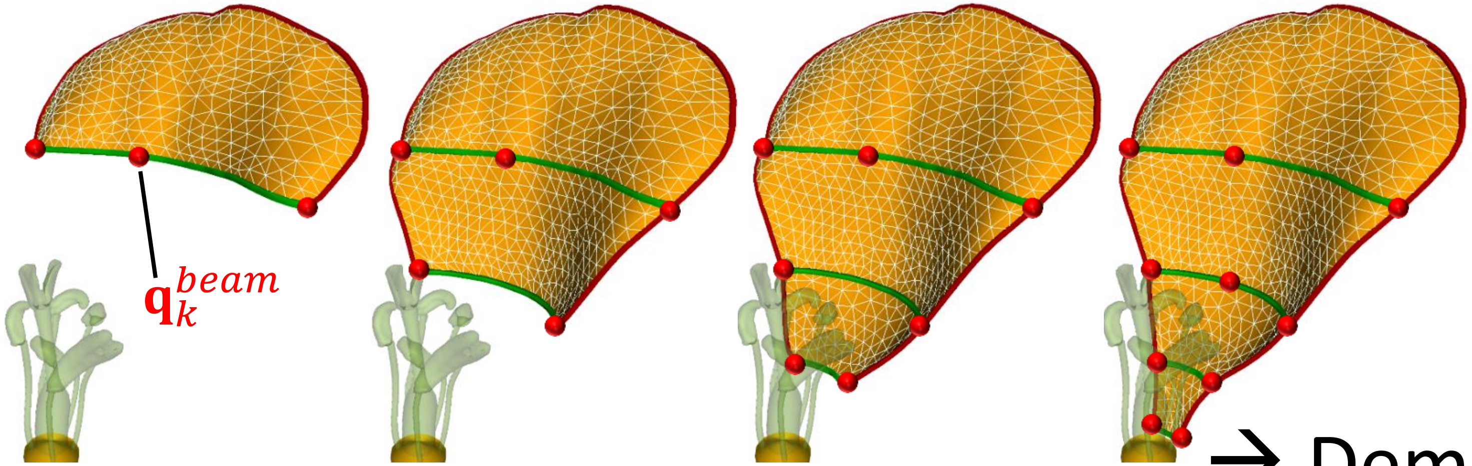
sheet

Surface with adaptive thickness

- Present a UI to place primitives
- Present novel active curve/surface to fit primitives

Modeling Petals & Sepals





→ Demo

Petal often appears as a curve on a horizontal cross section

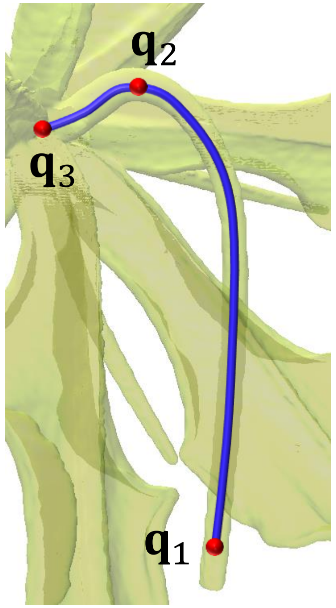
The user places CPs on a curve of the target petal

→ Beam/boundary curves & active surface is computed

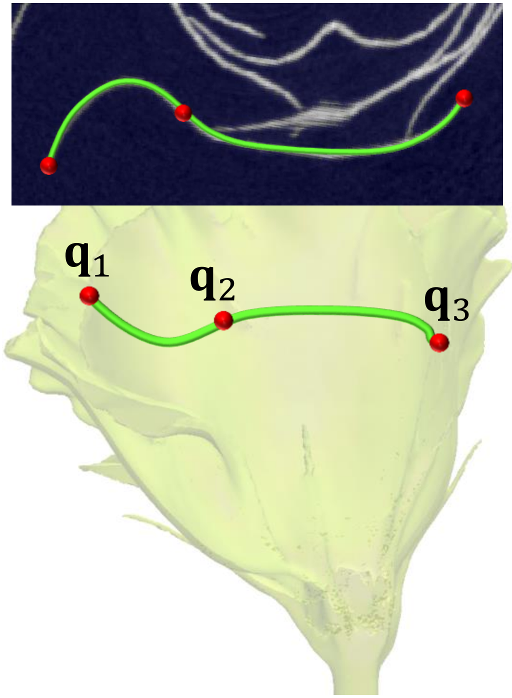
Active curves $\mathbf{C}(t)$

Interpolate CPs $(\mathbf{q}_1, \mathbf{q}_2, \ldots, \mathbf{q}_M)$ smoothly

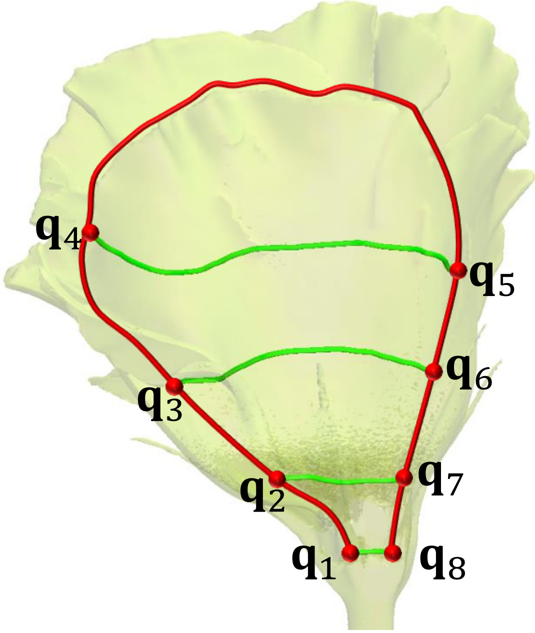
Trace their targets regions



Shaft axis



Beam

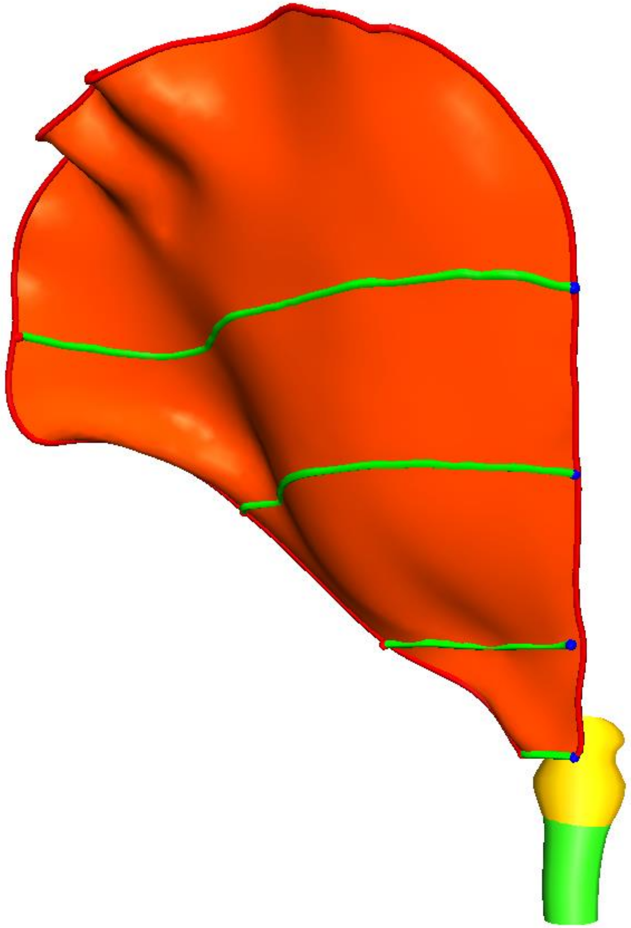


Boundary

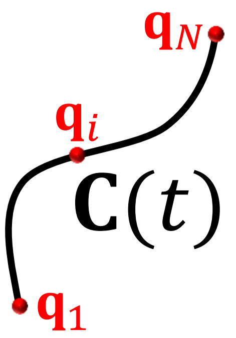
Active surface $\mathbf{S}(u, v)$

Interpolate curve network

Trace target region



Active curves / surface energies



$$E_c = \int_{\Omega_c} \frac{1}{2}|\mathbf{C}''(t)|^2 \quad + \quad \alpha|\mathbf{C}'(t)^T \boldsymbol{\mathcal{M}}(\mathbf{C}(t))\mathbf{C}'(t)|dt$$

Smoothing effects

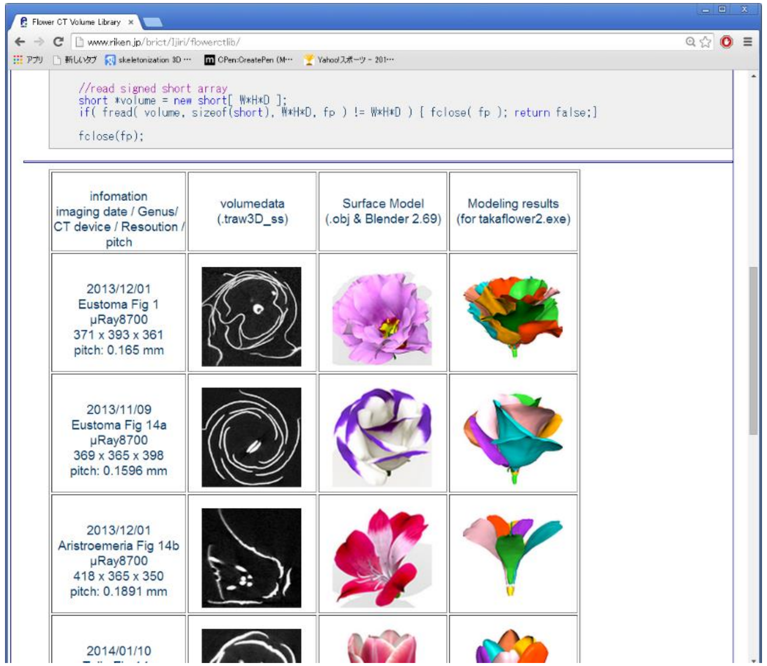
$\mathbf{S}(u, v)$

$$E_s = \int\int_{\Omega_s} \frac{1}{2}(\mathbf{S}_{uu}^2 + 2\mathbf{S}_{uv}^2 + \mathbf{S}_{vv}^2) \; + \; \beta|\boldsymbol{\mathcal{B}}\mathbf{S}_u \times \boldsymbol{\mathcal{B}}\mathbf{S}_v|dudv$$

Results

Present a flower modeling method via X-ray CT scanner

Achieved to reconstruct flowers with complicated structures



Our CT volumes are available

Google “Flower CT volume library”

Texture-lobes for tree modelling

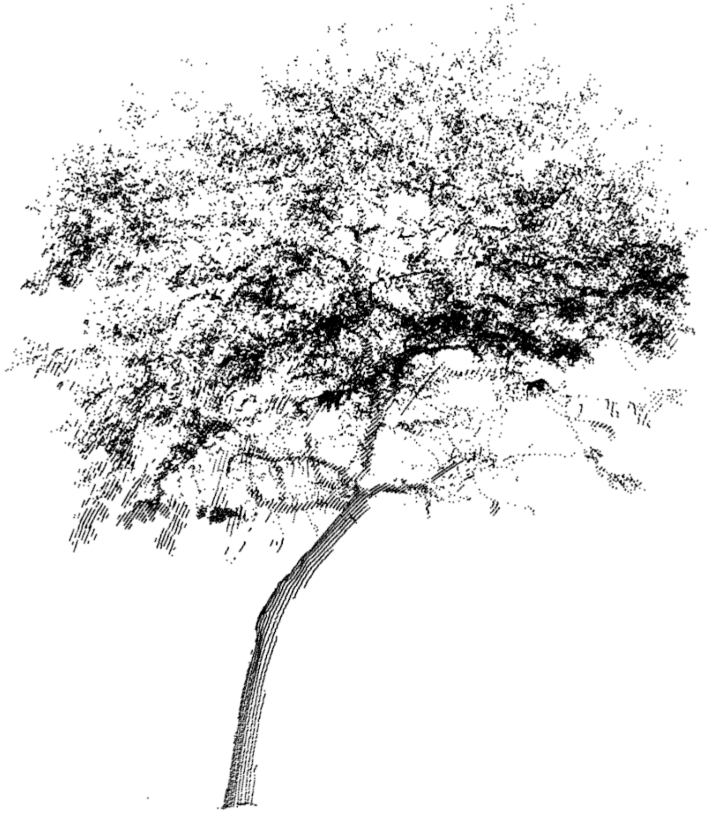
- Livny, Y., Pirk, S., Cheng, Z., Yan, F., Deussen, O., Cohen-Or, D., Chen, B. (2011) **Texture-lobes for tree modeling**. ACM Trans. Graph. 30, 4, 53:1–53:10.

Reconstruction of Urban Scenes

LiDAR-Scanner

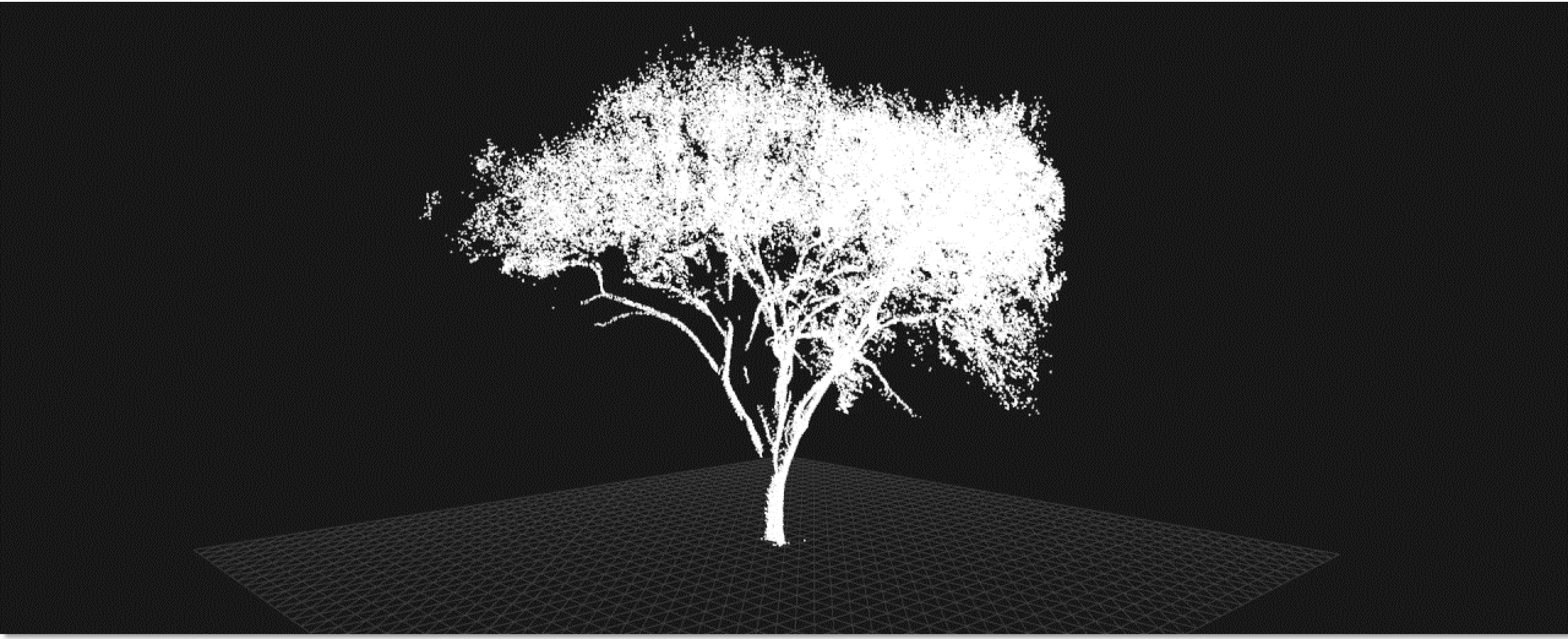
Real Tree

Scan

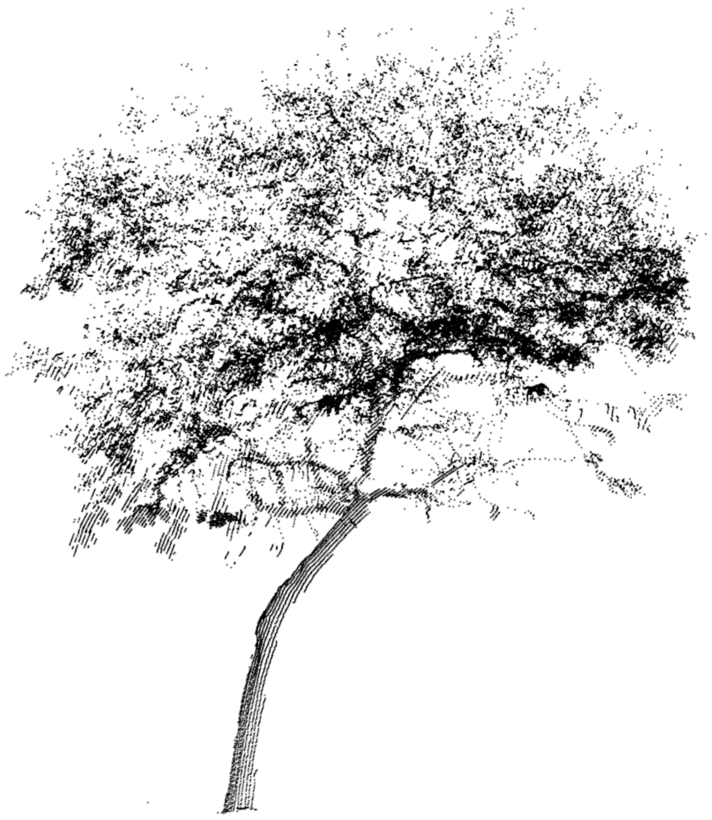


3D Point Cloud

3D Point Sets



From Point Sets to Meshes



3D Point Cloud

→ ?

3D Tree Model

A Tree is Complex

Human visual bandwidth is limited → abstraction

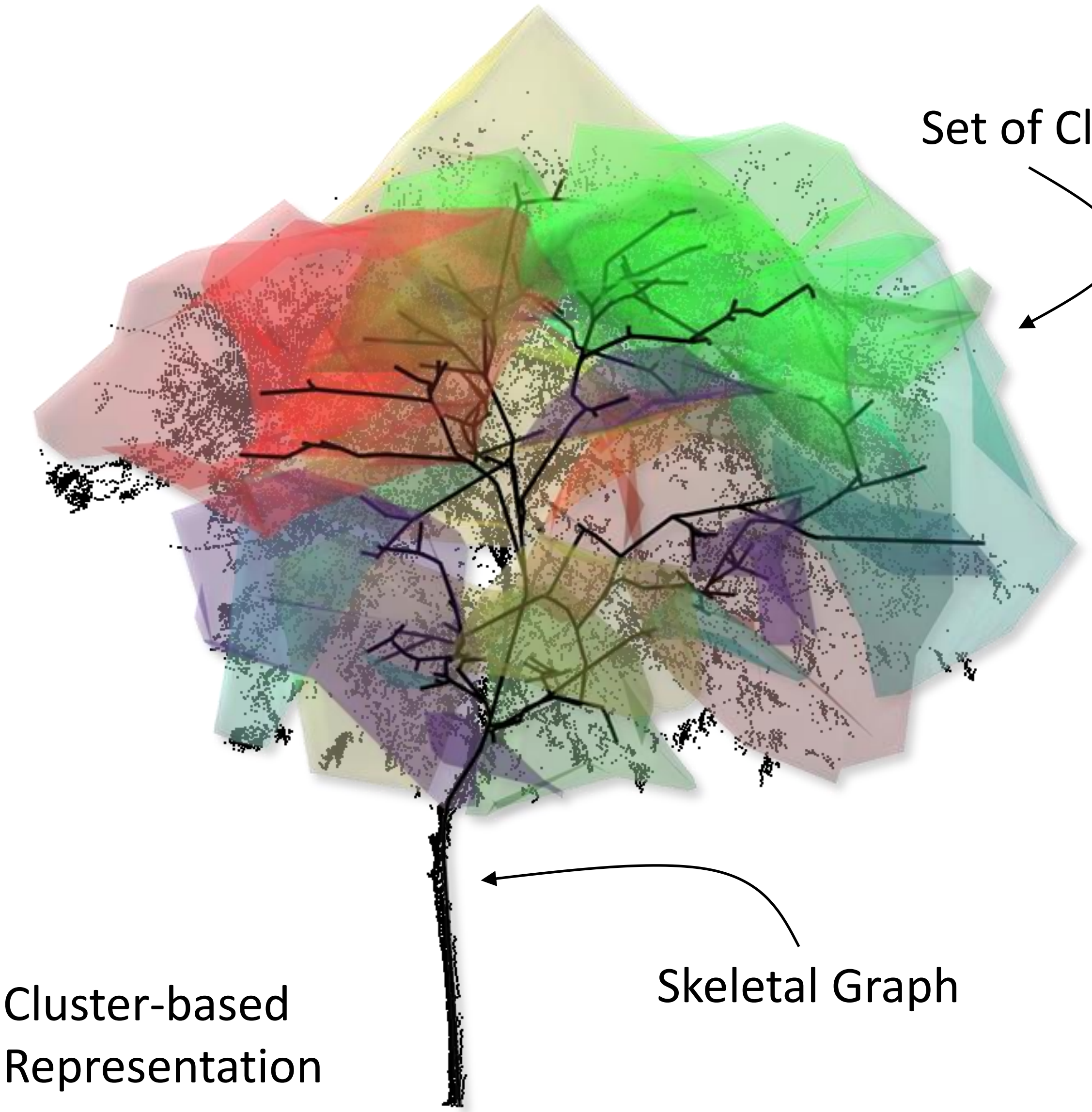
Cluster-based Representation

Separate leaf-points and branch-points.

Minimum-weight spanning tree over the input.

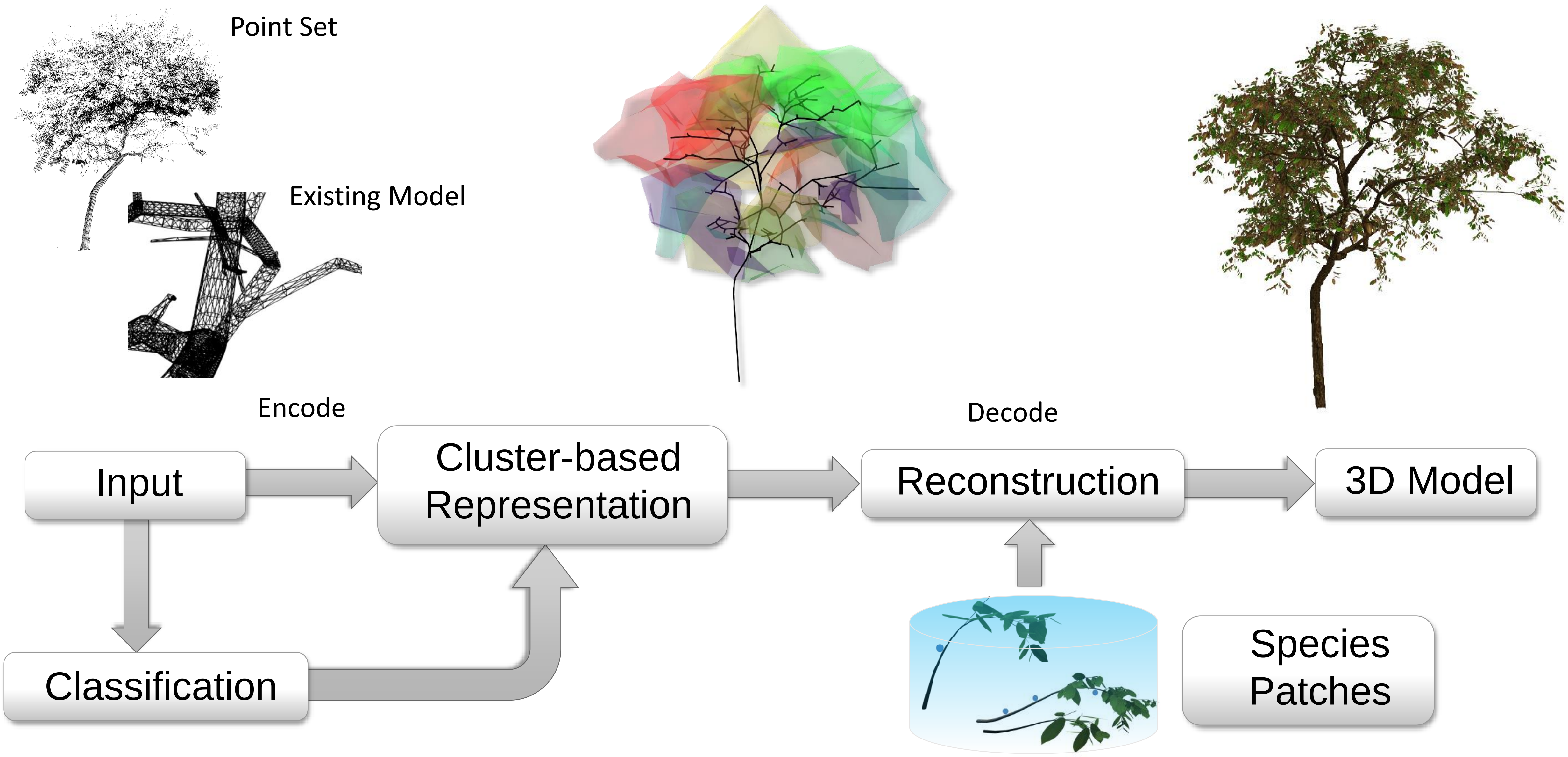
Determine thickness of branches based on allometric rules.

[Livny et al. 2011]



Render the Possibilities
SIGGRAPH2016

Pipeline



Resource Requirements

~30 kB

Cluster-based Representation

+

~100 kB

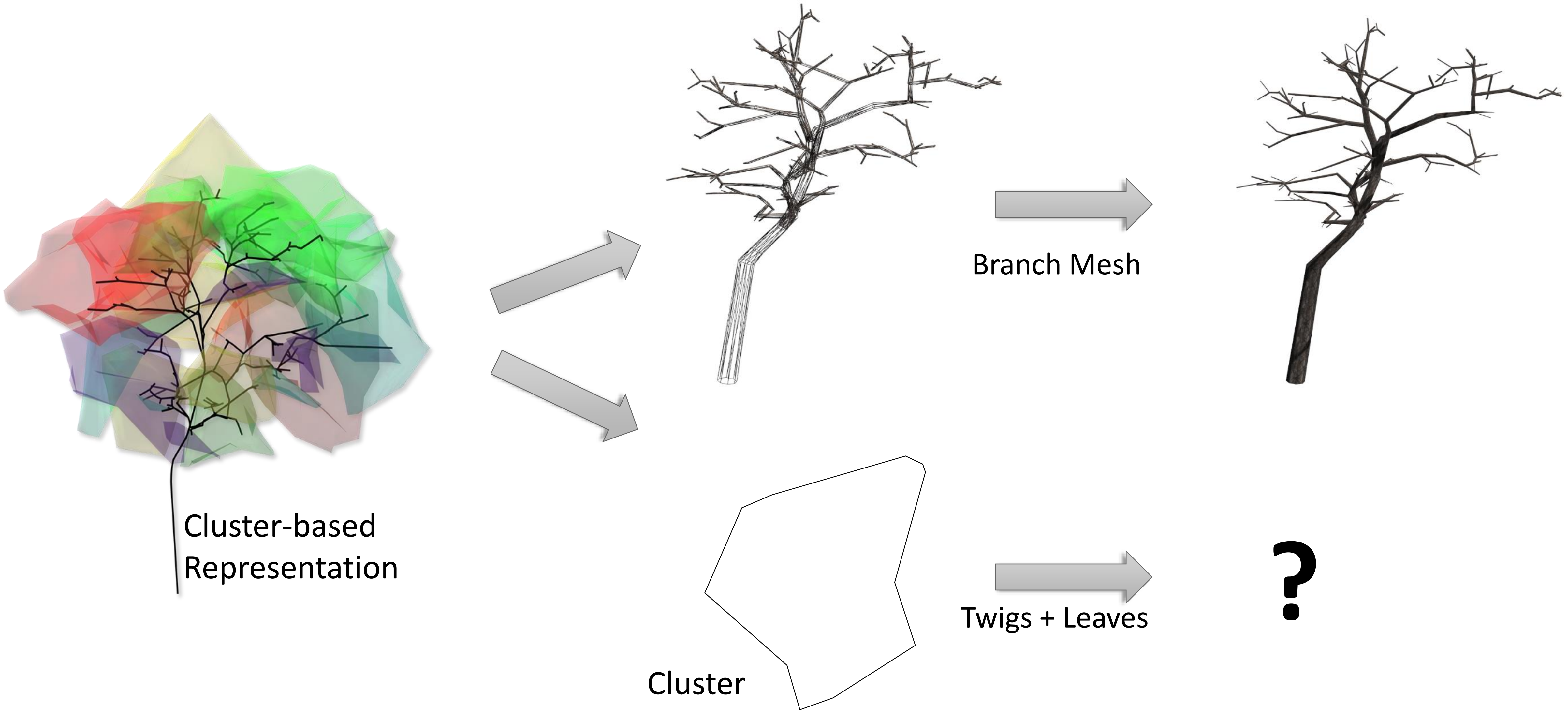
Species Information

=

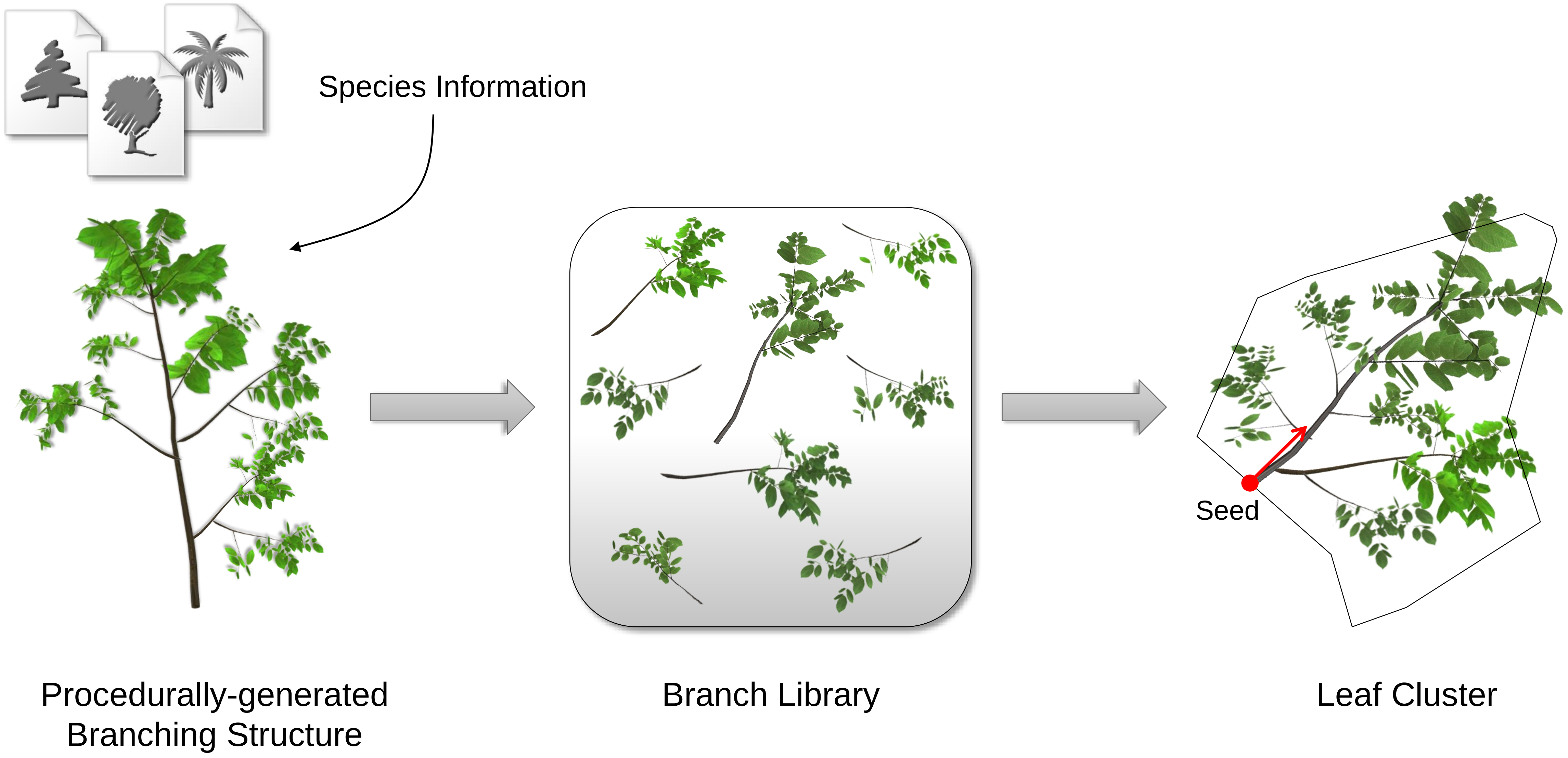
~60 MB

Reconstruction

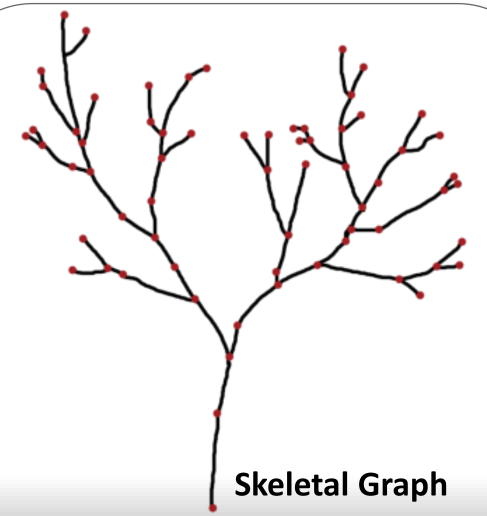
Reconstruction



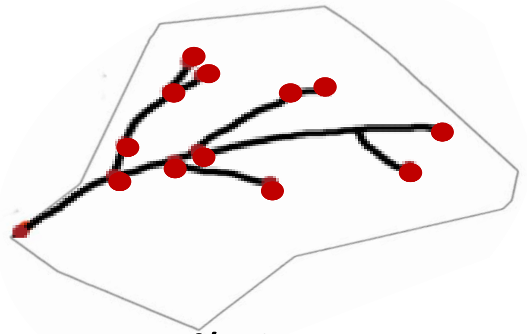
Geometry Synthesis



Mesh Construction

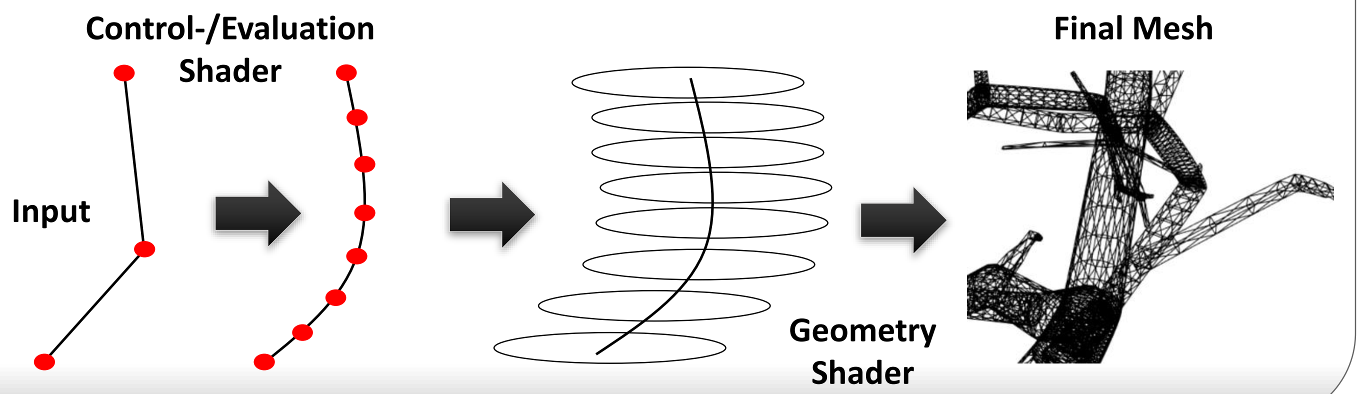


Skeletal Graph

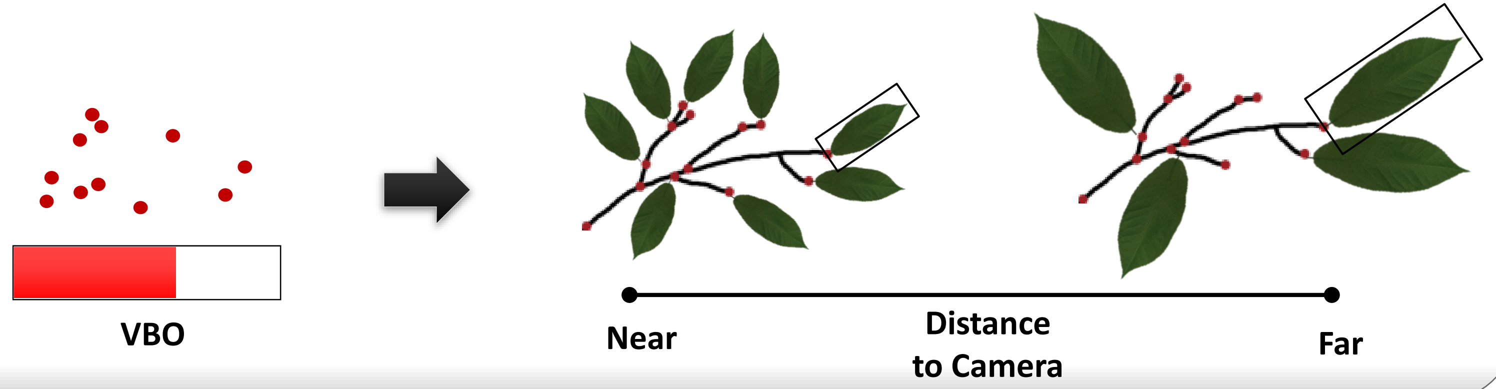


Leaf/Twig Data
(Cluster Reconstruction)

Branches: Mesh Generation [Bloomenthal 1985]



Leaves



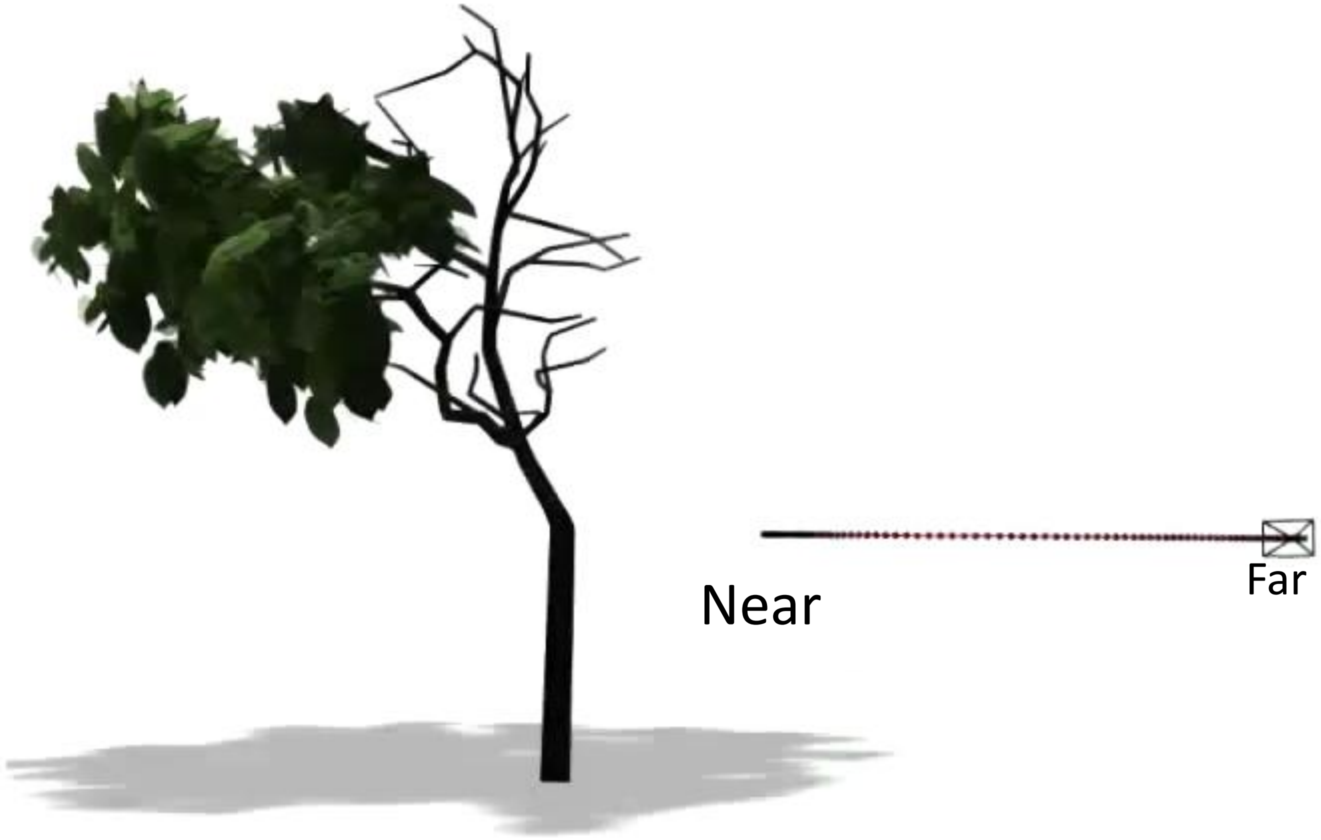
CPU | GPU

Dynamic Level of Detail

Render the Possibilities
SIGGRAPH2016

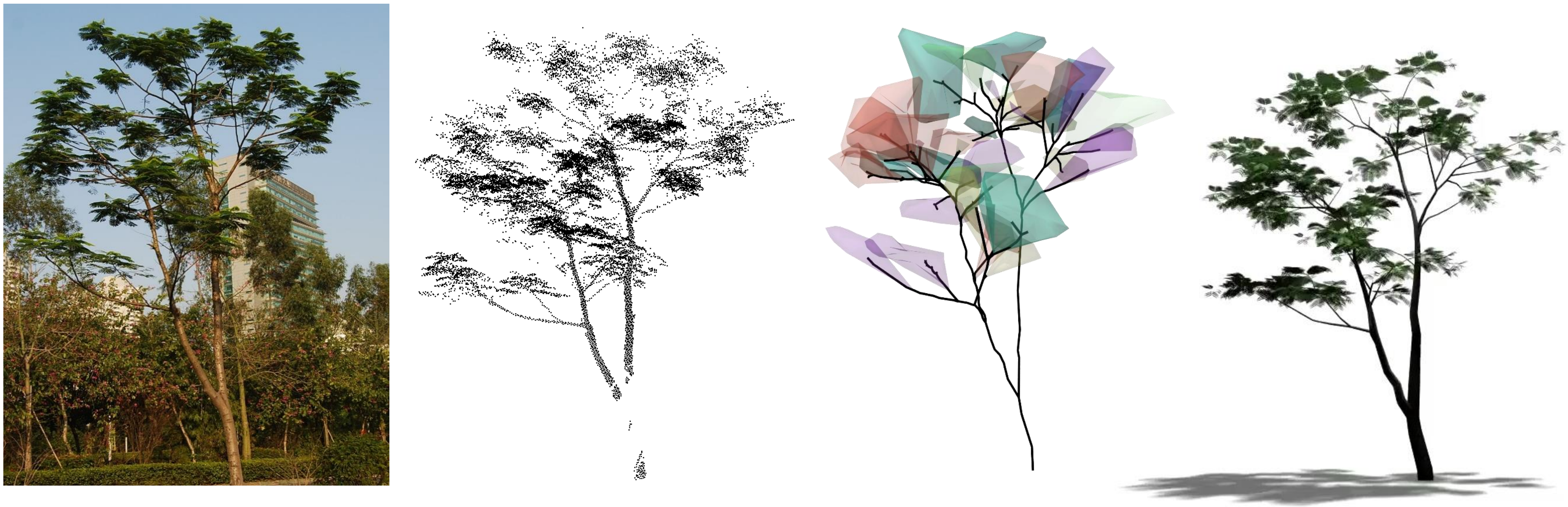
[Cook et al. 2007]

Camera View



Object View

Results: Delonix



Urban Reconstruction

Analyzing Growing Plants from 4D Point Cloud Data

- Li, Y. Fan, X., Mitra, N. J., Chamovitz, D., Cohen-Or, D., Chen, B. (2013). **Analyzing growing plants from 4D point cloud data**. *ACM Trans. Graph.* 32, 6, Article 157

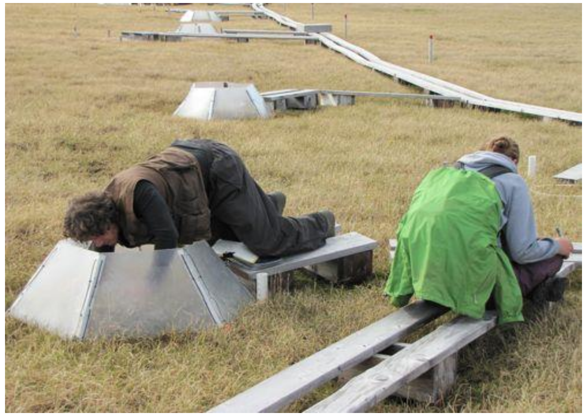
Time-lapse images of growing plants

Video courtesy to [Neil Bromhall] on Youtube: [Sycamore seedling growing time lapse]

Time-lapse of 3D Point Cloud (4D Point Cloud)

Charactering Plant Growth (1)

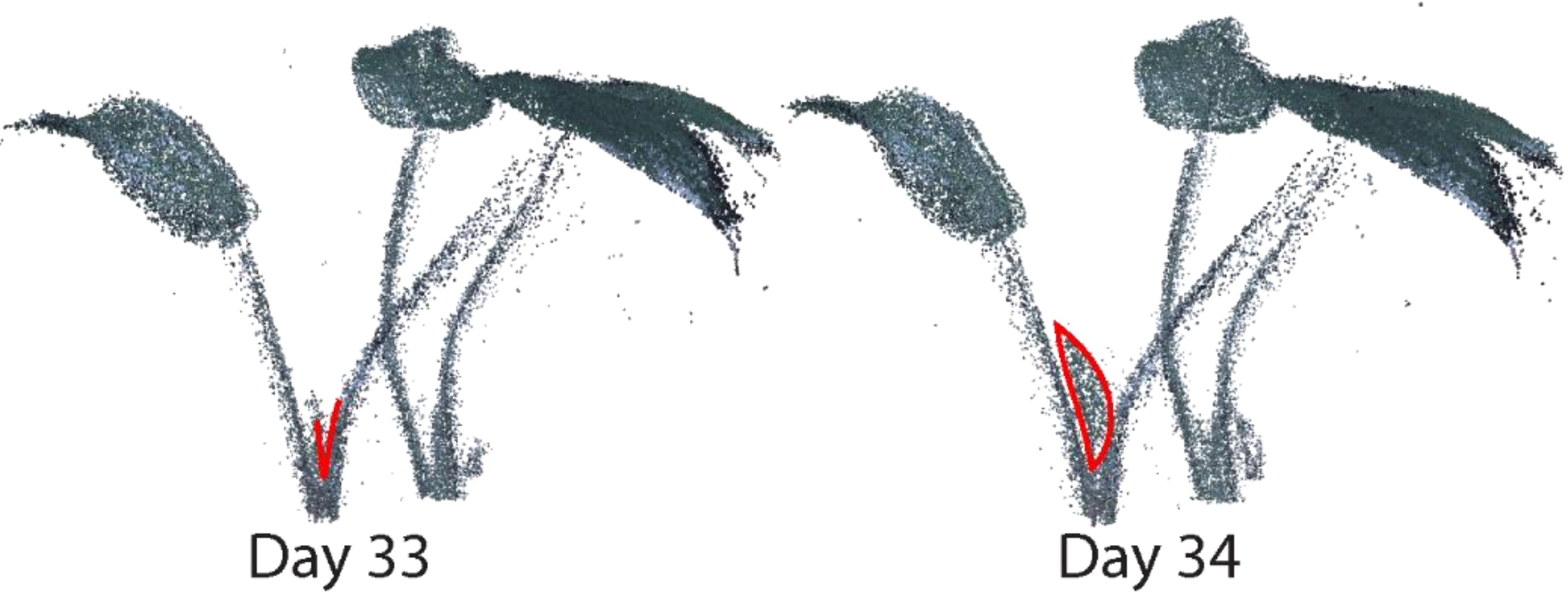
- Quantitative properties
  - Area, volume, etc.
  - Better in organ level




Huge amount of work!!!

Charactering Plant Growth (2)

- Growth events (qualitative changes)



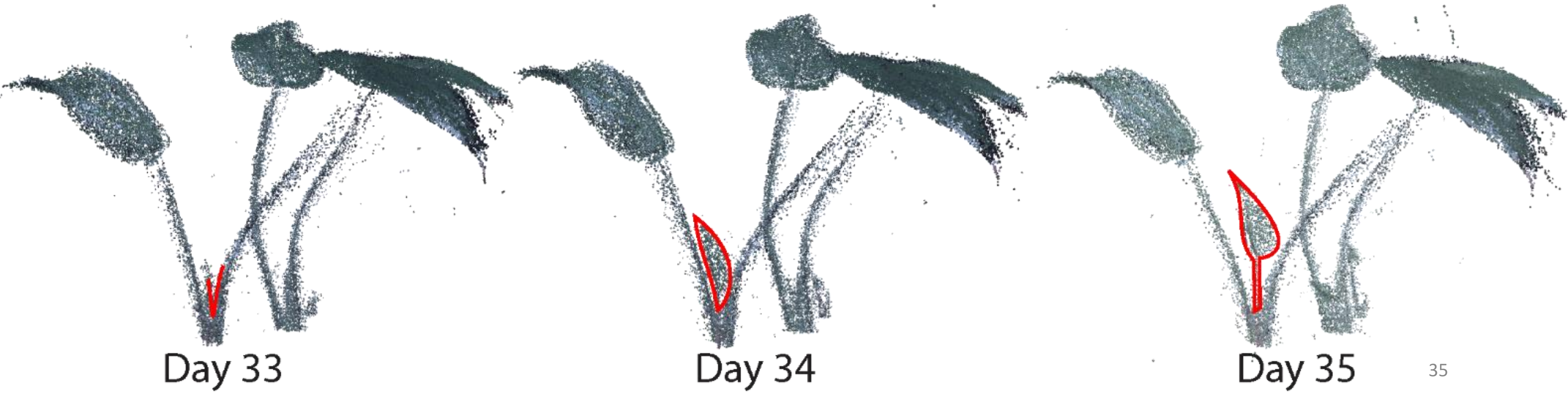
Bifurcation

Budding

Challenges

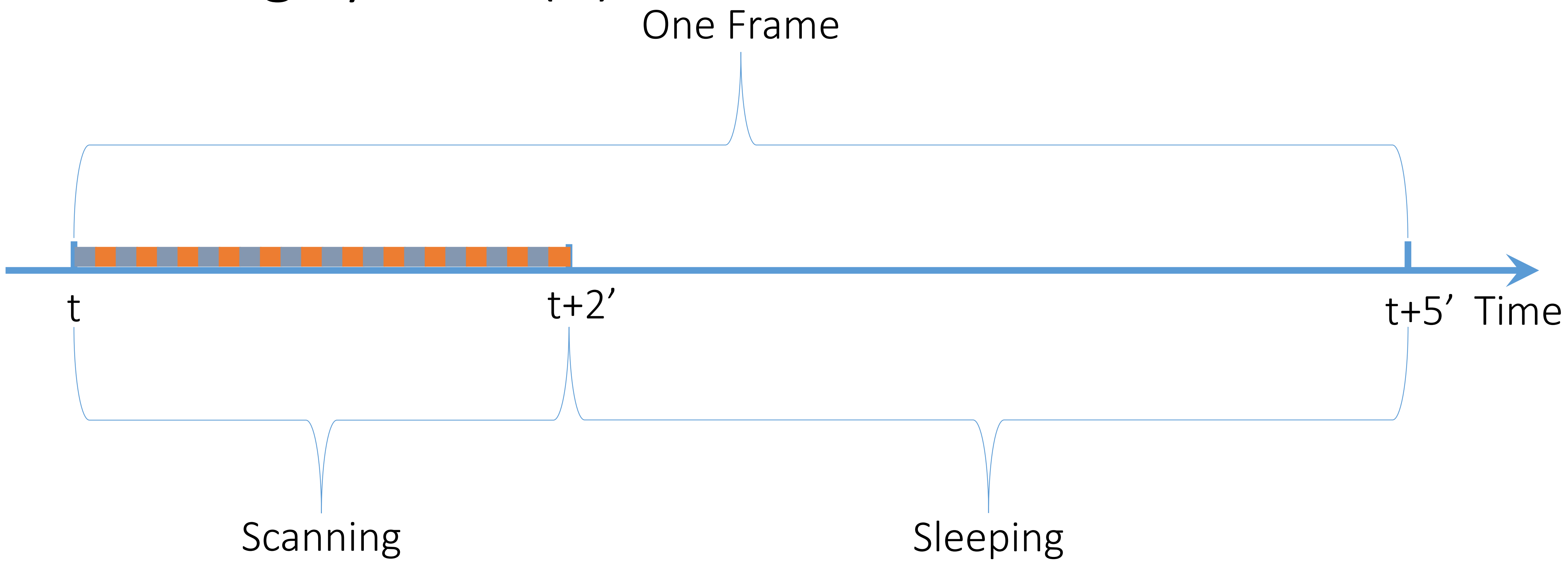
- Large deformation (violating incompressibility assumption)
- Large topology change
- No shape template

- Growth events
  - Subtle start (ending)
  - Similar, but not same
  - Ambiguities



Scanning system (1)

Scanning system (2)

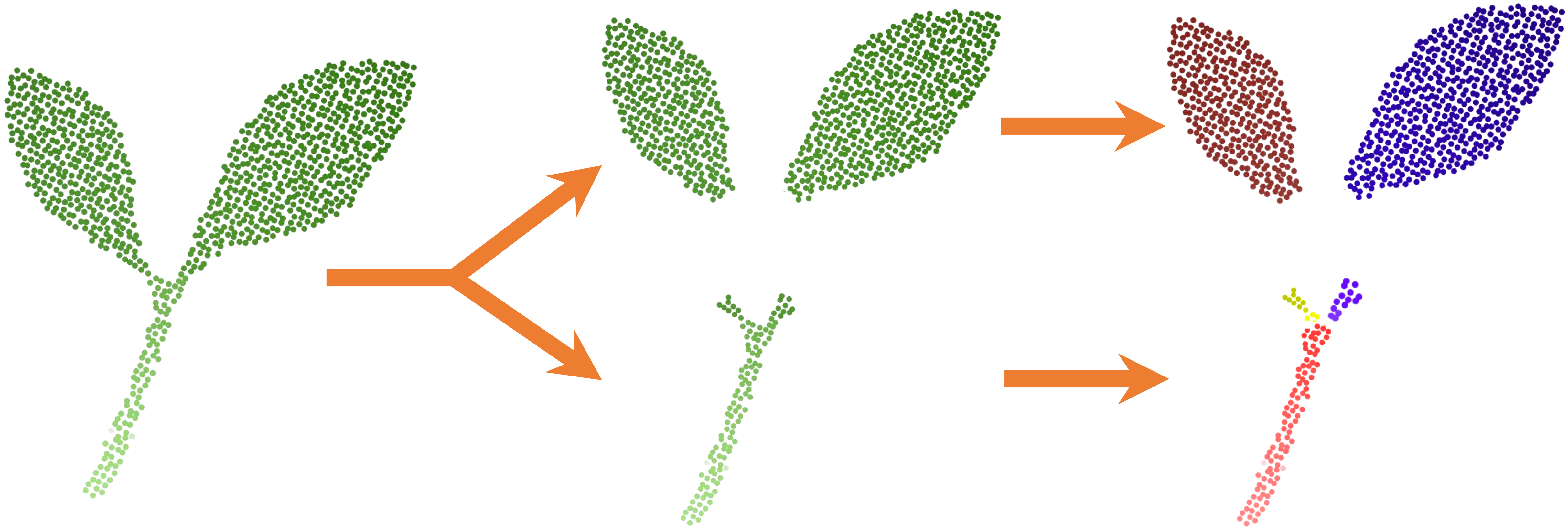


- structured light capturing
- turn table rotation (30°)

Detecting growth events → counting organ number

Counting organ number → point cloud segmentation

Algorithm pipeline: Two-stage Segmentation



Leaf-stem classification

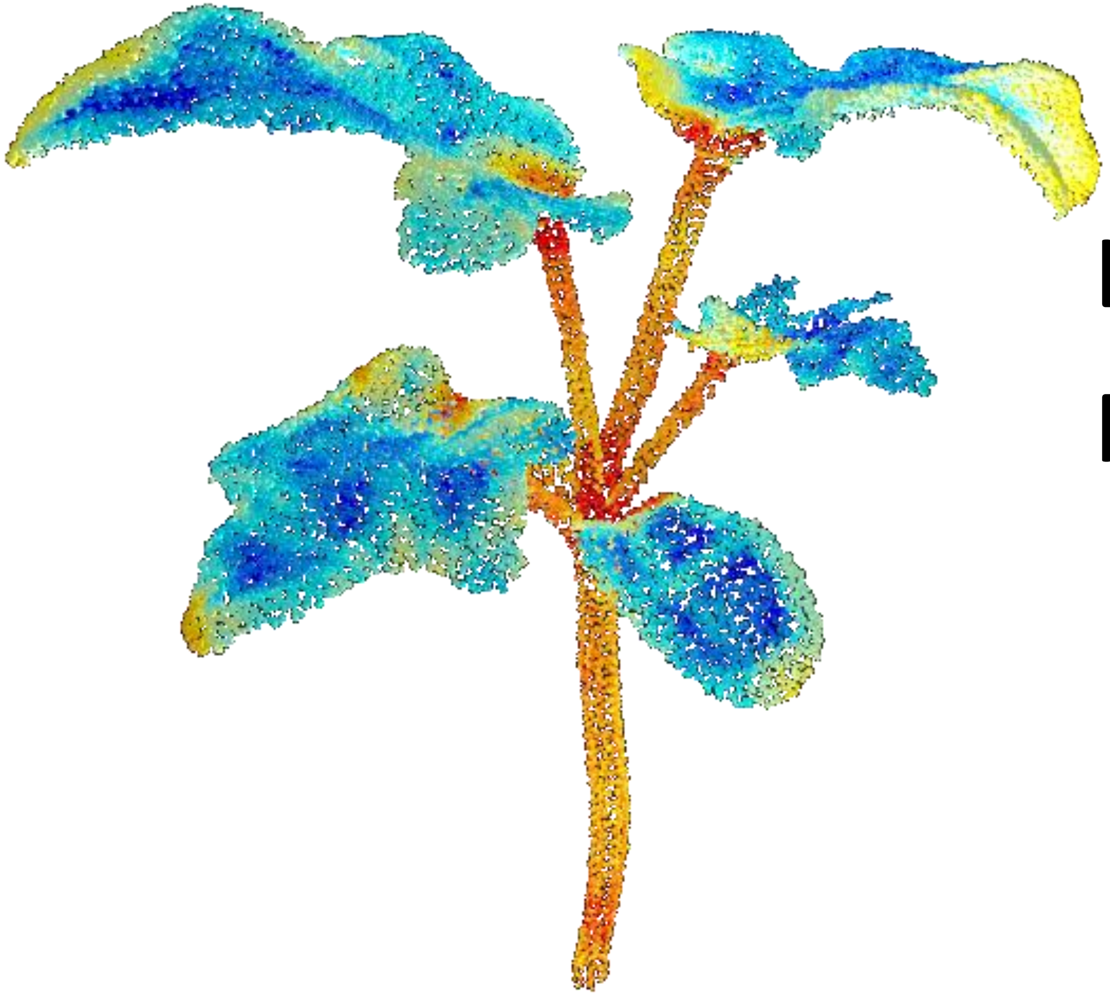
Binary labelling problem

Individual organ segmentation

Multi-labelling problem

Leaf-stem classification: discriminative feature

Render the Possibilities SIGGRAPH2016



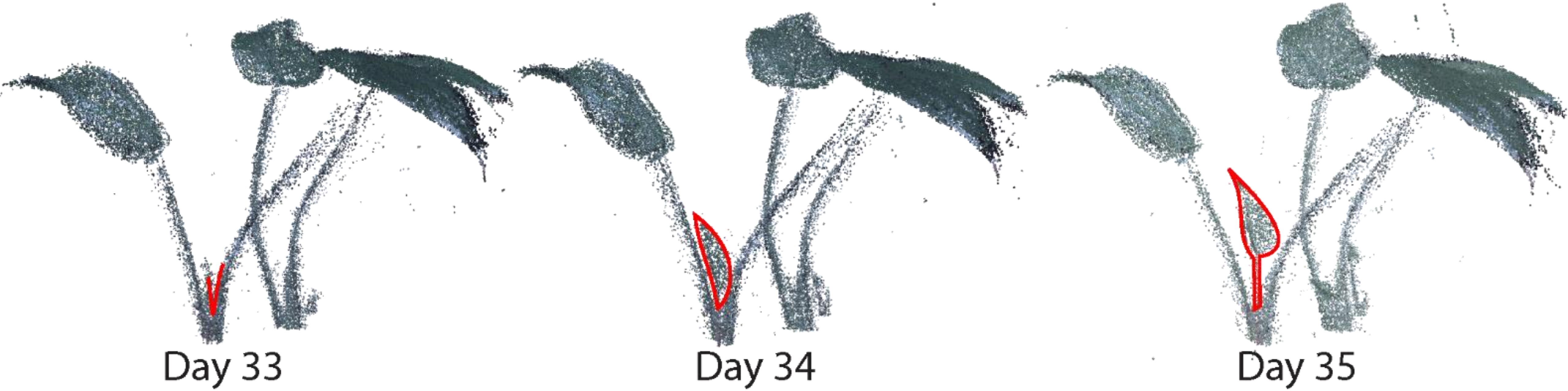
Leaves are more “flat”!

Find $f_B: P^t \rightarrow \{L, S\}$

$$f_B(p^t) = \begin{cases} S, \text{if } C(p^t) > t \\ \text{L, if } C(p^t) \leq t \end{cases}$$

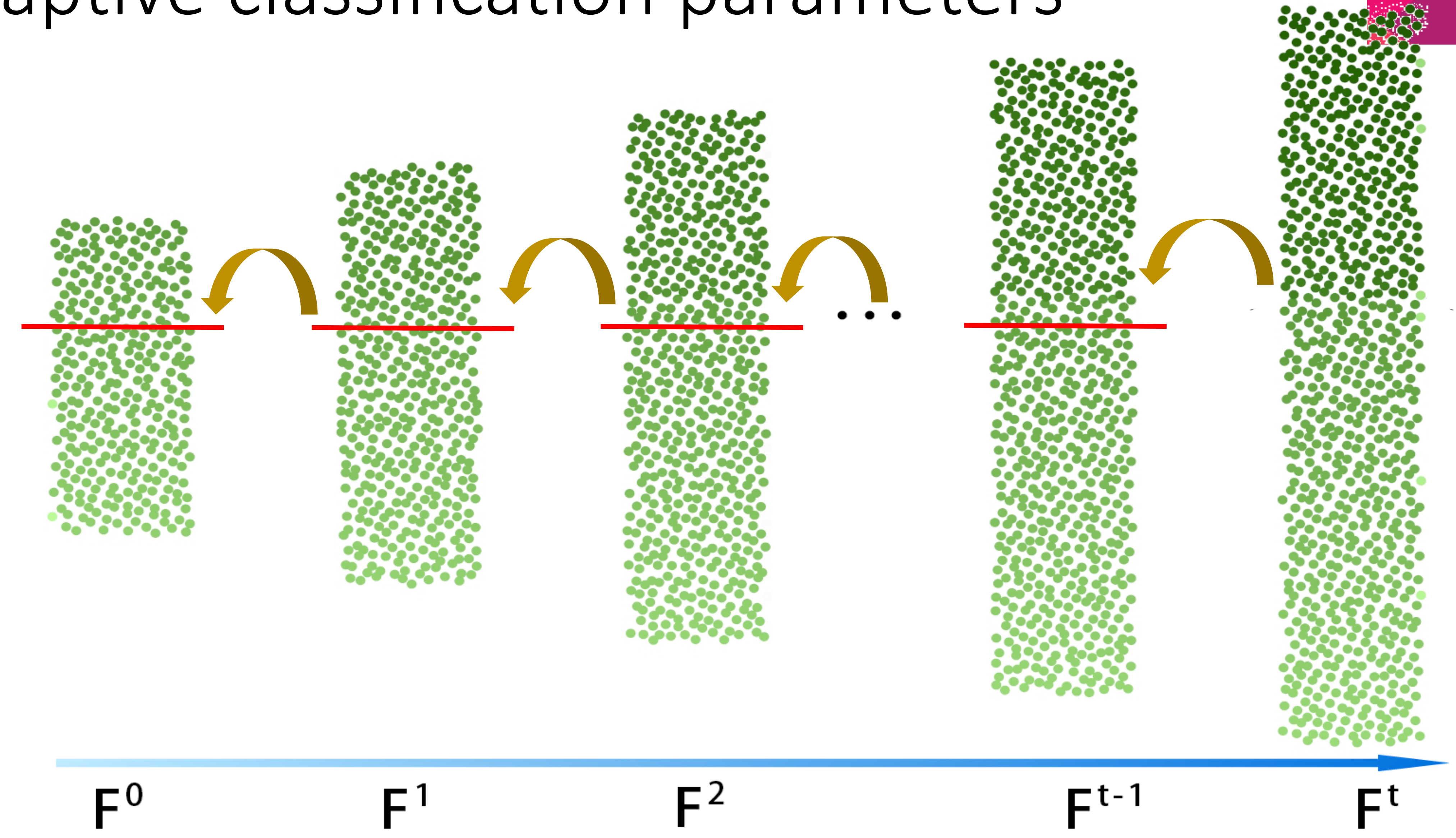
Curvature $C(p^t)$ of Plant Points

Mature leaves are more "flat" than stems.
New leaves can be less "flat" than some stems.



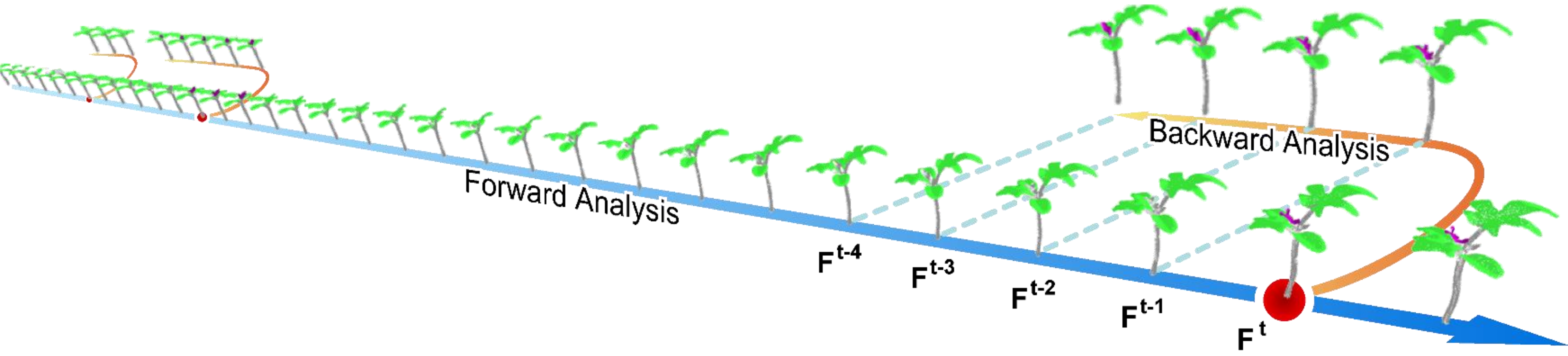
$$f_B(p^t) = \begin{cases} S, \text{if } C(p^t) > t \\ \text{L}, \text{if } C(p^t) \le t \end{cases}, \text{t has to be adaptive!}$$

Adaptive classification parameters



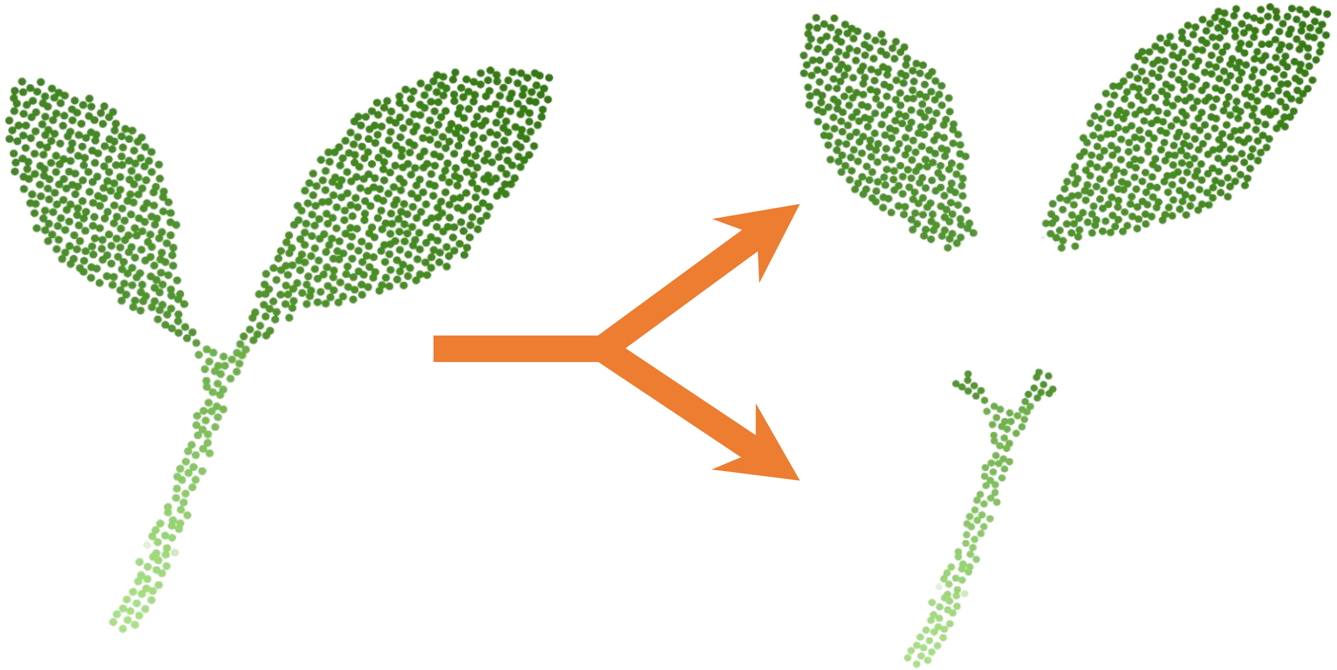
Growing leaf and stem in the feature space

Fwd-bwd analysis: bring back information from future



- Fwd analysis: detecting strong evidences
- Bwd analysis: smarter with the “after-effect”

Leaf-stem classification: MRF with known labels



Find $f_B: P^t \rightarrow \{L, S\}$, that minimizes

$$\mathrm{E}(f_B) = \boxed{\sum_{p^t \in P^t} D_{p^t}\left(f_B(p^t)\right)} + \sum_{p^t, q^t \in N_{p^t}} V\left(f_B(p^t), f_B(q^t)\right),$$

where $N_{p^t} = \{(p^t, q^t) \in Delaunay(P^t) : |p^t - q^t| < 3\mathrm{mm}\}$.

Leaf-stem classification: data term (1)

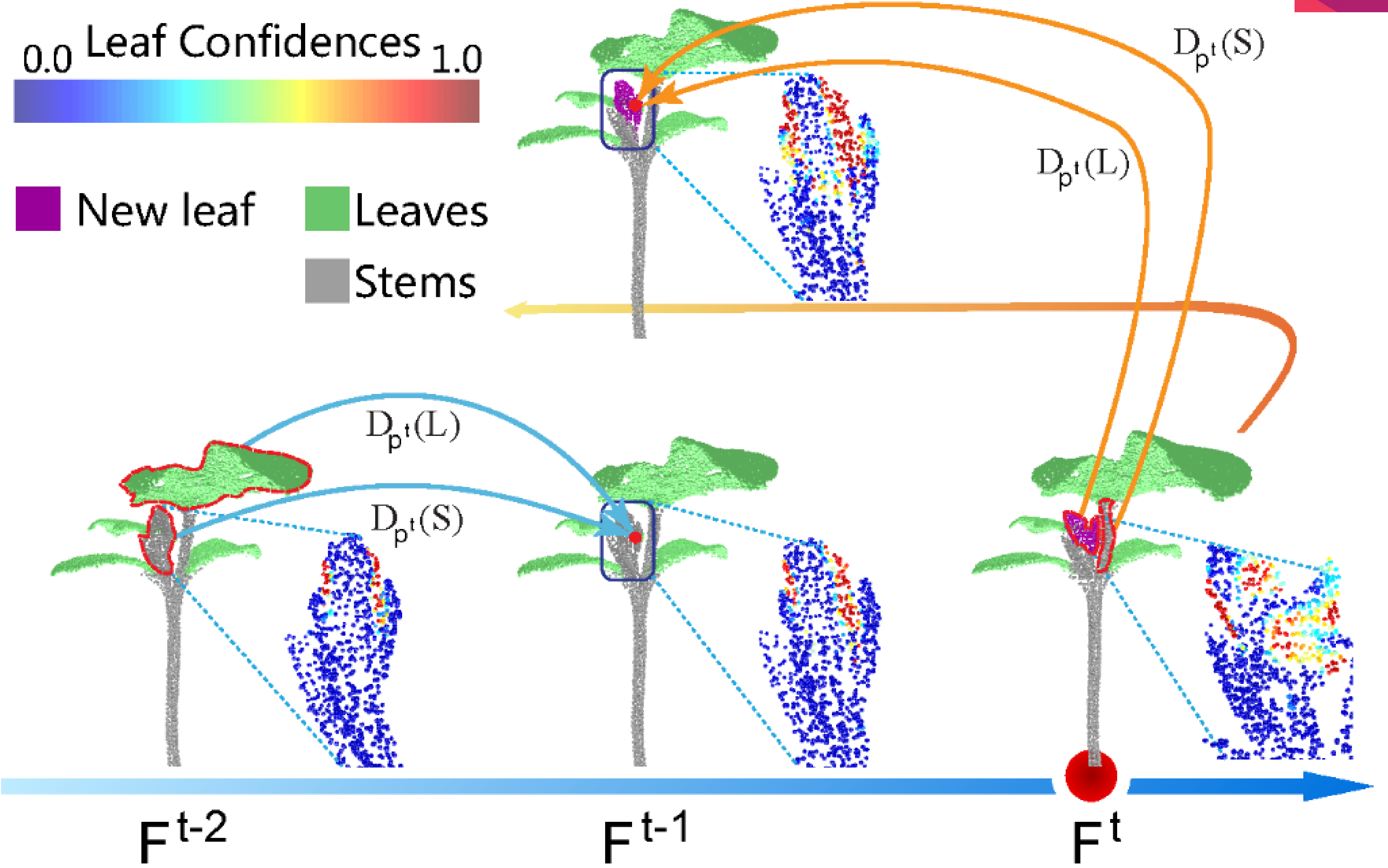
$$D_{p^t}(L) = \begin{cases} max\left(R(p^t) - R\left(L_{l*}^{t\pm1}\right), 0\right), if\ \Phi > 0 \\ R(p^t) - \boxed{\mathfrak{R}_L} \qquad\qquad\qquad\qquad if\ \Phi = 0 \end{cases},$$

$$D_{p^t}(S) = \begin{cases} max\left(R(S_{s*}^{t\pm1}) - R(p^t), 0\right), if\ \Phi > 0 \\ \boxed{\mathfrak{R}_S} - R(p^t), \qquad\qquad\qquad if\ \Phi = 0 \end{cases},$$

where $\Phi = |\{L_l^{t\pm1}\}| \times |\{S_s^{t\pm1}\}|$.

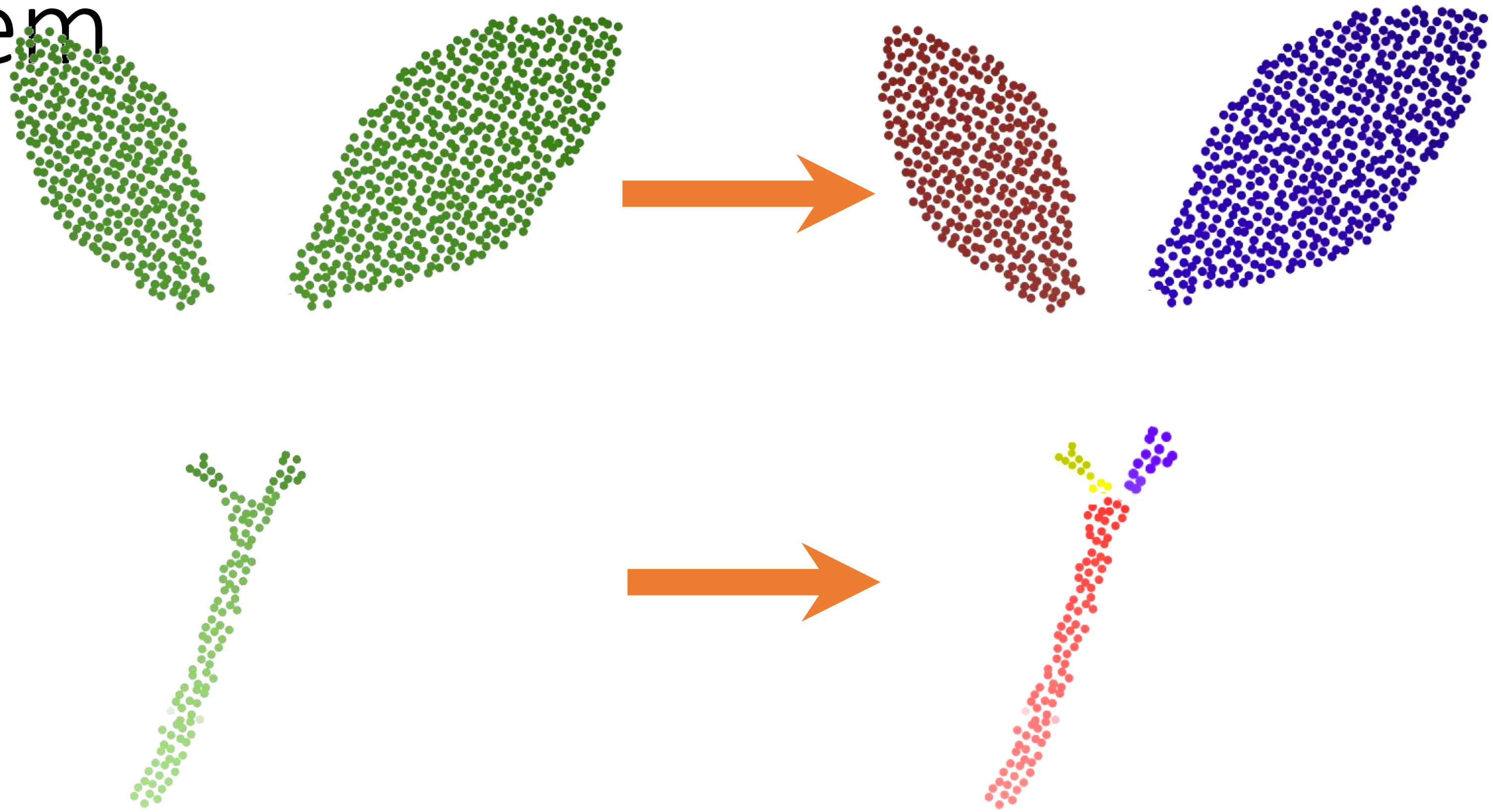
- **Spatial** and **temporal** adaption.
- Rarely relies on **global parameters**.

Leaf-stem classification: data term (2)



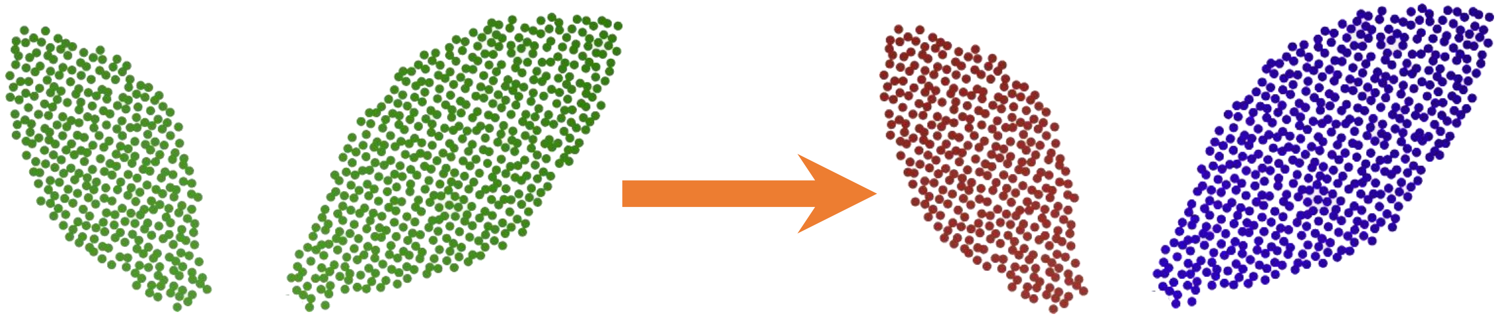
backward taking hints extractable only from future sequences

Individual organ segmentation: Multi-labelling problem



Label hypothesis generation + MRF optimization

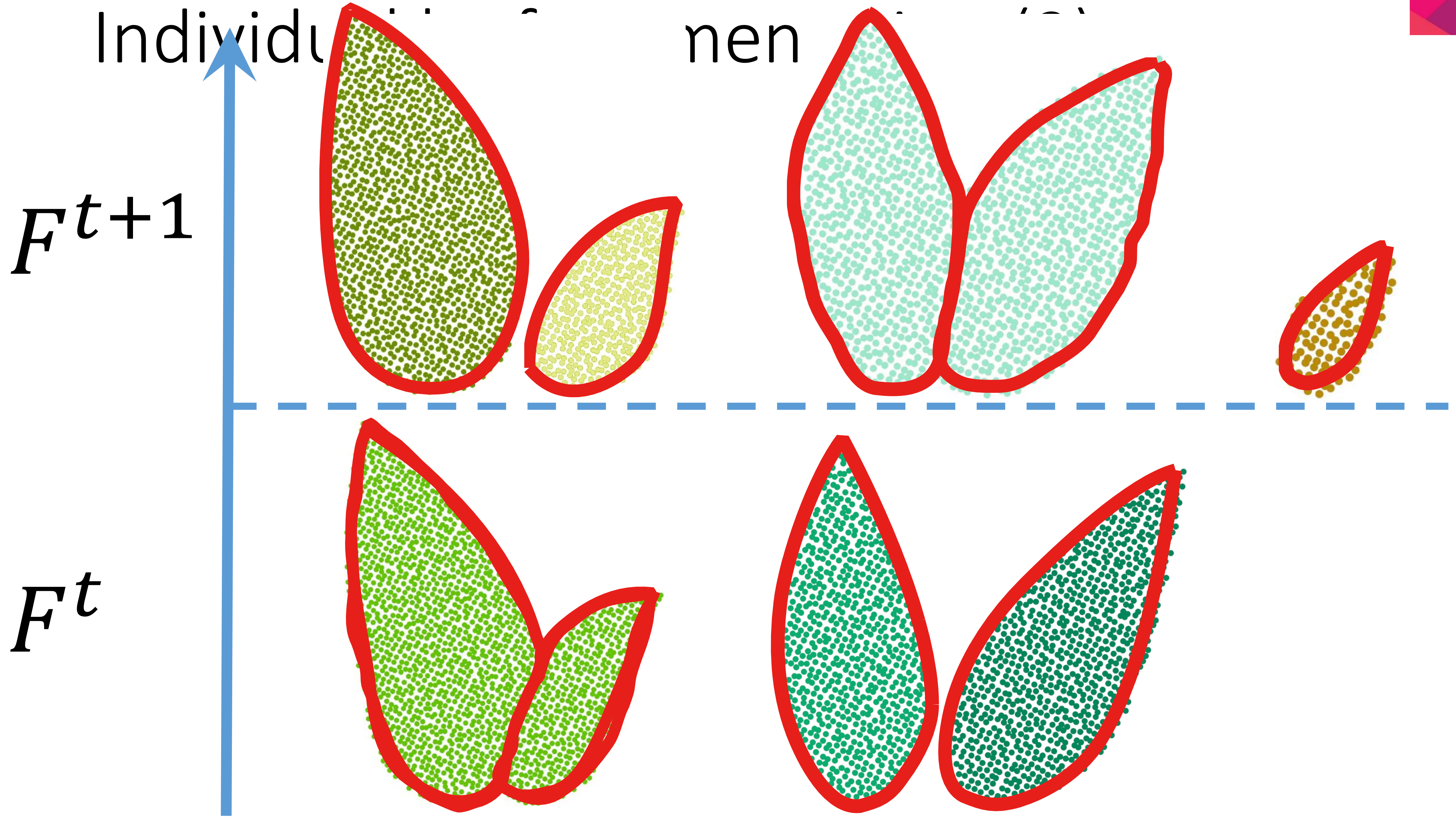
Individual leaf segmentation (1)



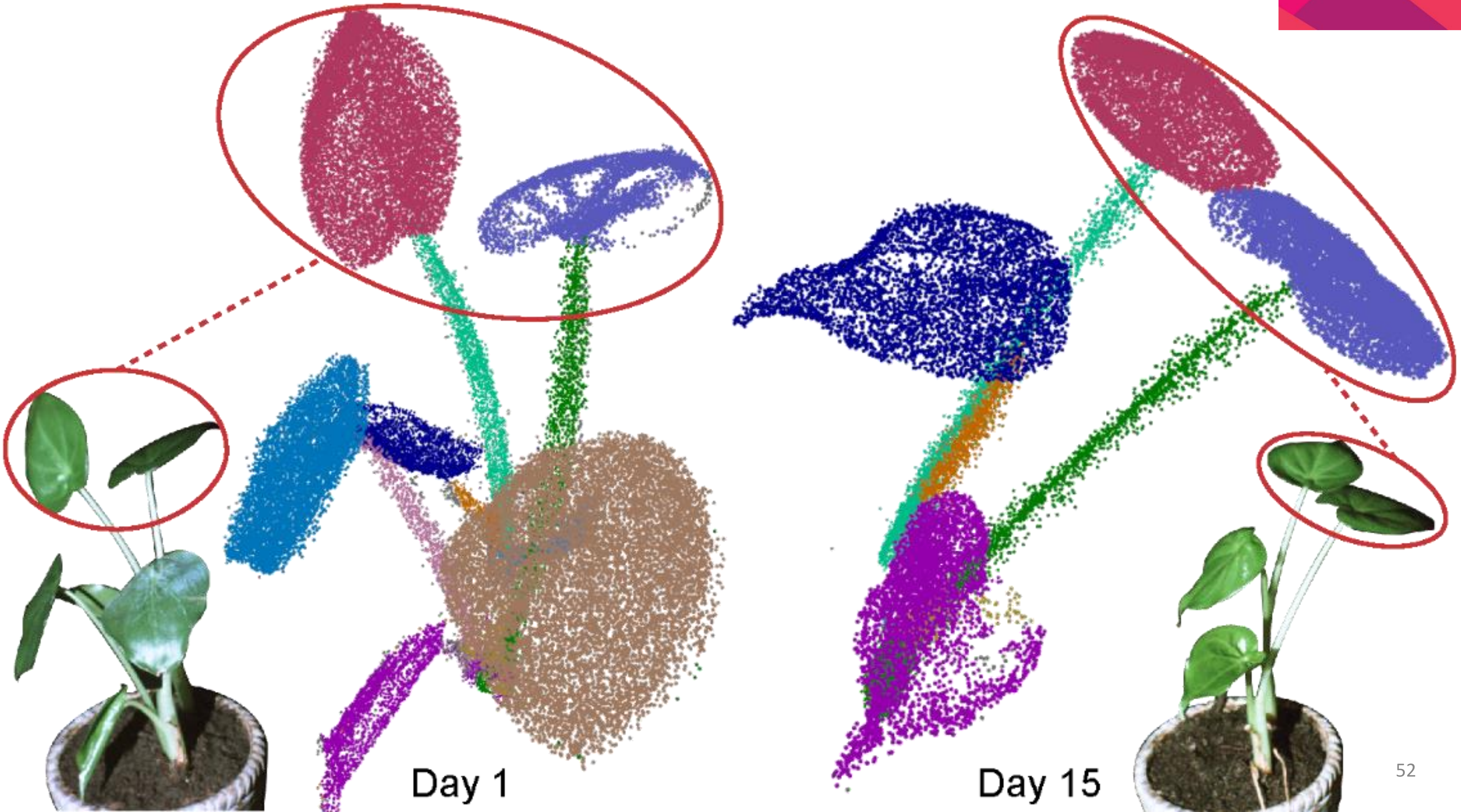
Individual leaf = one connected component

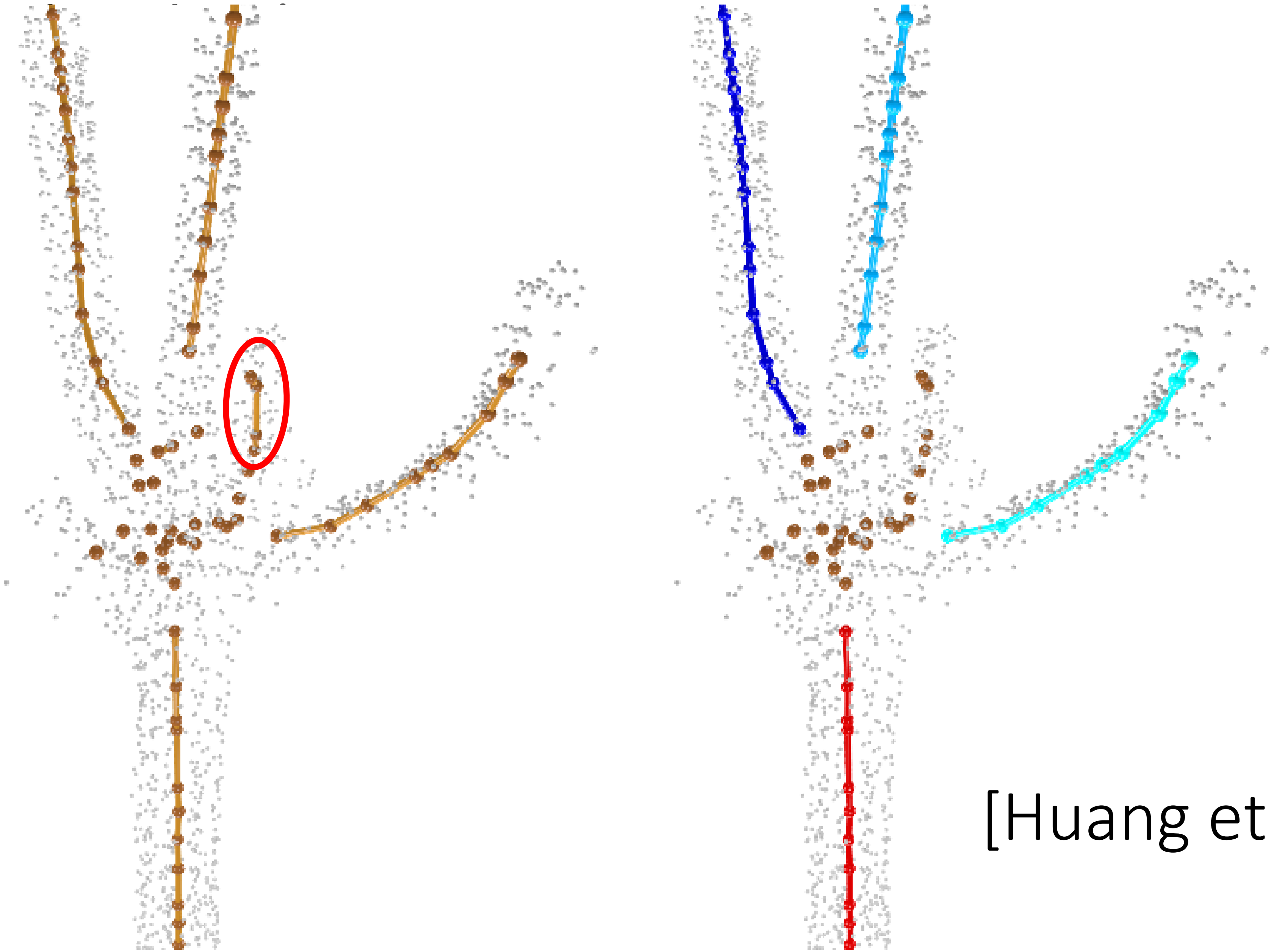
(true, if the leaves don't touch each other)

Individu… …nen…



Transfer leaf information over time



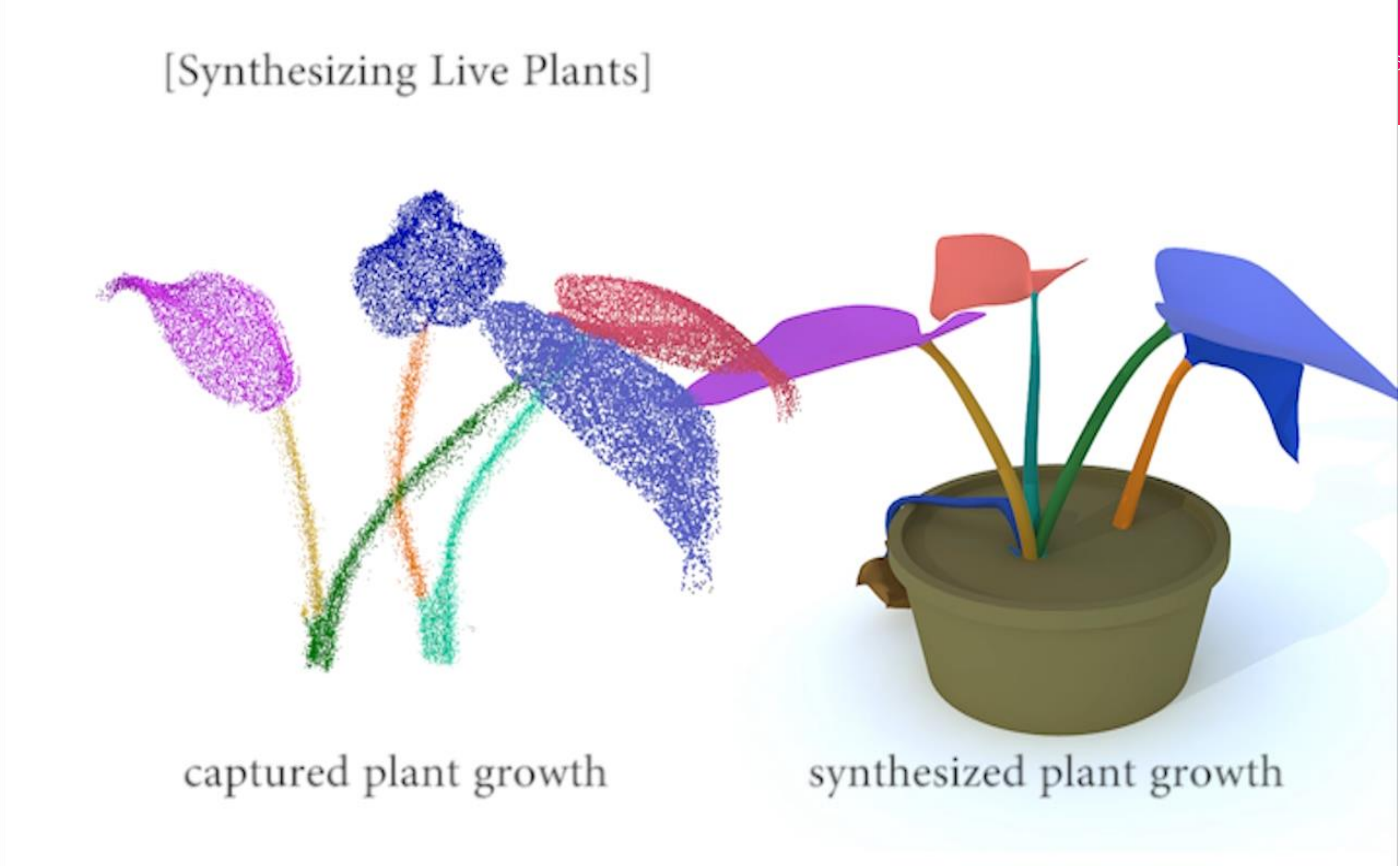


[Huang et al. 2013]

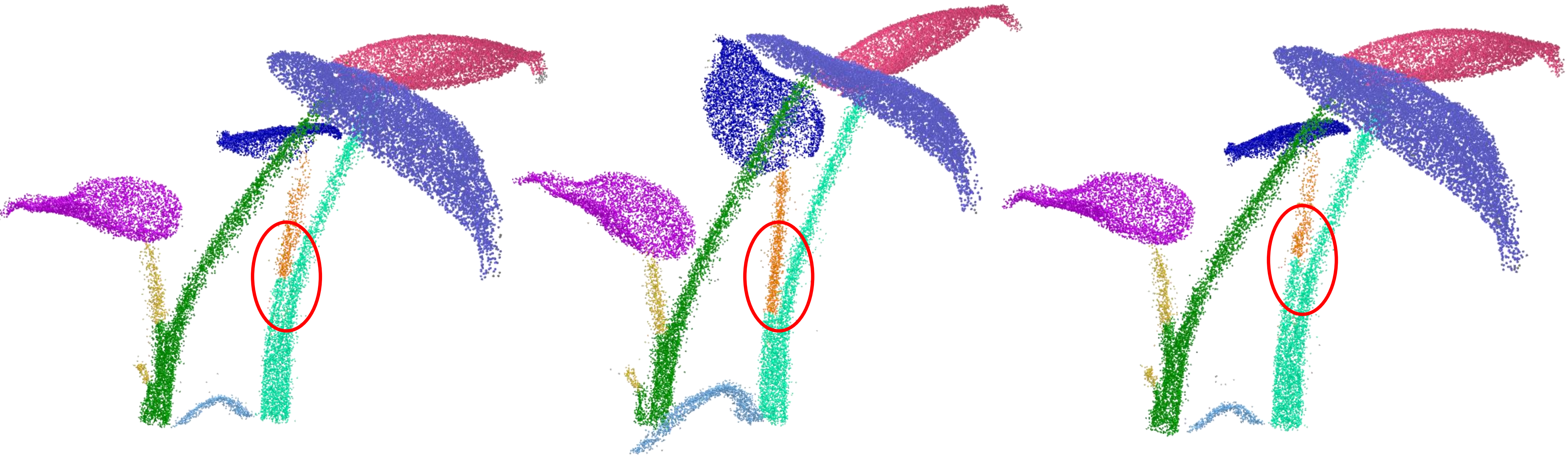

[Dishlia]
Day 1

[Segmentation for Simulation]
(using simulator from [Zhao and Barbič 2013])

[Organ Properties for Simulation]


[Synthesizing Live Plants]
captured plant growth
synthesized plant growth

Future work: quantitative analysis



An important constraint is missing here:

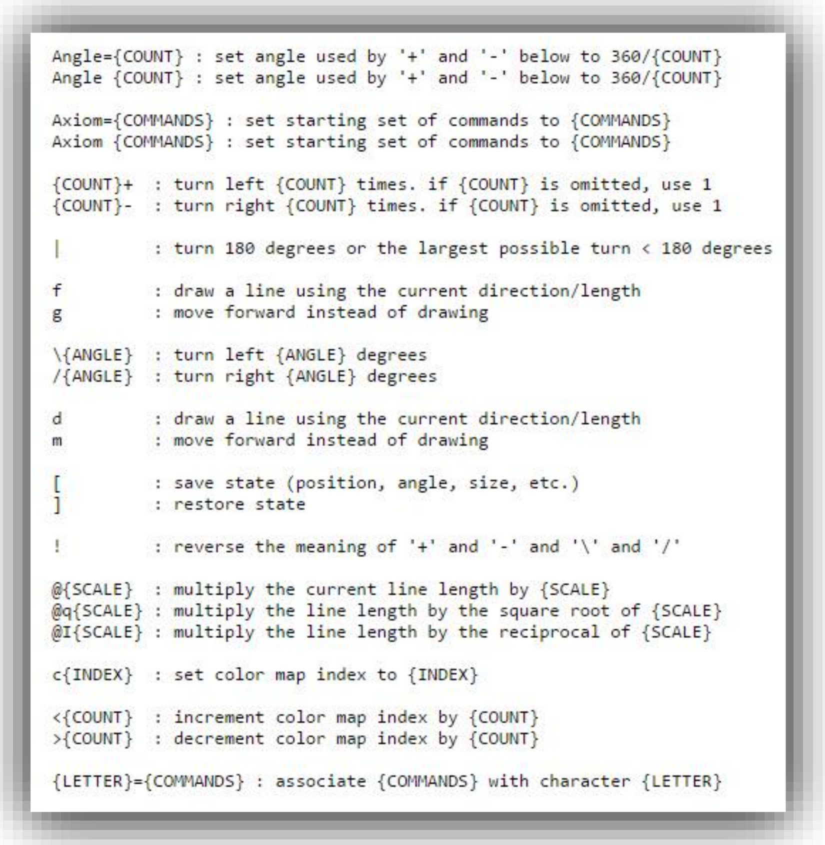
the volume of each organ should change gradually!

Inverse Procedural Modeling of Trees

- Stava, O., Pirk, S., Kratt, J., Chen, B., Měch, R., Deussen, O., & Benes, B. (2014). ***Inverse procedural modeling of trees.*** In Computer Graphics Forum (Vol. 33, No. 6, pp. 118-131).

Procedural Modeling

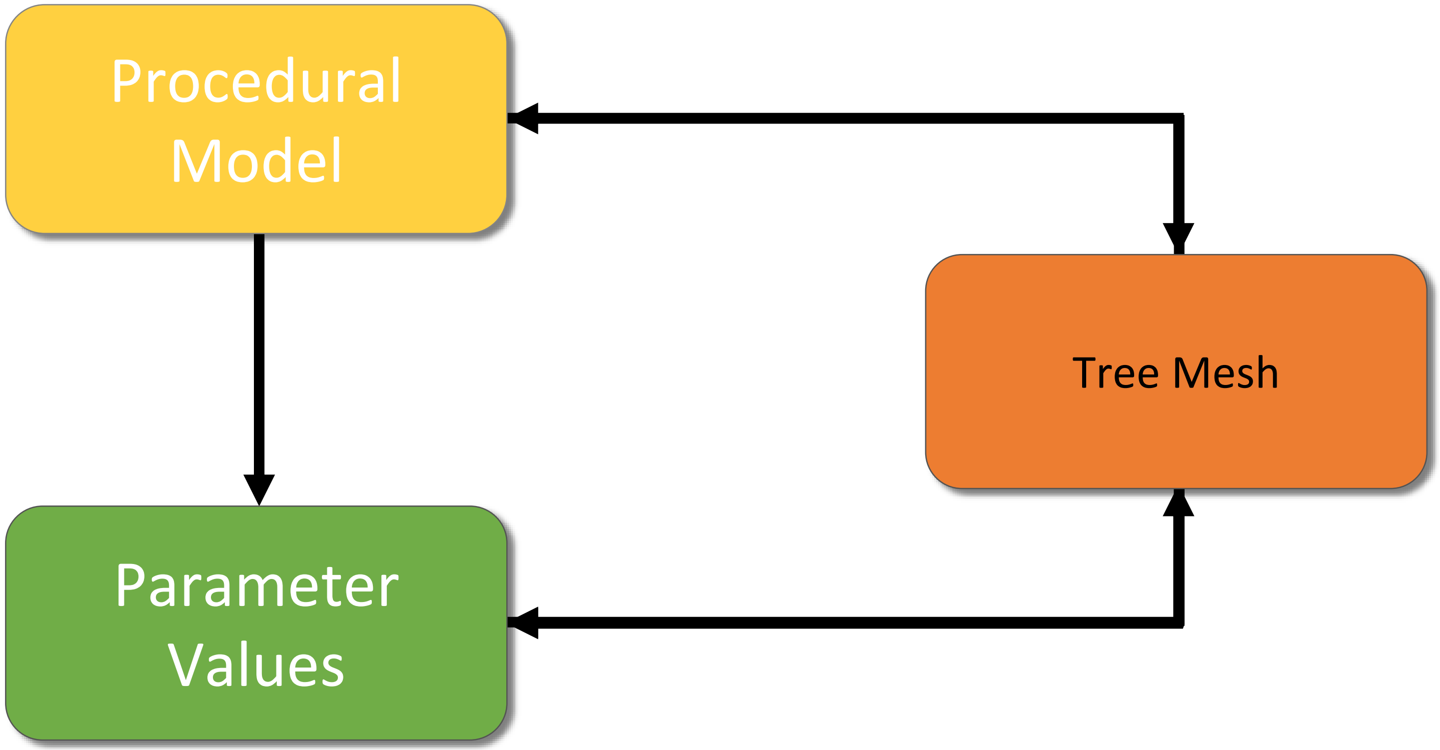
?



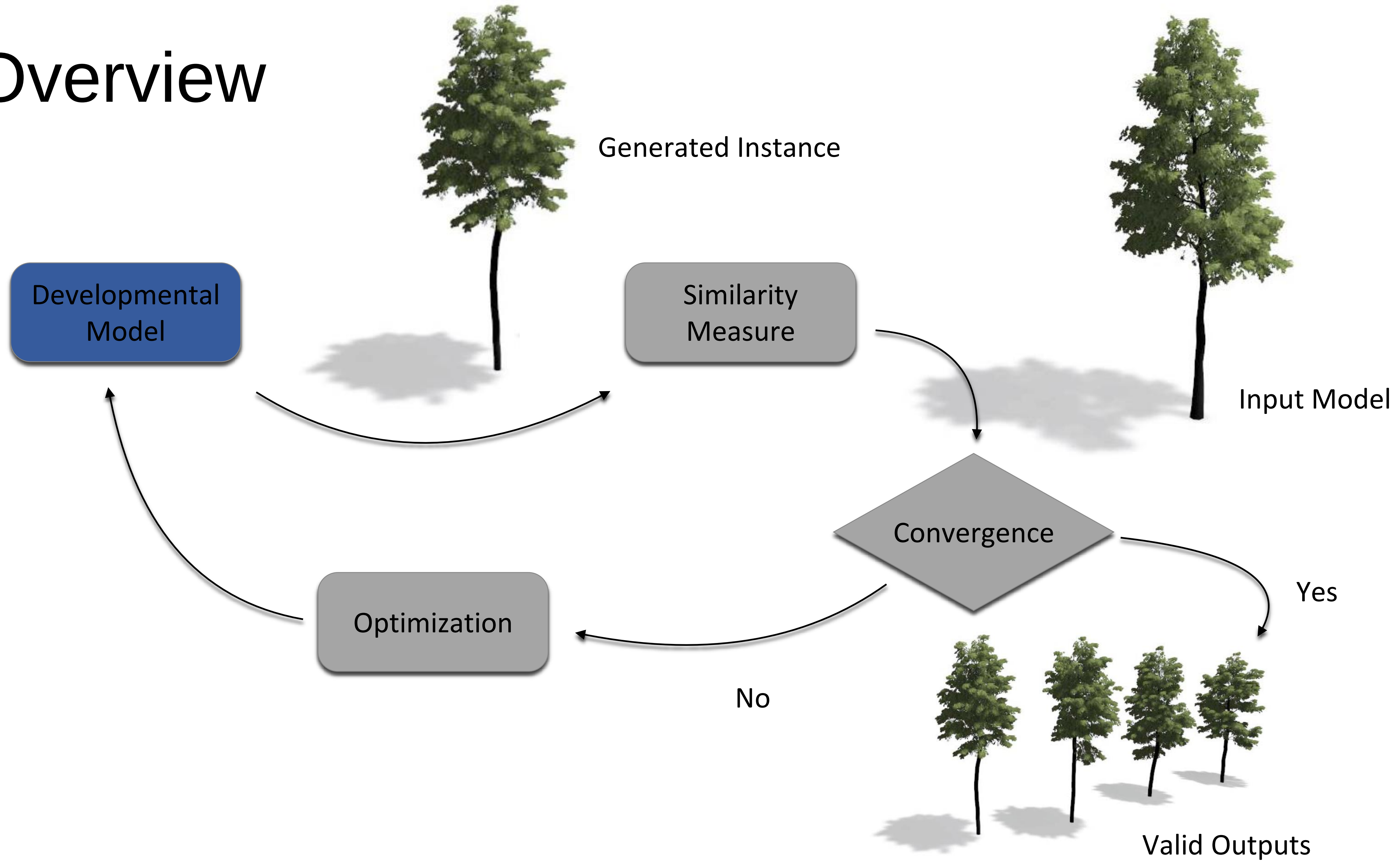
```
Angle={COUNT} : set angle used by '+' and '-' below to 360/{COUNT}
Angle {COUNT} : set angle used by '+' and '-' below to 360/{COUNT}

Axiom={COMMANDS} : set starting set of commands to {COMMANDS}
Axiom {COMMANDS} : set starting set of commands to {COMMANDS}

{COUNT}+   : turn left {COUNT} times. if {COUNT} is omitted, use 1
{COUNT}-   : turn right {COUNT} times. if {COUNT} is omitted, use 1

|          : turn 180 degrees or the largest possible turn < 180 degrees

f          : draw a line using the current direction/length
g          : move forward instead of drawing

\{ANGLE}   : turn left {ANGLE} degrees
/{ANGLE}   : turn right {ANGLE} degrees

d          : draw a line using the current direction/length
m          : move forward instead of drawing

[          : save state (position, angle, size, etc.)
]          : restore state

!          : reverse the meaning of '+' and '-' and '\' and '/'

@{SCALE}   : multiply the current line length by {SCALE}
@q{SCALE}  : multiply the line length by the square root of {SCALE}
@I{SCALE}  : multiply the line length by the reciprocal of {SCALE}

c{INDEX}   : set color map index to {INDEX}

<{COUNT}   : increment color map index by {COUNT}
>{COUNT}   : decrement color map index by {COUNT}

{LETTER}={COMMANDS} : associate {COMMANDS} with character {LETTER}
```

Procedural Modeling

Inverse Procedural Modeling

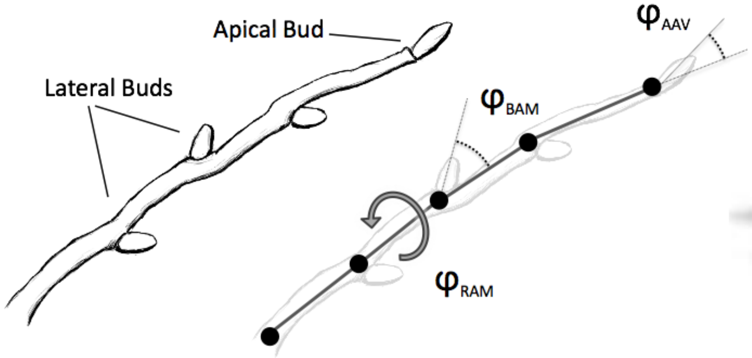


Overview


Generated Instance
Developmental Model
Similarity Measure
Input Model
Convergence
Yes
Optimization
No
Valid Outputs

Developmental Model

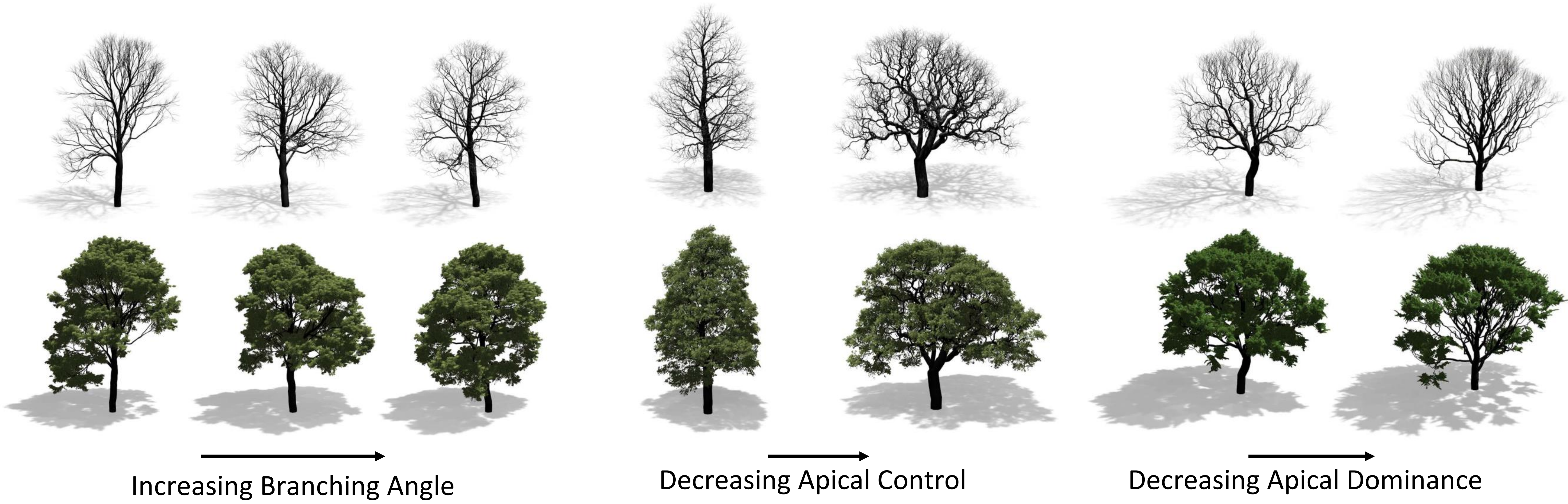
- Captures new biological findings
  [Cline et al. 2006, Cline et al. 2009]
- Geometric,environmental and bud fate parameters
- Patch-based foliage modeling
  [Livny et al. 2011]



Developmental Model

Geometric Params	Environment Params	Bud Fate Params
Growth Rate	Gravitropism	Apical Angle Variance
Internode Length	Phototropism	Number of Lateral Buds
Internode Angle Factor	Pruning Factor	Branching Angle Mean and Variance
Apical Control Level	Low Branch Pruning Factor	Roll Angle and Variance
Apical Dominance Factor	Gravity-bending Strength	Apical and Lateral Light Factor
…	…	…

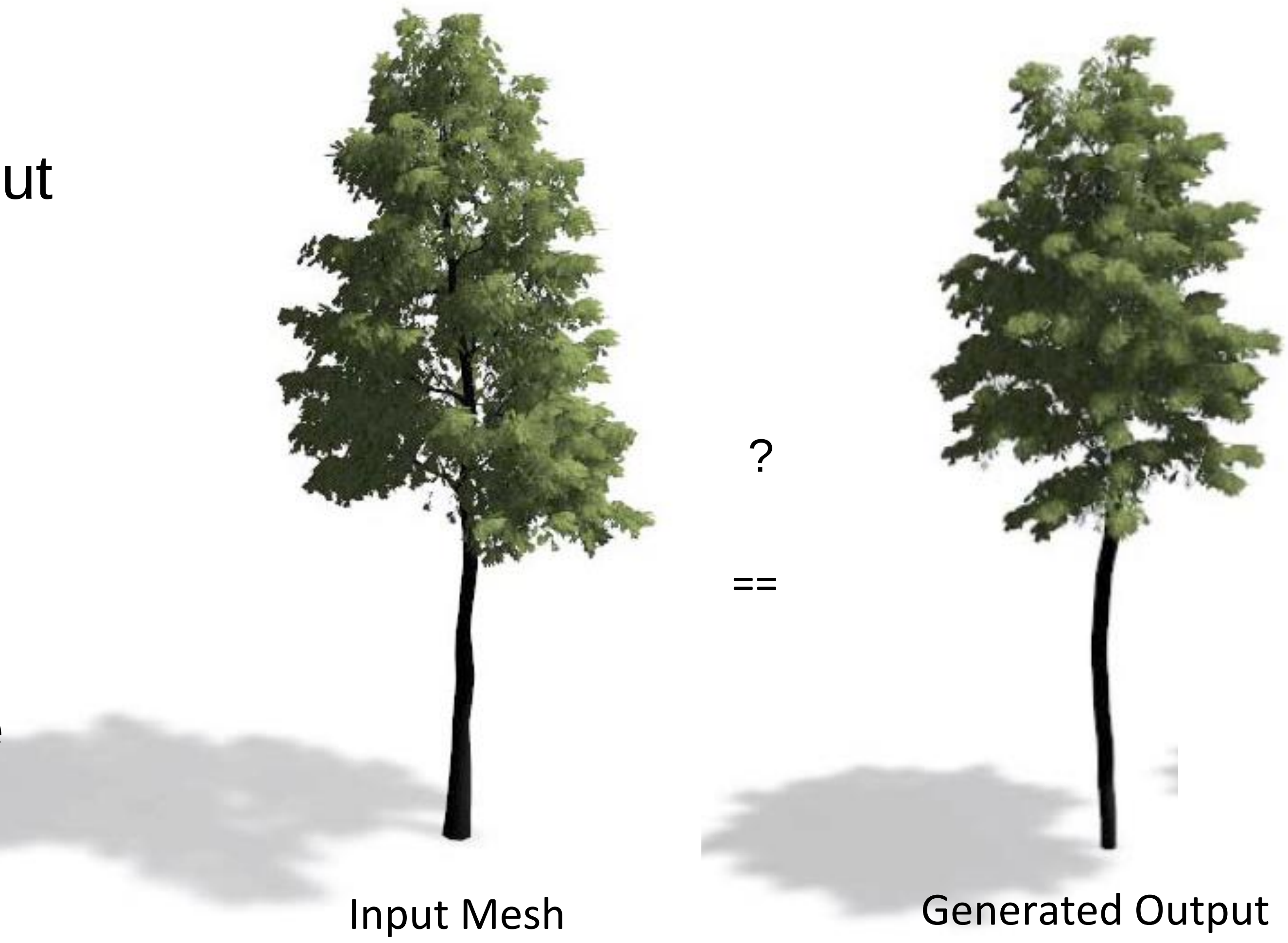
Developmental Model



Optimization

- Find parameters for developmental model
- Maximize similarity between input and generated instance
- What does similar mean?

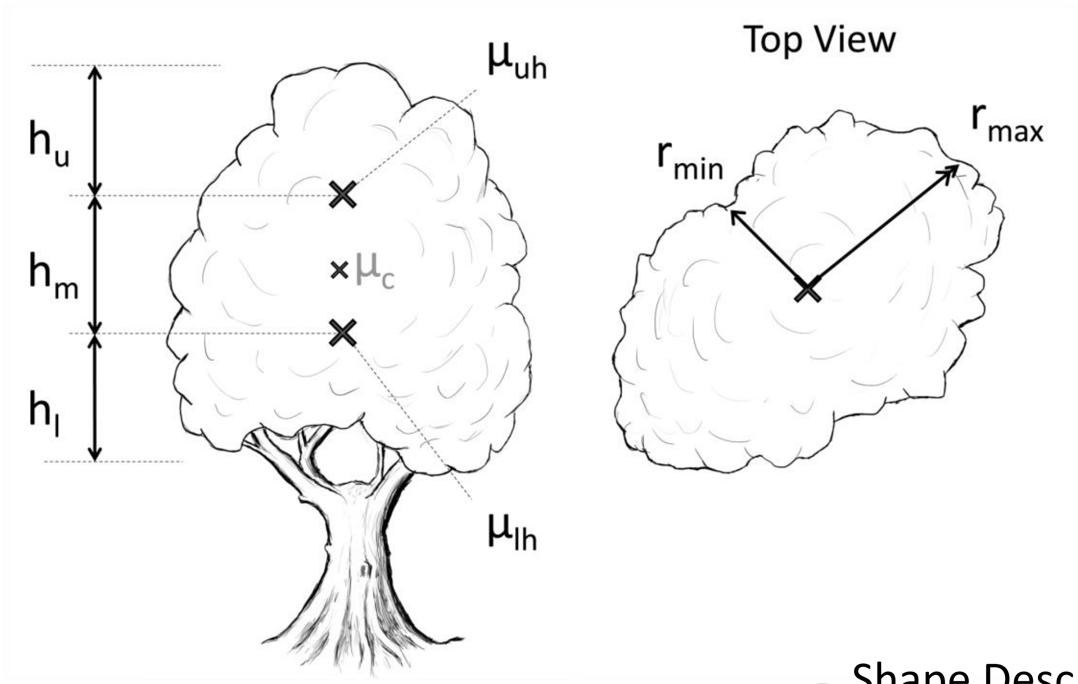
Fitness function based on geometry, shape and structure



Shape Distance

- Crown shape affected by distribution of branches
- Divide tree into slabs to capture variance
- Compute shape descriptors for each slab:

Height, radius, principal directions, leaf-branch density



Shape Descriptors

Difference of descriptors

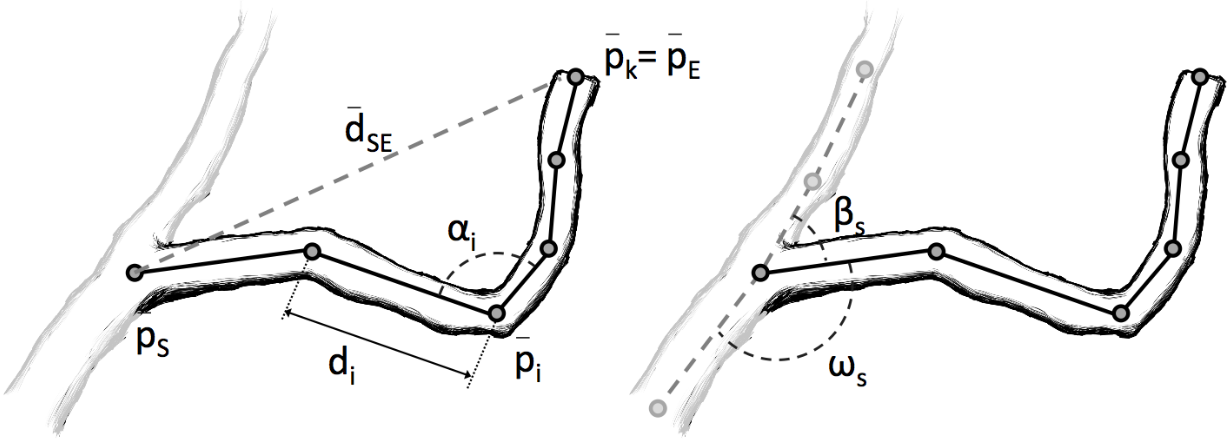
$$\delta_{\lambda_{S,i}} = 1 - \exp\left(-\frac{\left(\lambda_{S,i}(\tau_1) - \lambda_{S,i}(\tau_2)\right)^2}{2\sigma^2_{\lambda_{S,i}}}\right)$$

Normalization Factor

Geometric Distance

- Statistics of branch geometry computed from the tree graph
- Sample weight based on length and thickness of a branch
- Descriptors are defined as mean and variance of these samples

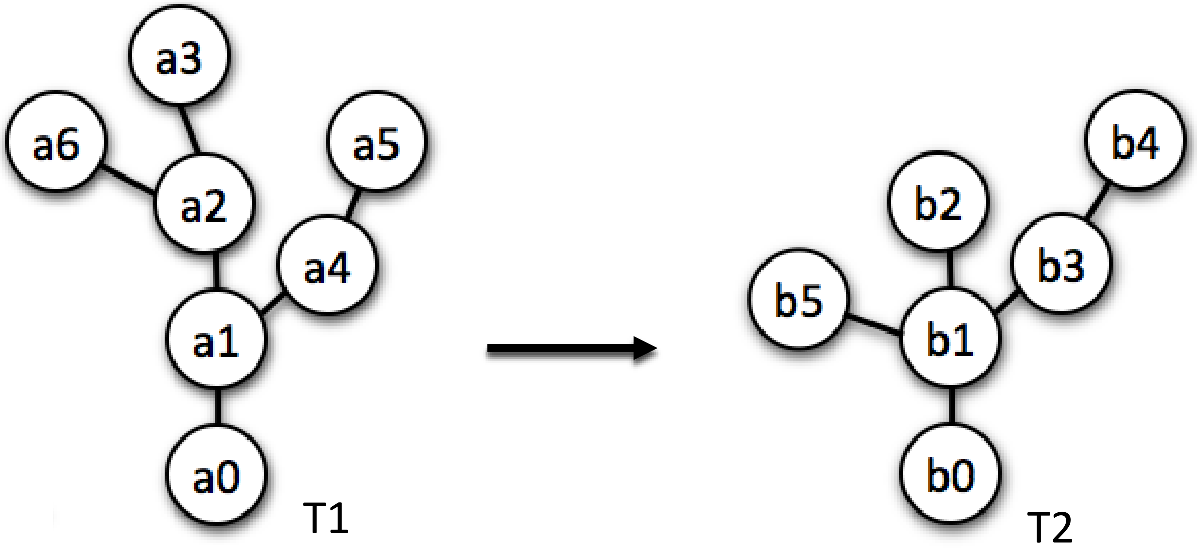
Name	Formula
Length	$\sum_{i=1}^{k} d_i$
Thickness	$\max_{\forall d_i} t_i$
Deformation	$\sum_{i=1}^{k-1} \alpha_i$
Straightness	$\frac{\lvert \bar{d}_{SE} \rvert}{b_L}$
Slope	$\angle \bar{d}_{SE}$
Sibling Angle	β_S
Parent Angle	ω_S



Structural Distance

[Zhang 1996, Ferraro and Godin 2000]

- Transform graph T1 into graph T2
- Costs for transforming the nodes (edit distance)
- Possible transformations: **assign, insert, delete**
- Quickly loses accuracy when geometric resolution differs



Trees

Edit distance

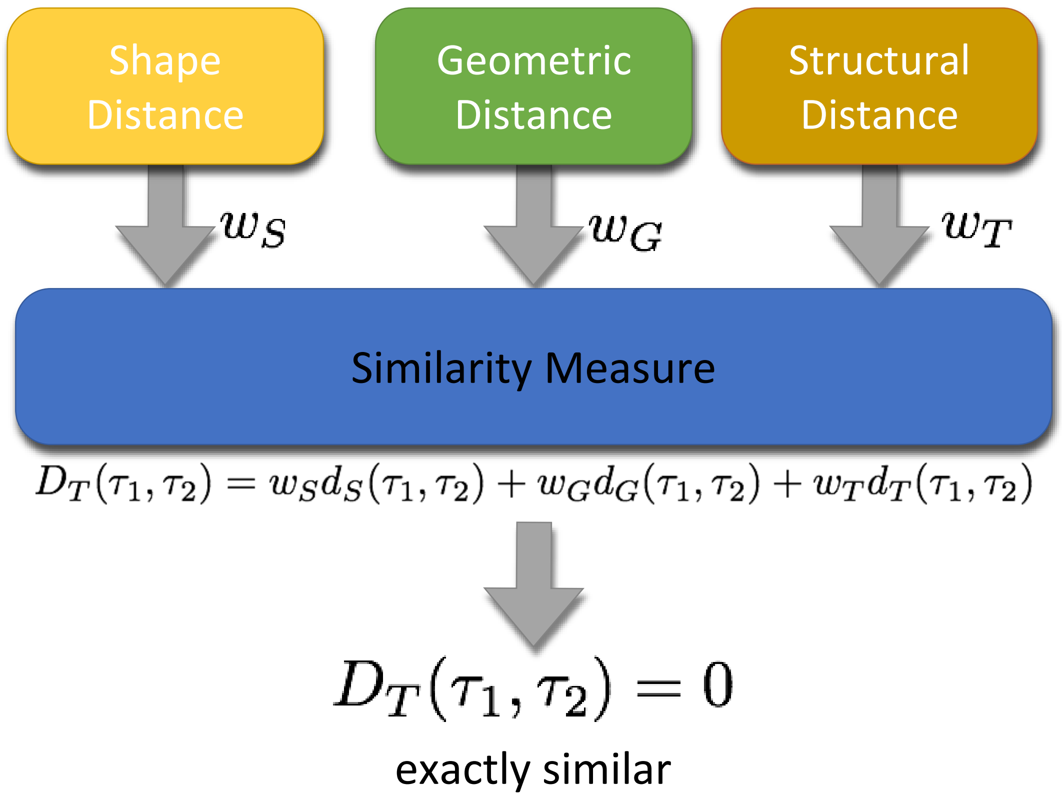
$$d_T(\tau_1, \tau_2) = \frac{d_N(t_1, t_2)}{2 \max\left(d_N(t_1, \varepsilon), d_N(\varepsilon, t_2)\right)}$$

Structure-based distance

Roots

Similarity Measure

- The sum of shape-, geometry and structure-based distances
- Corresponding weights for each distance (w_S, w_G, w_T)
- Results generated with equal weight

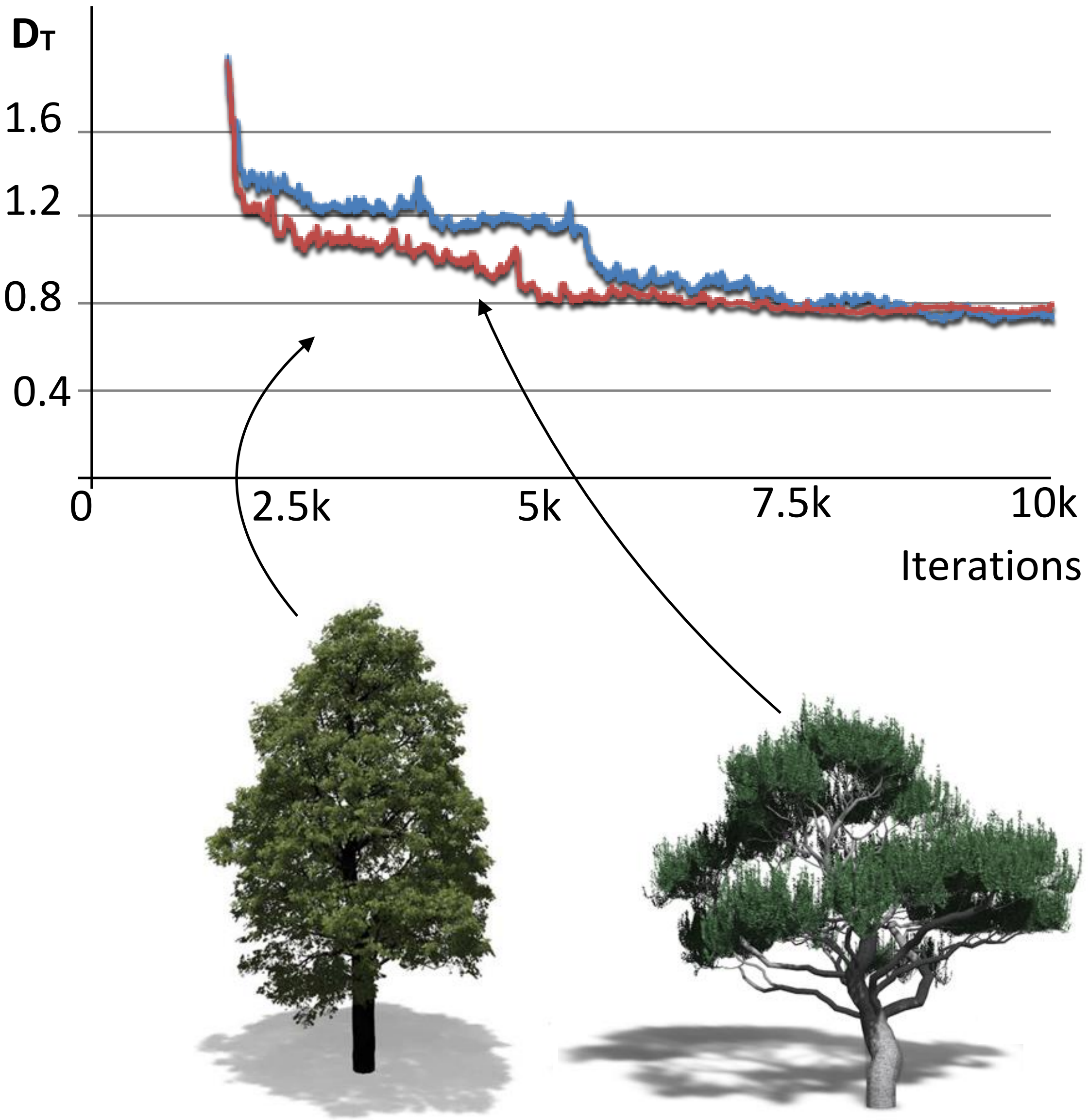


Optimization of Parameters

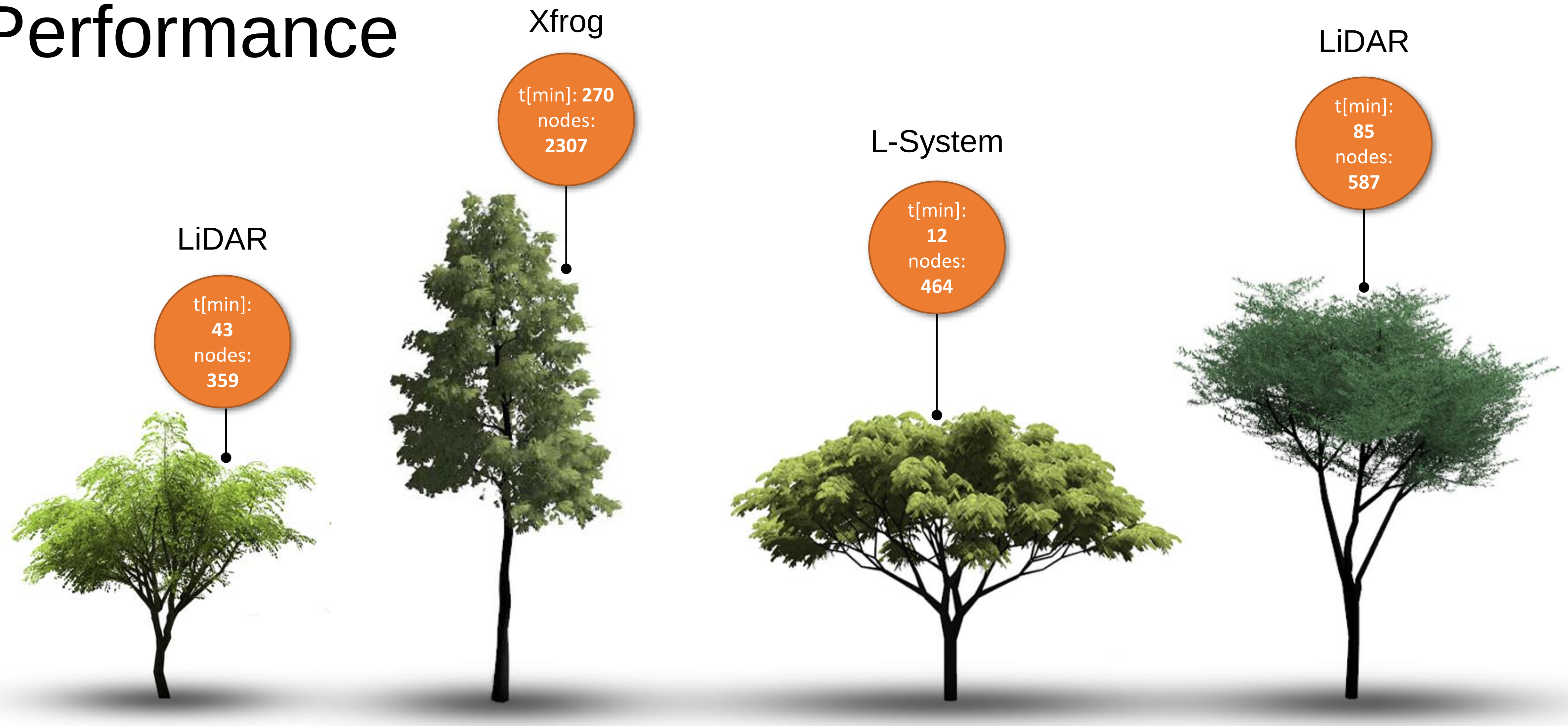
[Metropolis et al. 1953]

- Find parameter set that generates „similar enough“ tree models
- Simulated annealing
- Stochastic sampling based on Metropolis-Hastings
- Solve approximate optimization problem:

$$\operatorname*{argmin}_{\bar{\varphi}_{\mathcal{M}},t} \left(\sum_{\omega_j} D_T\left(\tau^r, \tau^{\mathcal{M}}(\omega_j)\right) \right)$$



Performance



Results

Environment

Interpolation of Parameters

Different Species

Modeling Plant Life in Computer Graphics

User-assisted Modeling

Siggraph 2016 Course

Sören Pirk, Bedrich Benes, Takashi Ijiri, Yangyan Li,
Oliver Deussen, Baoquan Chen, Radomír Měch

Overview

- User-Assisted Plant Modeling [10 minutes]
  - Interactive Flower Modeling **(Ijiri)**
  - Sketch-based Tree Modeling **(Ijiri)**

Introduction

Plants and Trees

- Free form curves and surfaces
- Highly repetitive structures

For modeling them

- Free form components
- Local structures
- Overall shapes

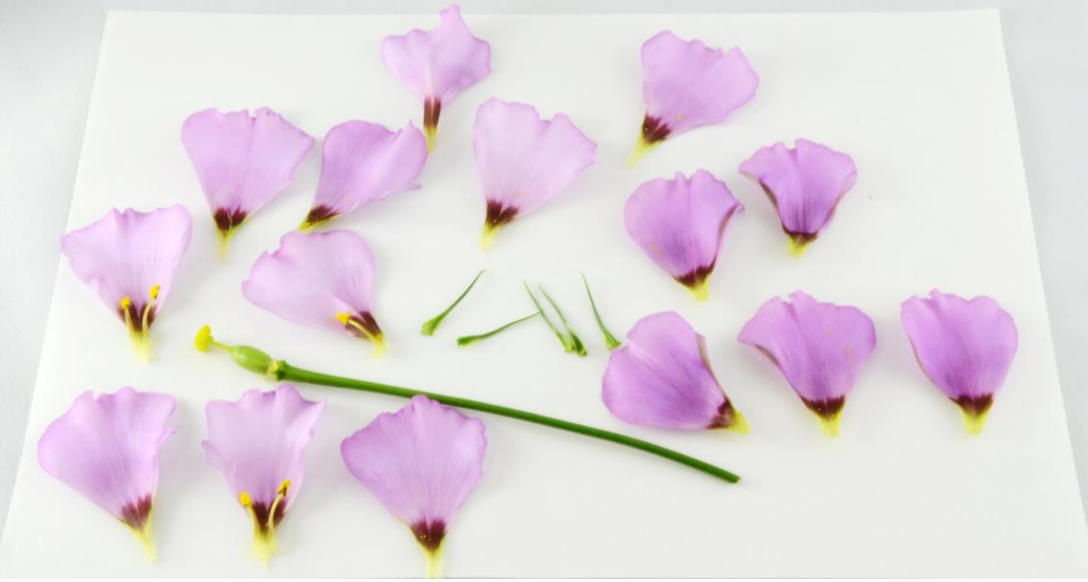
→ Sketch is well suited

Floral Diagrams and Inflorescences: Interactive Flower Modeling Using Botanical Structural Constrains

- T. Ijiri, S. Owada, M. Okabe, and T. Igarashi: **Floral diagrams and inflorescences: Interactive flower modeling using botanical structural constraints.** Transactions on Graphics, 24, 3, pp. 720-726, 2005.

Background

Flower Modeling is difficult



Many free form components

Structure specific to spices

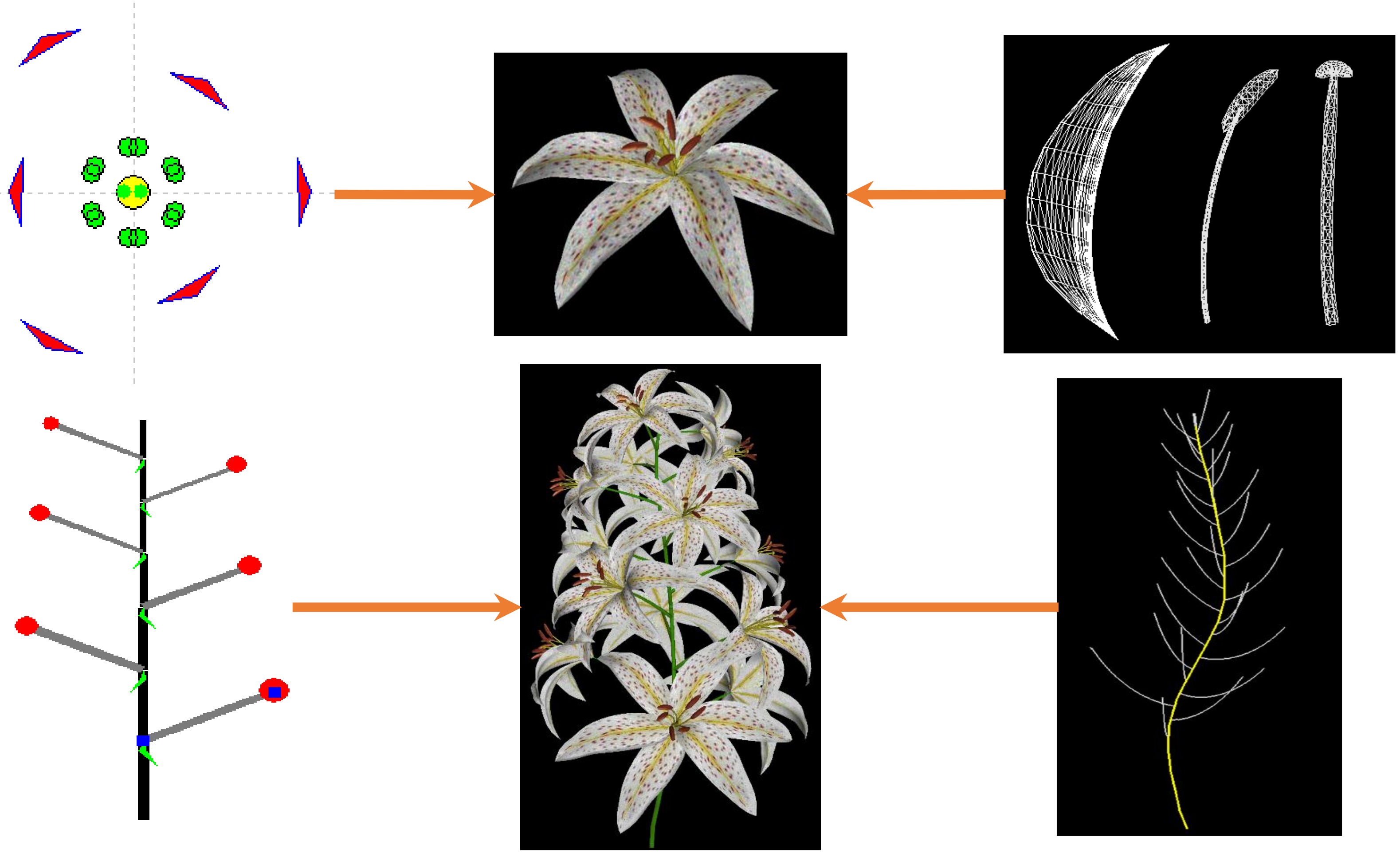
Goal : Easy-to-use interactive flower modeling framework

Key idea

- Separate “structural specification” and “Geometry modeling”

Floral diagrams

Inflore-scences

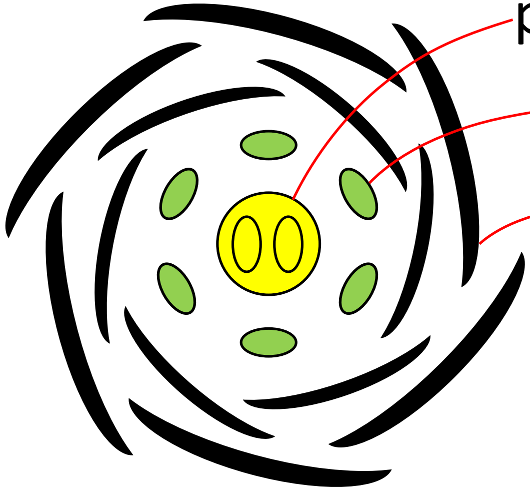


Sketch-based Interface

Design editor by using botanical representation

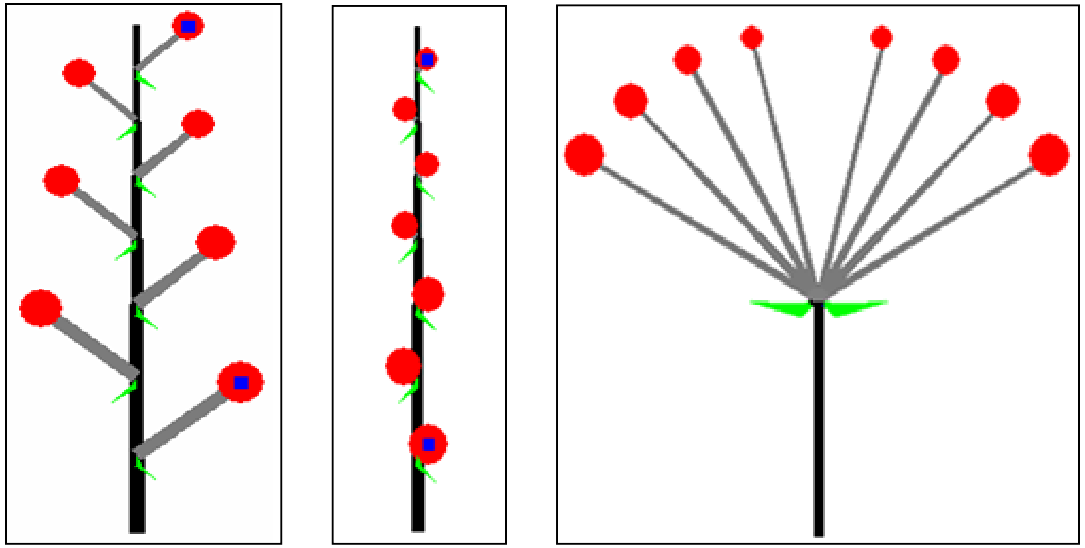
Floral Diagrams

Arrangement of flower components



Inflorescences

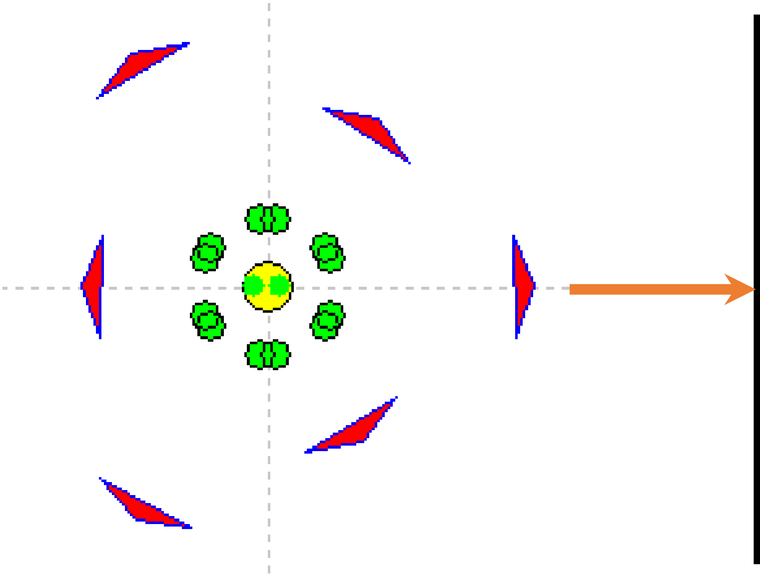
A branch bearing a lot of small flowers

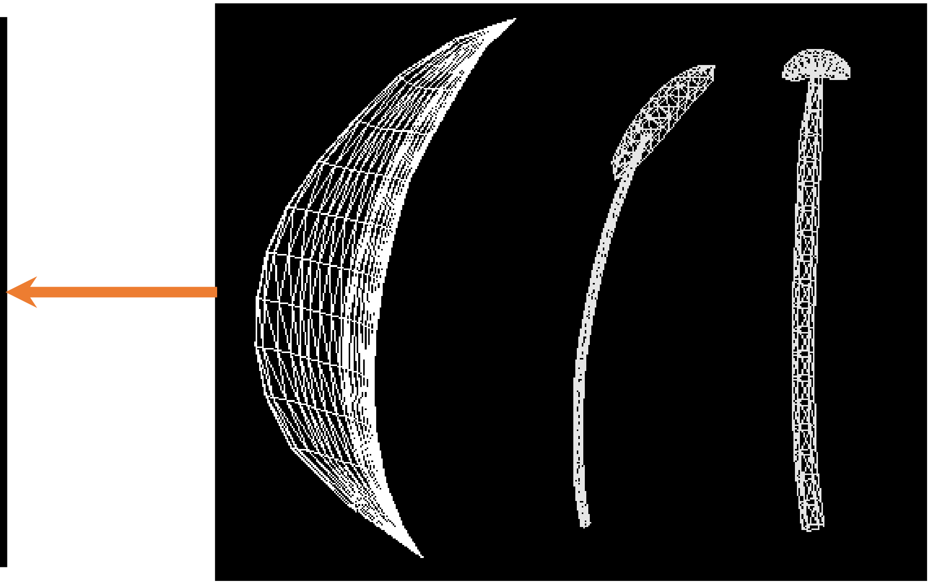


[Bell. Plants form, *Timber press, 1991*]

→ Design structure editors based on them

Modeling process (Demo)





Summary

Easy to use flower modeling tool

Divide modeling process

+ structure editing

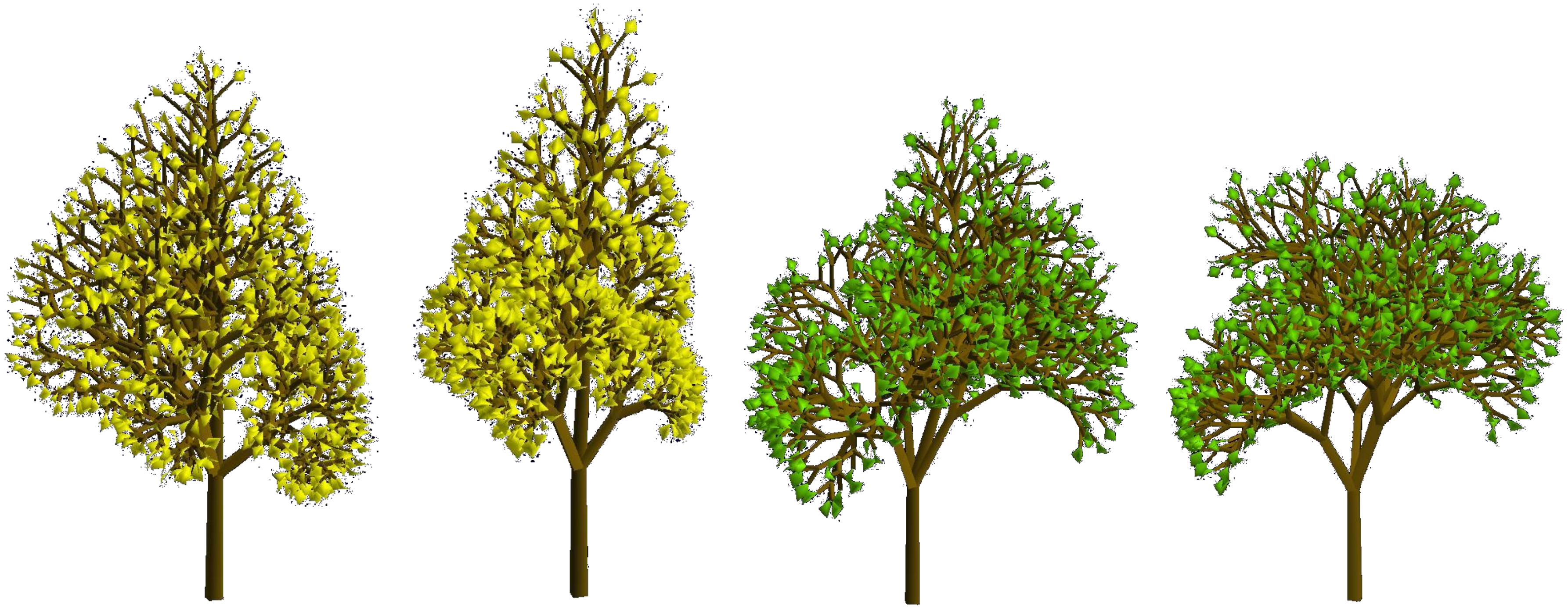
+ geometry modeling

The Sketch L-System: Global Control of Tree Modeling using Free-form Strokes

- Ijiri T., Owada S., Igarashi T.: **The sketch L-system: Global control of tree modeling using free-form strokes**. In Smart Graphics 2006, Vol. Volume 4073 of *Lecture Notes in Computer Science*, Springer, pp. pp.138-146.

Our Goal

- Easy-to-use tree modeling framework
- Large **variations** of trees with a little effort



Our idea

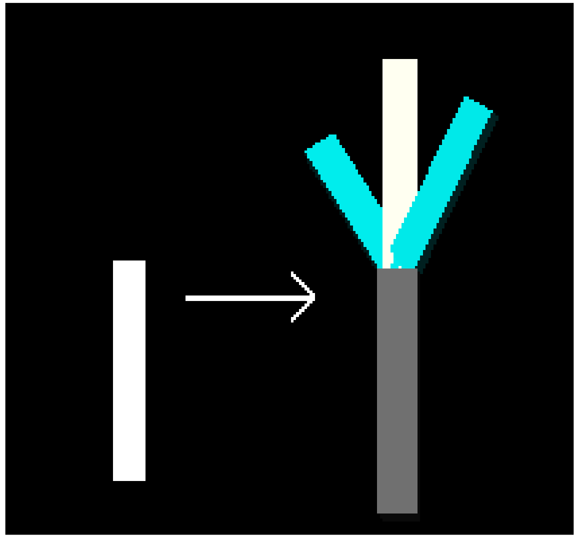
Combine two frameworks !!

- L-System → Describe complicated branching structures
- Sketch → Specify global appearance

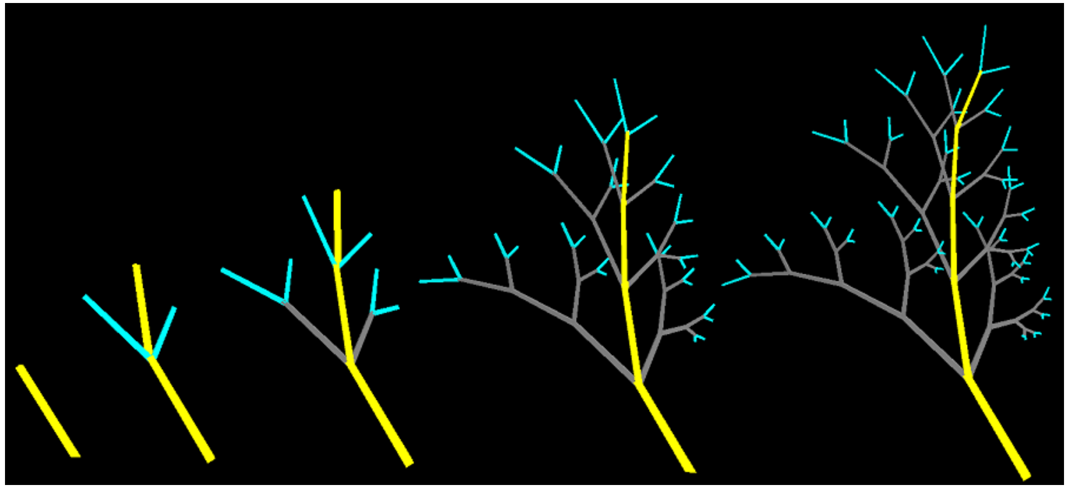
	L-System	Sketch
Detail structure	Good	Bad
Overall Shape	Bad	Good

Introduce two elements to L-System

- Interaction module
  - Its growing direction is decided by the stroke
- Sketch interface for controlling growth of L-System
  - Central axis & depth of recursion



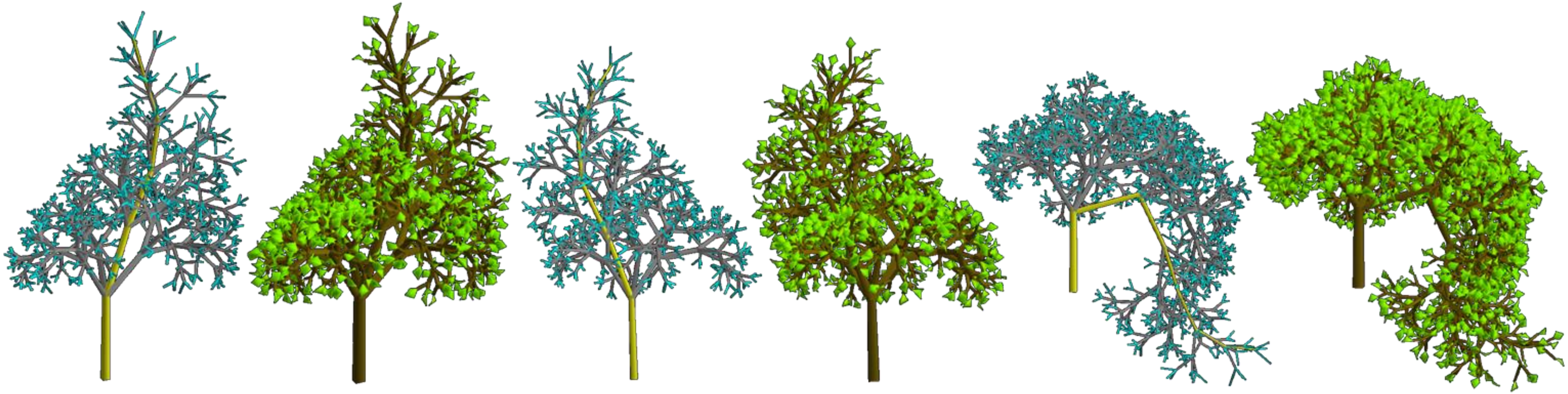
Interaction module



Sketch interface

Summary

- Combined sketch and L-system
- Large variation of trees with a little effort
- Only a simple trial and many future work
    - Specify overall shapes, Specify the shape of 2^{nd} branches



Conclusion : user assisted modeling

- **Sketch based Interface** : global shapes
- **Procedural approach** : local structures

→ **Their combination becomes powerful tool for plant modeling**

Many sketch based plant modeling tools appear

Sketch-based tree modeling
[Longay et al. SBIM 2012]
[Wither et al. 2009]
[Chen et al. SIGGRAPH ASIA 2008]
[Okabe et al. EuroGraphics 2005]

Sketch-based plant modeling
[Anastacio et al. CG 2005]

Sketch-based Ornament modeling
[LU et al. SIGGRAPH 2014]
[MECH and MILLER, JCGT, 2012]

Additional references

SIGGRAPH2016 Render the Possibilities

Sketch based tree modeling

LONGAY, S., RUNIONS, A., BOUDON, F., AND PRUSINKIEWICZ, P. Treesketch: Interactive procedural modeling of trees on a tablet. In Proc. SBIM, 107–120, 2012

Jamie Wither, Frederic Boudon, Marie-Paule Cani, Christophe Godin. Structure from silhouettes: a new paradigm for fast sketch-based design of trees. Computer Graphics Forum, Wiley, 28 (2), pp.541-550, 2009

Xuejin Chen, Boris Nerburt, Ying-Qing Xu, Oliver Deussen, Sing Bing Kang. Sketch-Based Tree Modeling Using Markov Random Field. ACM Siggraph Asia and Transaction on Graphics, Vol. 27, No. 5, 2008

OKABE, M., OWADA, S., AND IGARASHI, T. Interactive design of botanical trees using freehand sketches and example based editing. Comput. Graph. Forum 24, 3, 487–496, 2005.

Sketch-based plant modeling

ANASTACIO, F., PRUSINKIEWICZ, P., AND SOUSA, M. Sketch-based parameterization of L-systems using illustration inspired construction lines and depth modulation. Comput. Graph. 33, 4, 440–451, 2009

Sketch-based Ornament modeling

LU, J., BARNES, C., WAN, C., ASENTE, P., MECH, R., AND FINKELSTEIN, A. Decobrush: Drawing structured decorative patterns by example. ACM Transactions on Graphics, 2014.

MECH, R., AND MILLER, G. The Deco framework for interactive procedural modeling. Journal of Computer Graphics Techniques (JCGT) 1, 1 (Dec), 43–99, 2012.

Modeling Plant Life in Computer Graphics

Conclusion

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What did we learn?

- **Introduction to vegetation modeling** in computer graphics.
- **Plant anatomy, plant growth, and environmental response** as a way to model plant geometry.
- Environmental response algorithms, such as **space colonization and self-organizing model**.

What did we learn?

- Algorithms for tree and flower **reconstruction from various data sources**, such as point sets, images, videos and CT.
- **Inverse Procedural Modeling** of Trees.
- **Sketch-based interface** for plant modeling.

Open problems

1. **Modeling**
   Can we algorithmically describe a shape of a plant?
2. **Controllability**
   How can an artist generate a plant with a desired shape?
3. **Evaluation**
   How can we say the model is real?
4. **Reconstruction**
   How can we get a model from a real-world sample?

Q&A

Course material available at:

http://goo.gl/PaJjy4