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

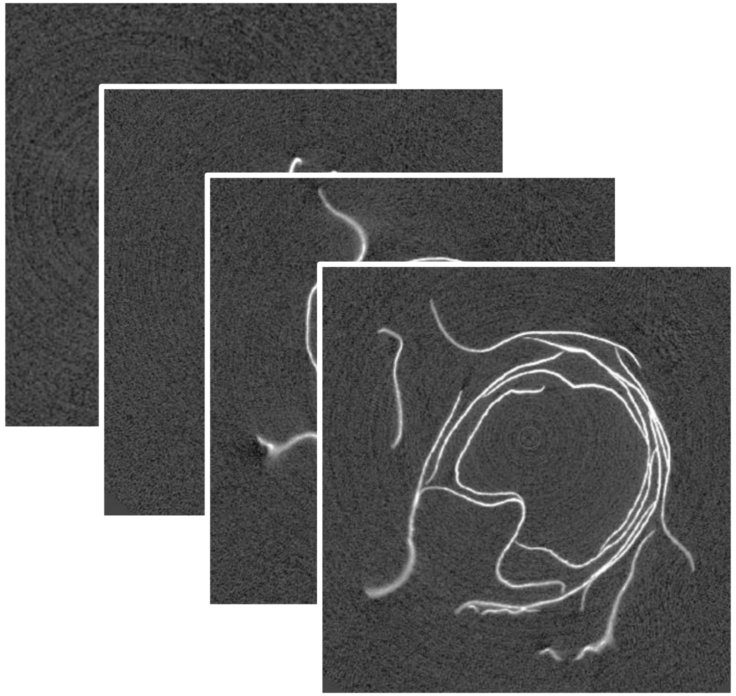
Occluded structure

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*

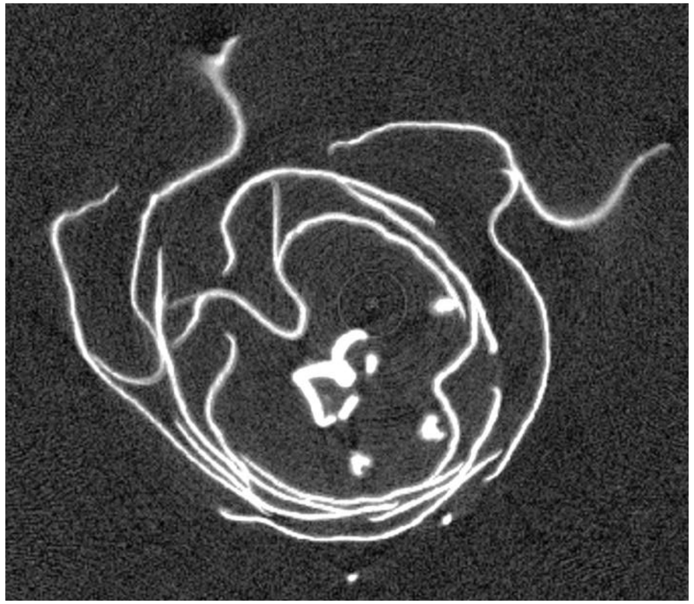


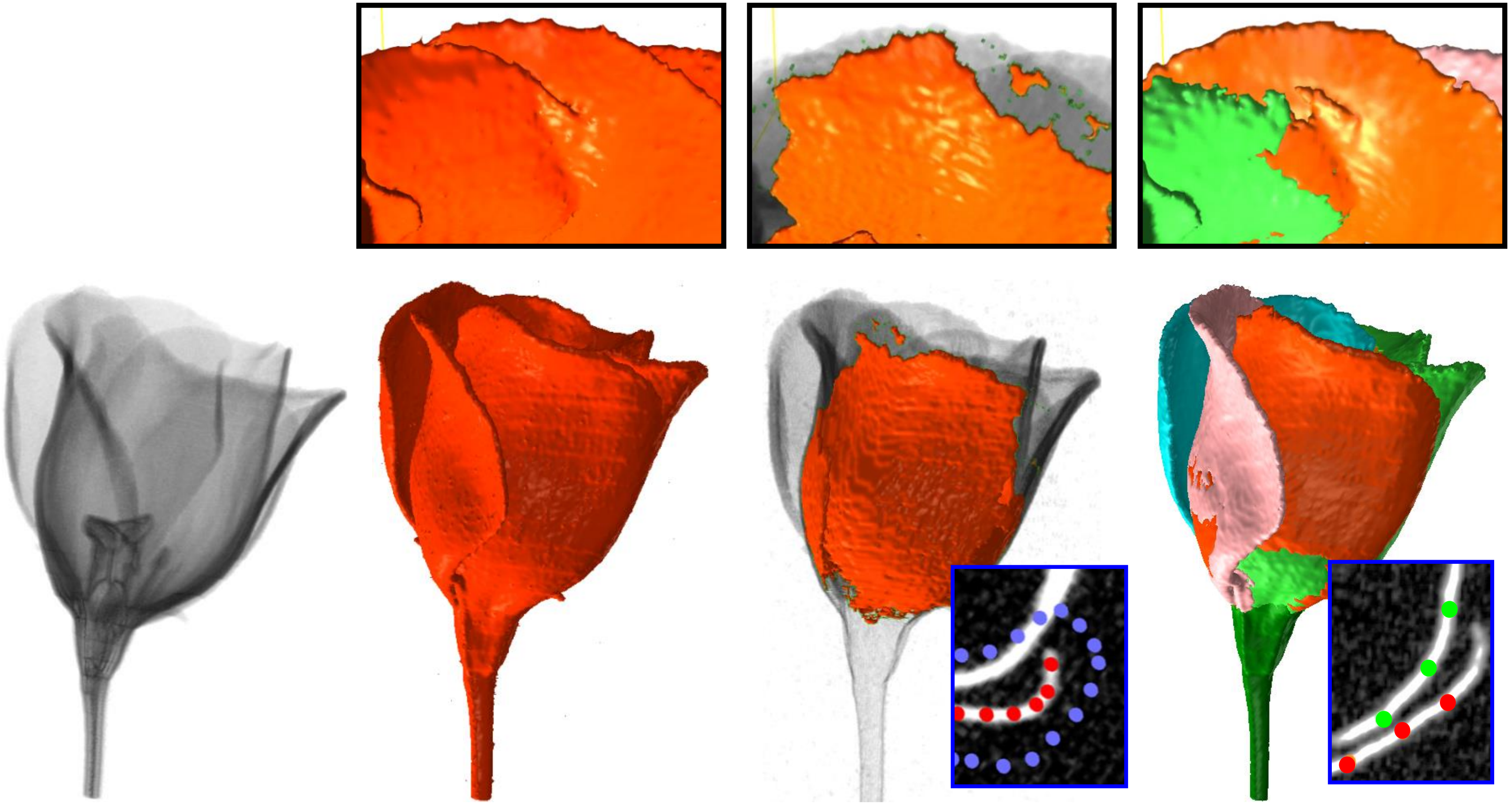
Obtain occlusion-free
flower CT volume image

Challenge – Segment volume into flower components

Flower components

- Thin shapes
- Similar CT intensity
- Contact one another



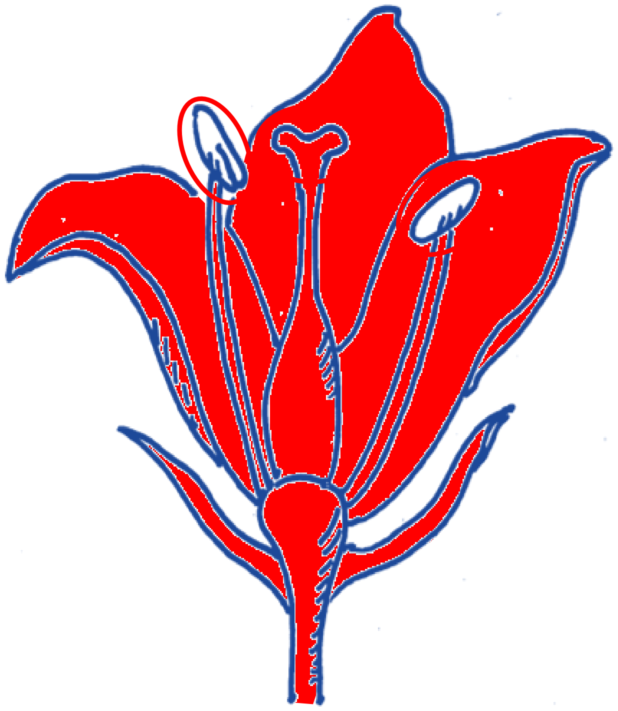


Iso surface [Lorensen et al 1987]

Graph Cut [Boykov et al 2001]

Region Grow [Adms 1994]

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



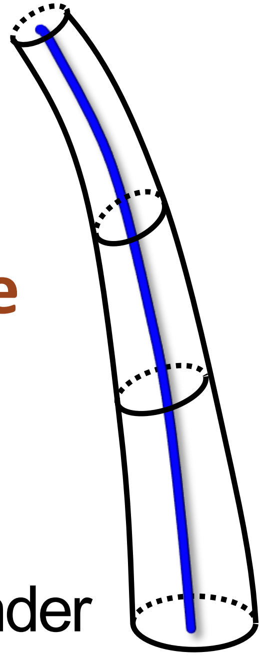
Pistils

Stamens

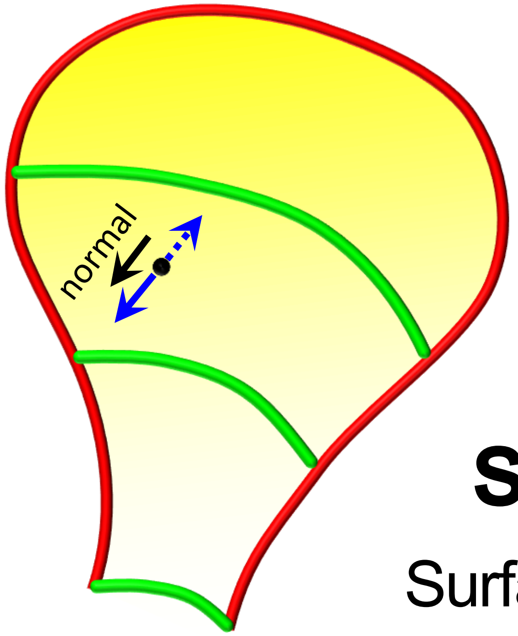
Receptacle

Stem

shaft



Curved cylinder radius varies along axis



Petals

Sepals

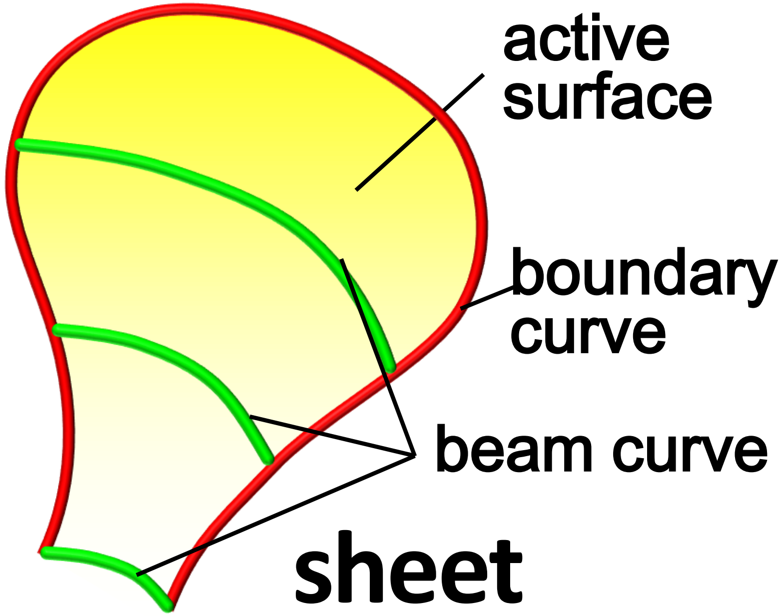
sheet

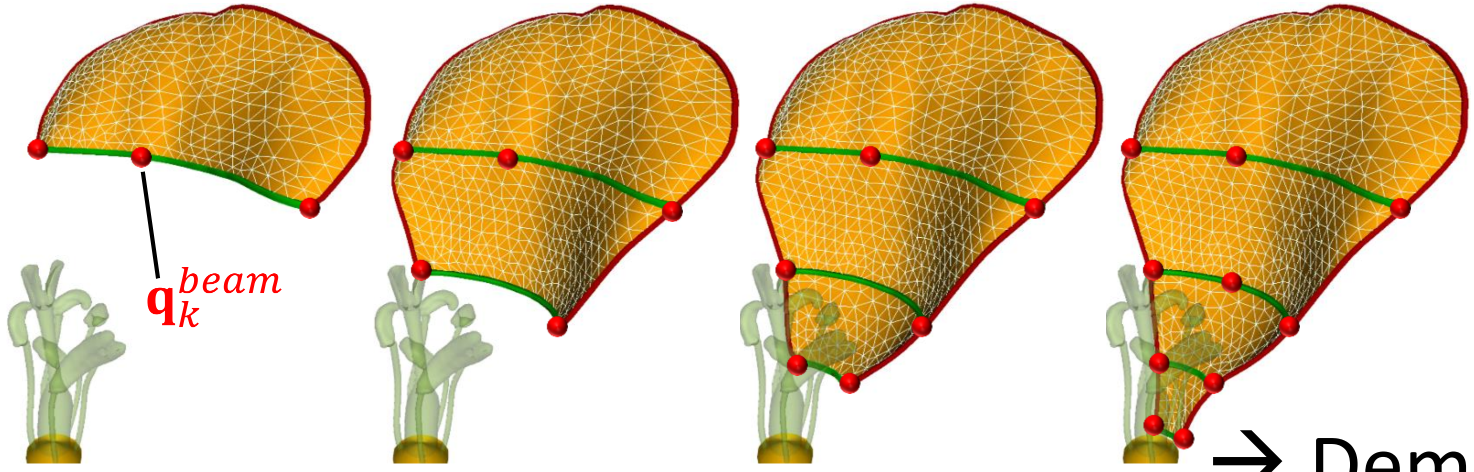
Surface with adaptive thickness

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

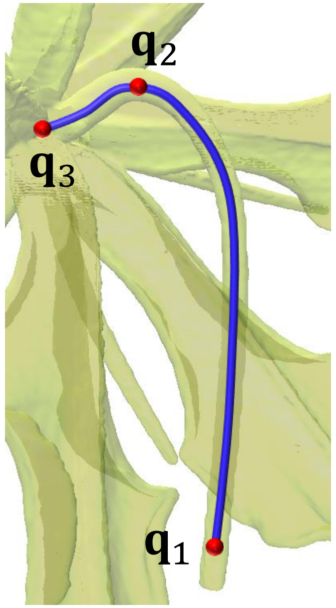
The user places CPs on a curve of the target petal

→ Beam/boundary curves & active surface is computed

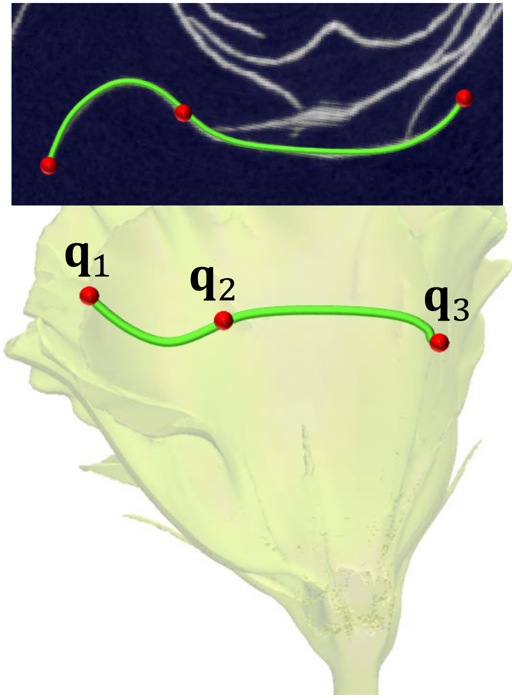
Active curves $\mathbf{C}(t)$

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

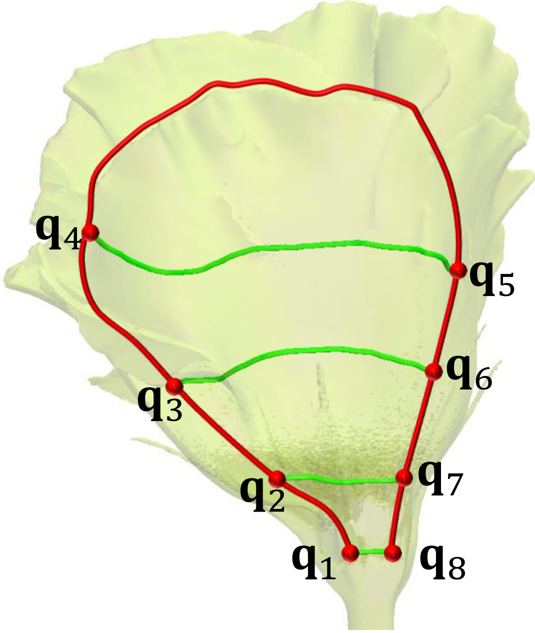
Trace their targets regions



Shaft axis



Beam

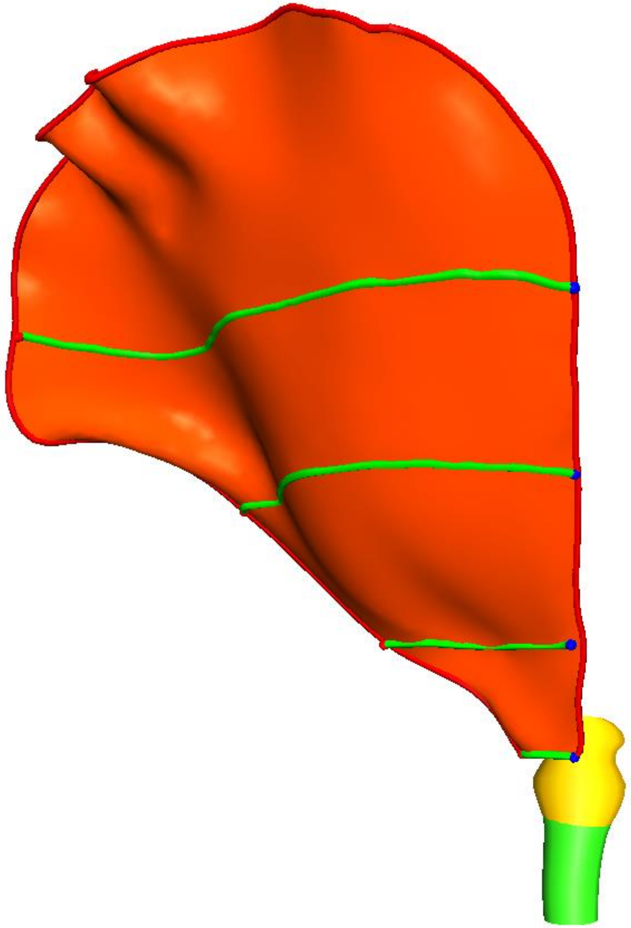


Boundary

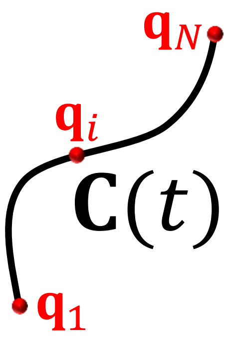
Active surface $\mathbf{S}(u, v)$

Interpolate curve network

Trace target region



Active curves / surface energies



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

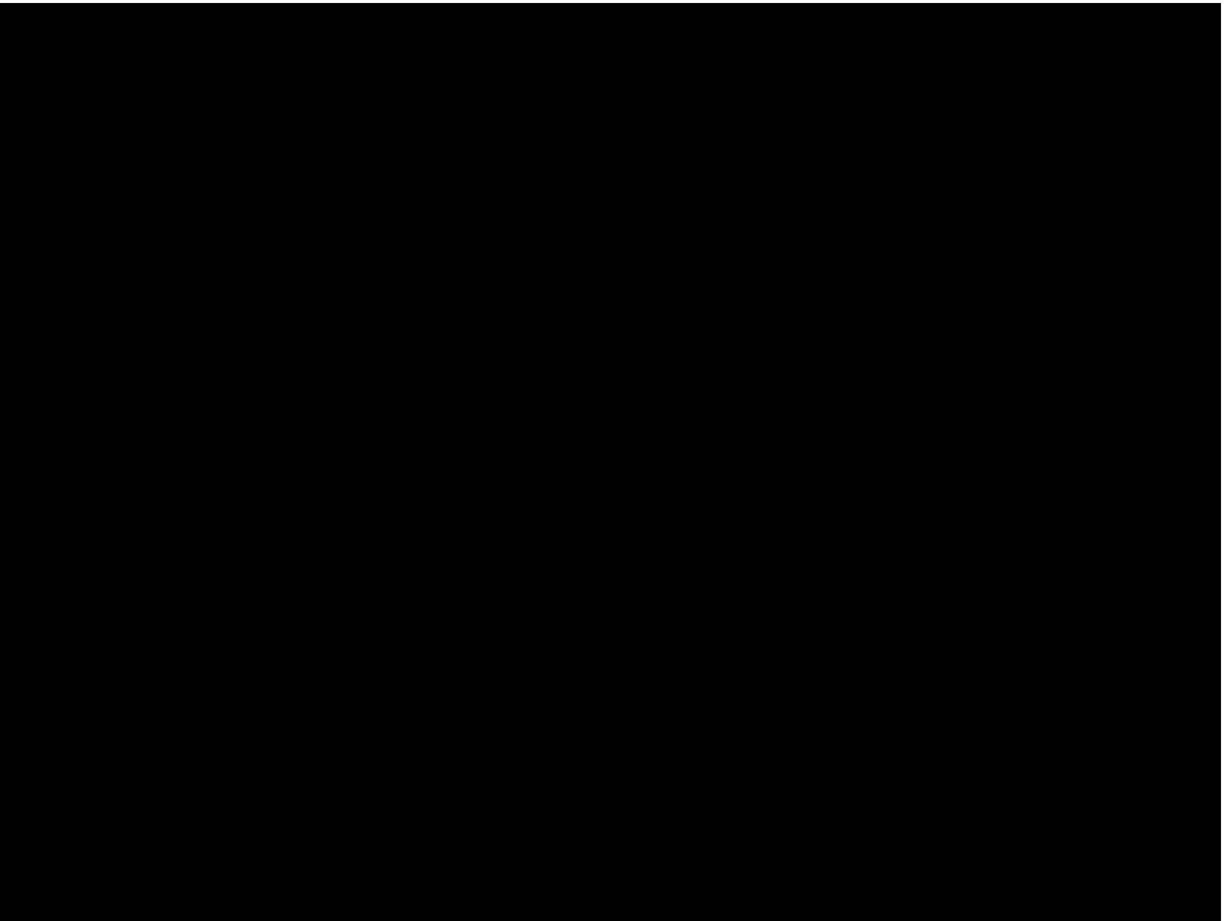
Smoothing effects

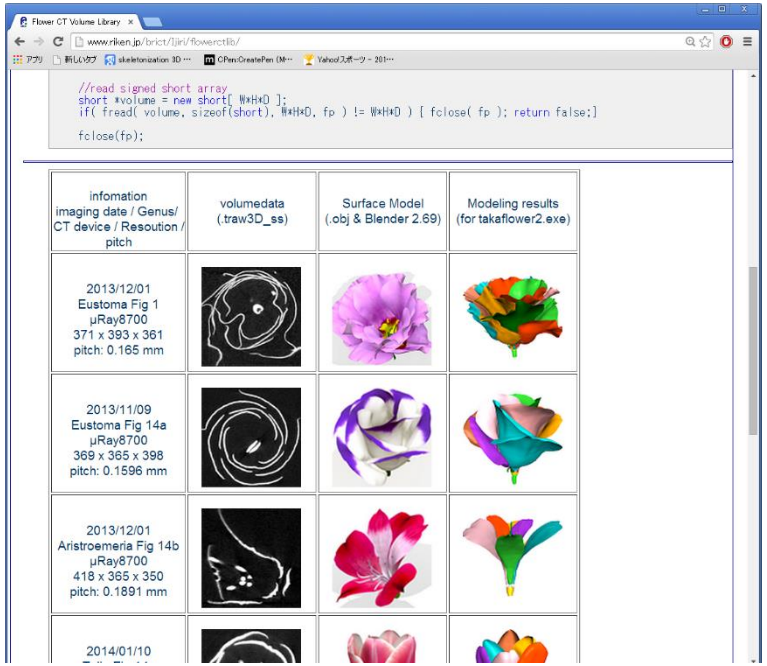
$$E_s = \int\int_{\Omega_s} \frac{1}{2}(\mathbf{S}_{uu}^2 + 2\mathbf{S}_{uv}^2 + \mathbf{S}_{vv}^2) \; + \; \beta|\boldsymbol{\mathcal{B}}\mathbf{S}_u \times \boldsymbol{\mathcal{B}}\mathbf{S}_v|dudv$$

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

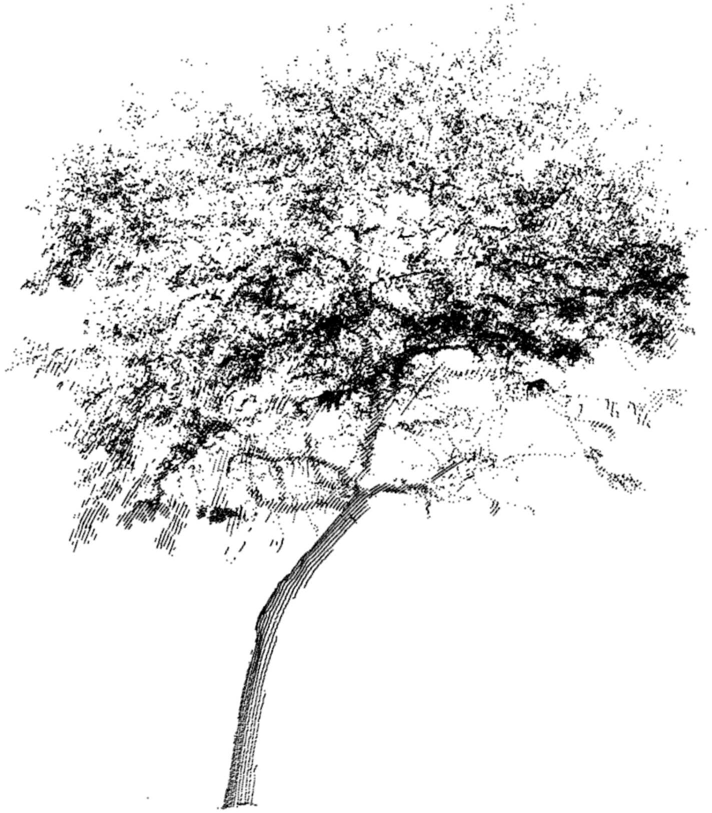
- Livny, Y., Pirk, S., Cheng, Z., Yan, F., Deussen, O., Cohen-Or, D., Chen, B. (2011) **Texture-lobes for tree modeling**. ACM Trans. Graph. 30, 4, 53:1–53:10.

Reconstruction of Urban Scenes

LiDAR-Scanner

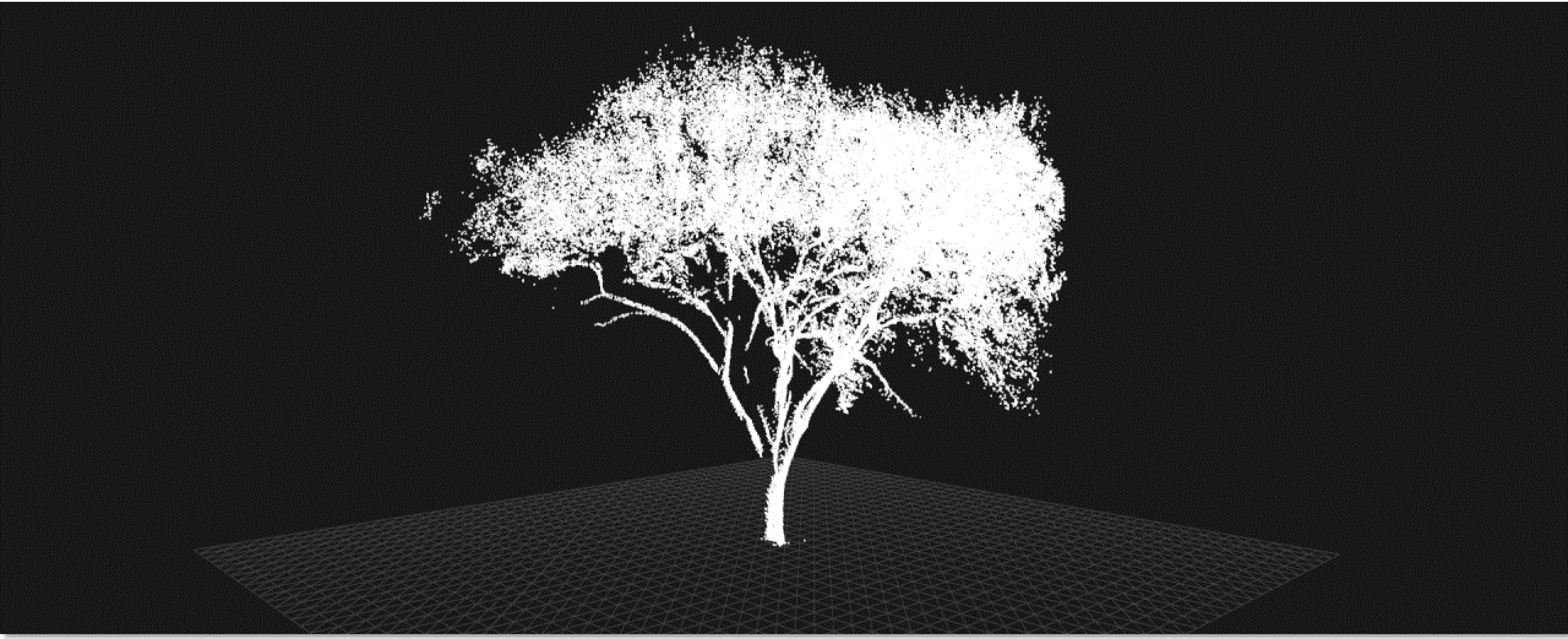
Real Tree

Scan

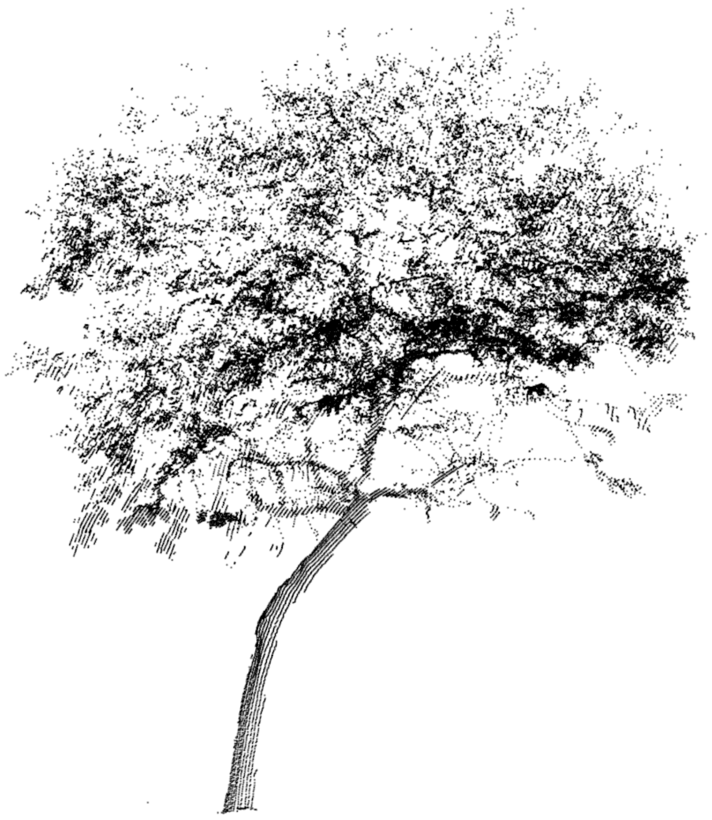


3D Point Cloud

3D Point Sets

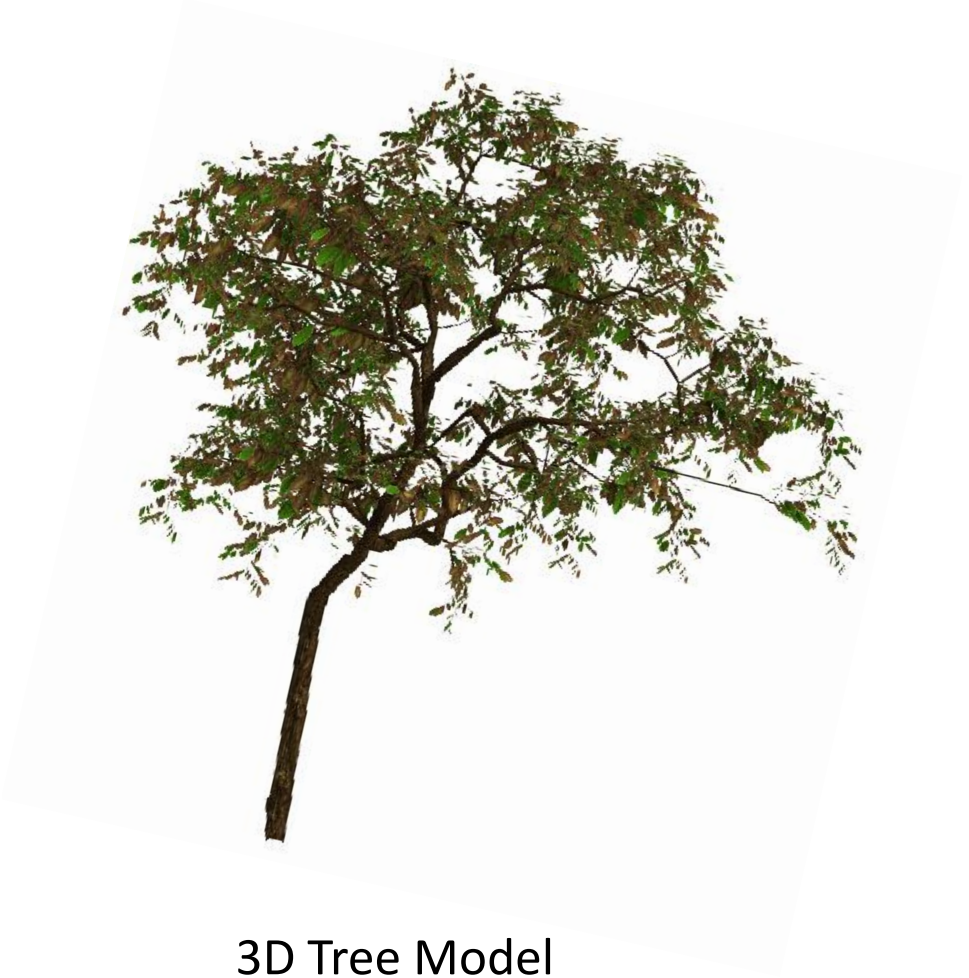


From Point Sets to Meshes



3D Point Cloud

?



3D Tree Model

A Tree is Complex

Human visual bandwidth is limited → abstraction

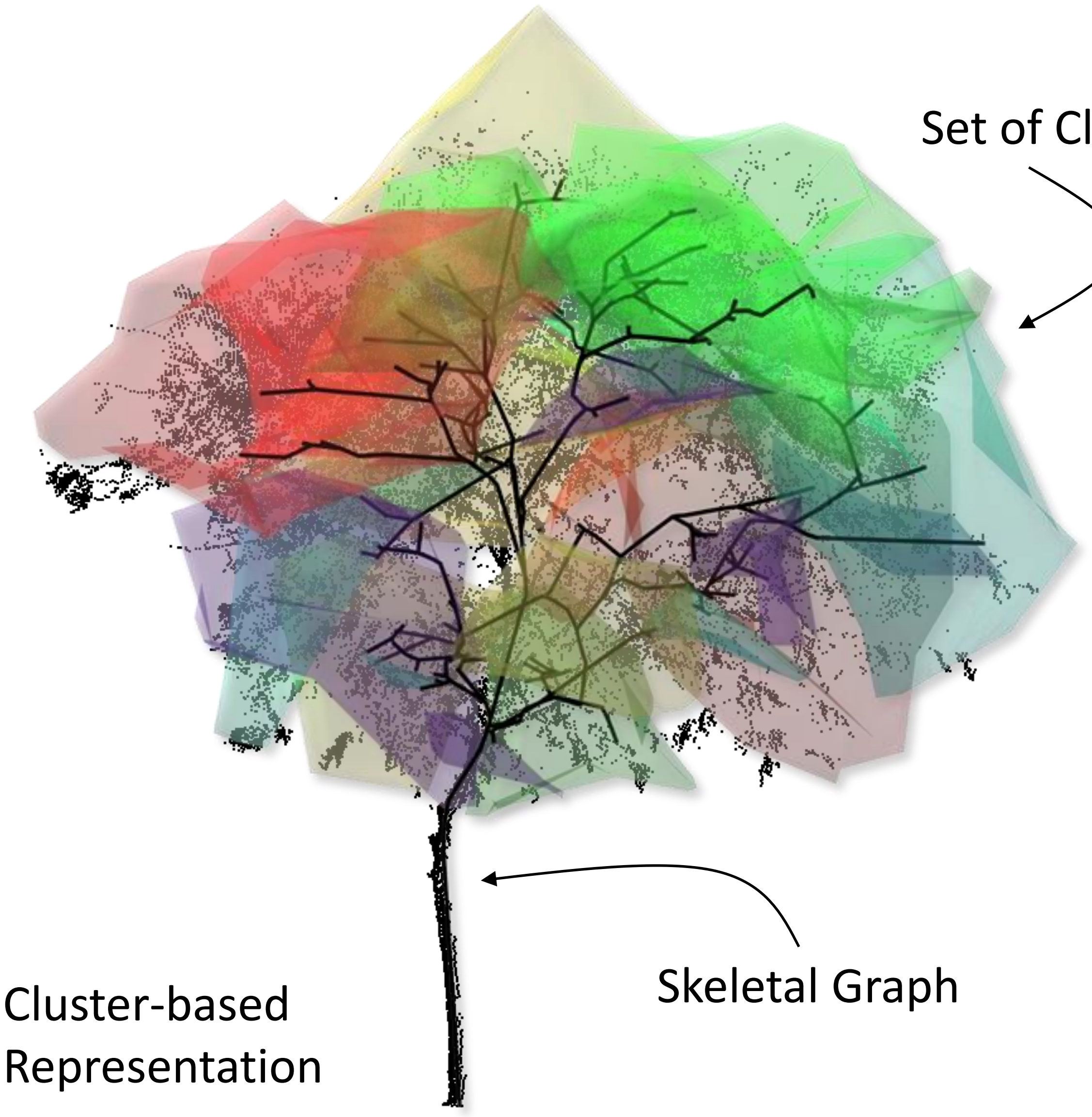
Cluster-based Representation

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]

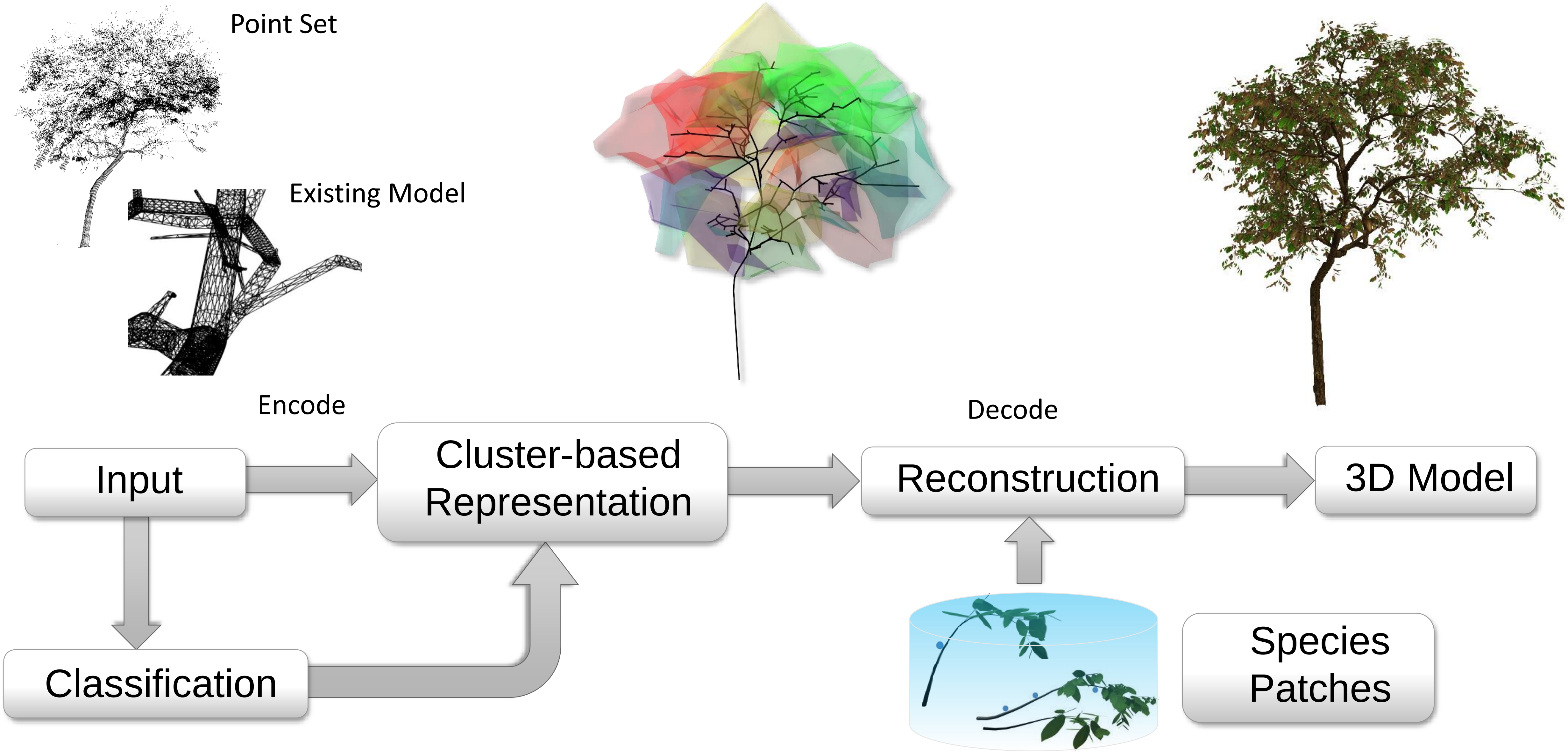


Set of Clusters

Skeletal Graph

Cluster-based Representation

Pipeline


Point Set
Existing Model
Encode
Decode
Input
Cluster-based Representation
Reconstruction
3D Model
Classification
Species Patches

Resource Requirements

~30 kB

Cluster-based Representation

+

~100 kB

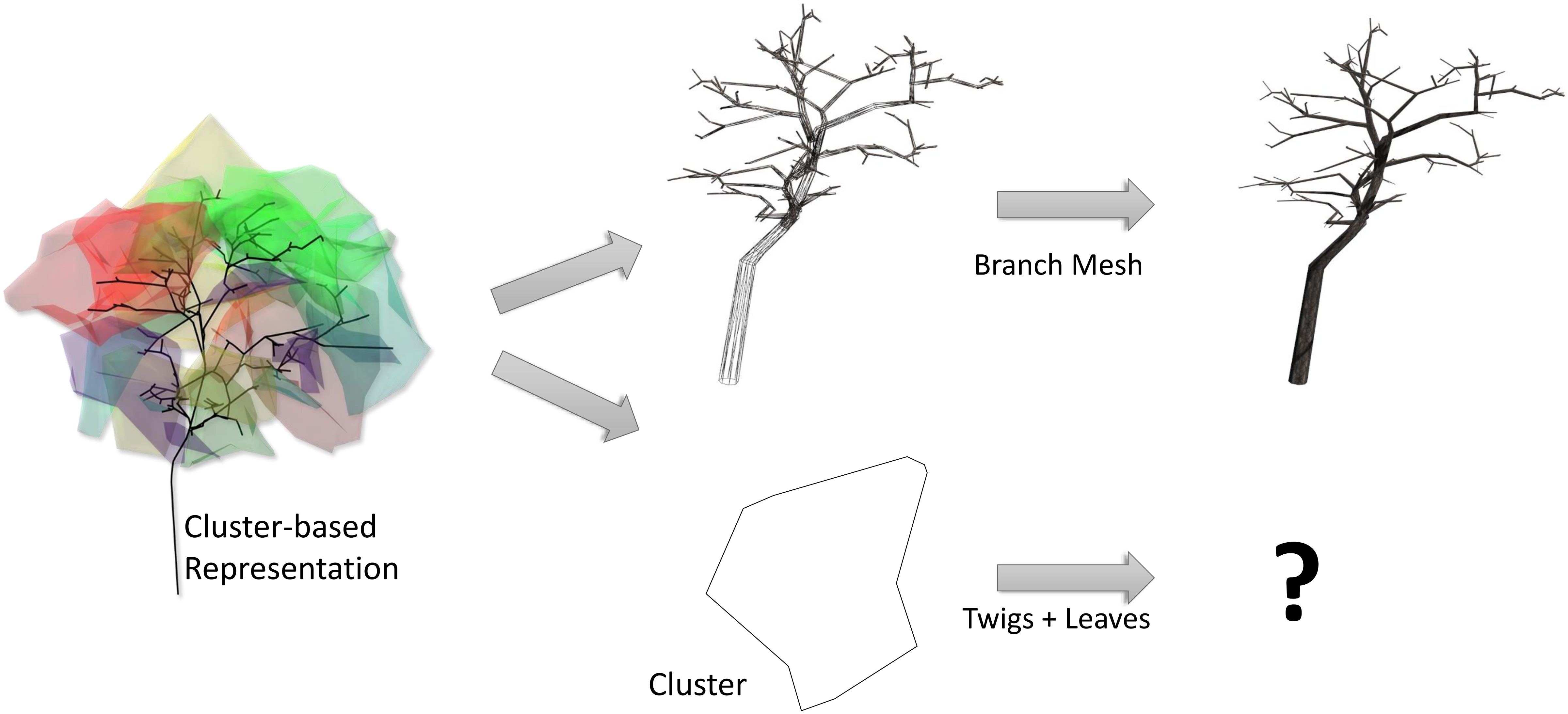
Species Information

=

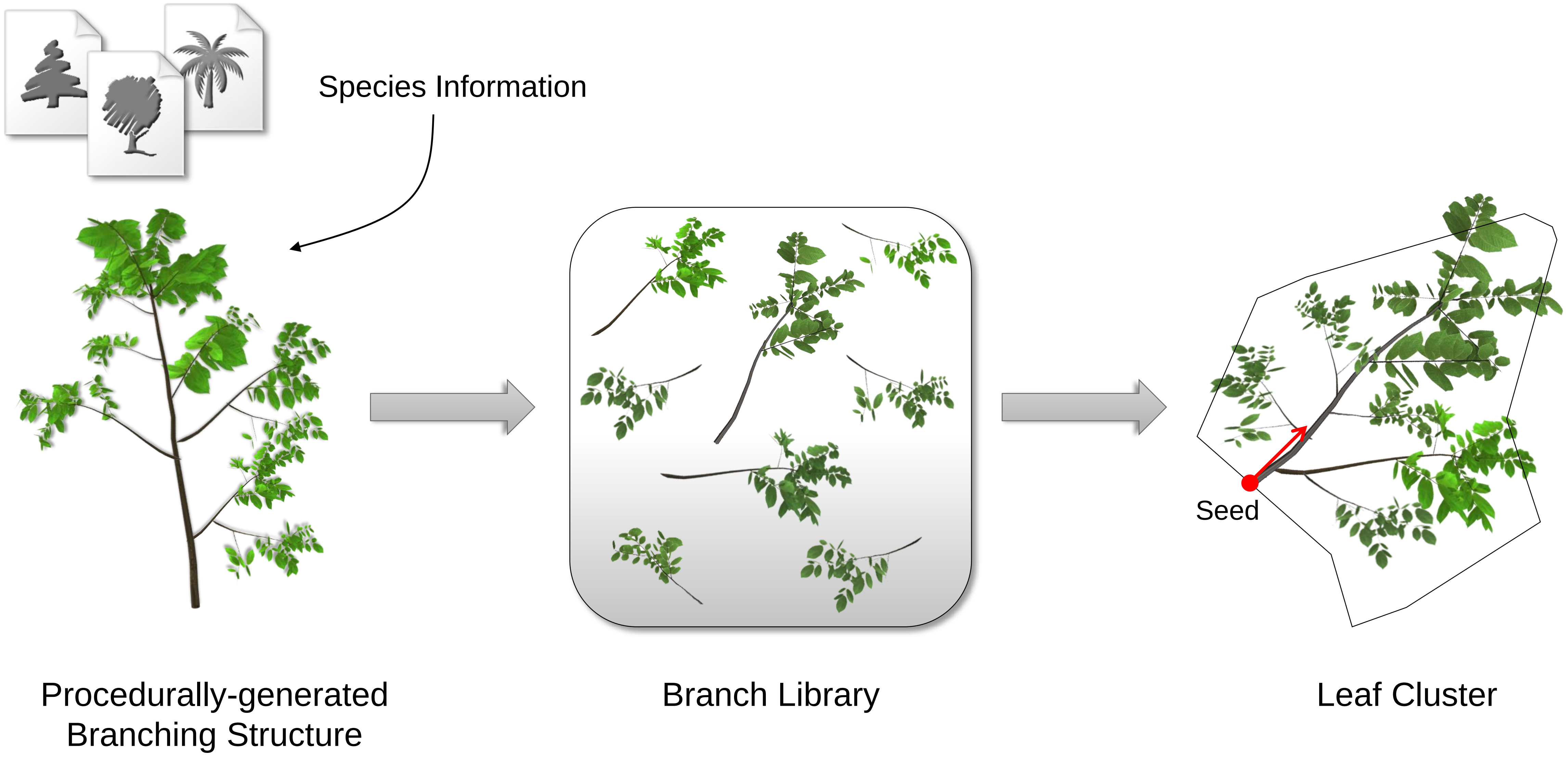
~60 MB

Reconstruction

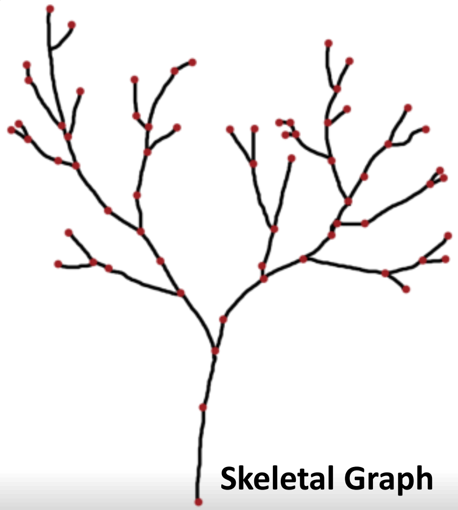
Reconstruction

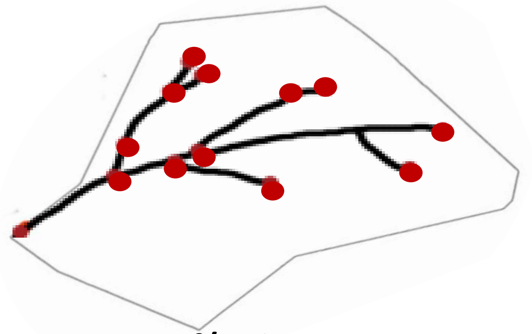


Geometry Synthesis

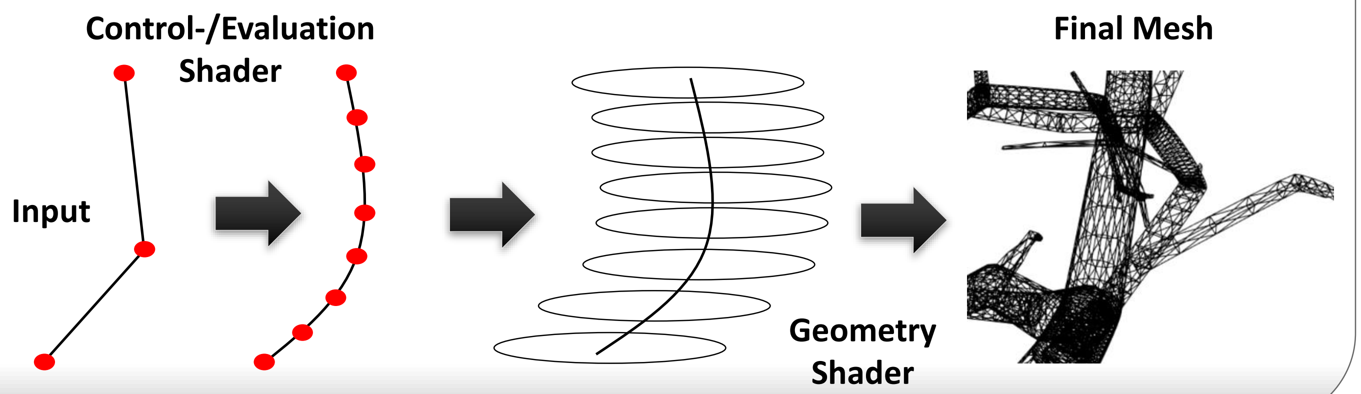


Mesh Construction

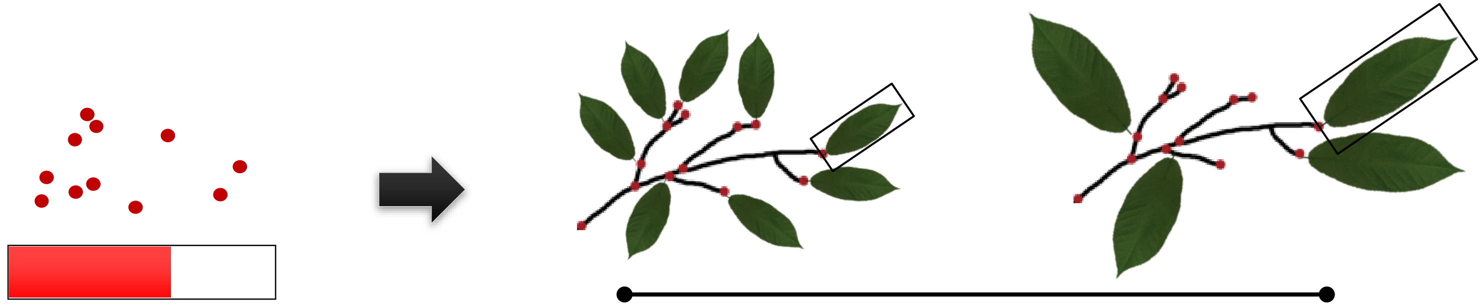




Branches: Mesh Generation [Bloomenthal 1985]



Leaves

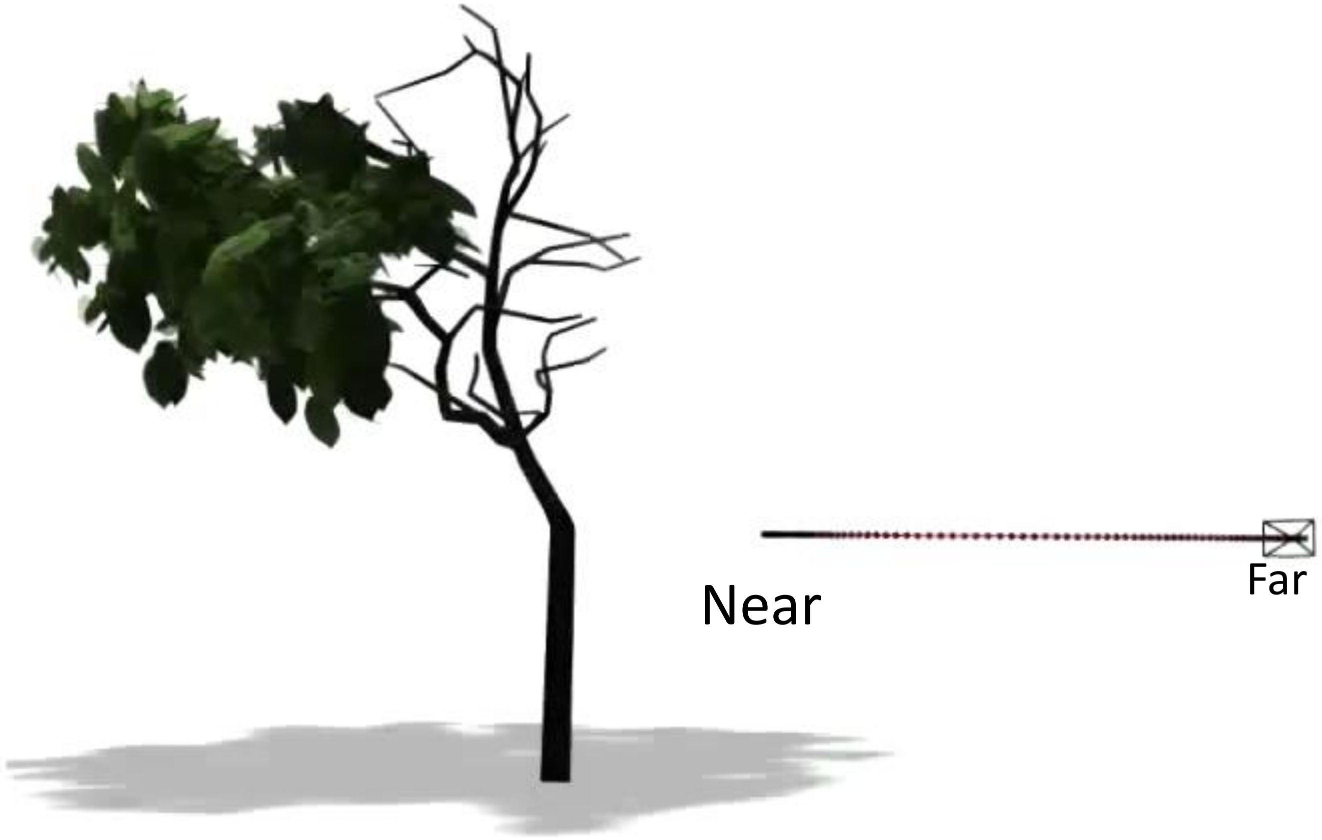


CPU | GPU

Dynamic Level of Detail

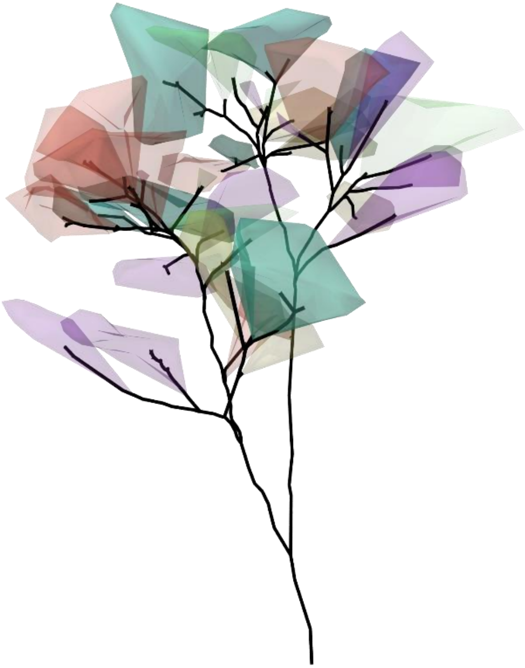
[Cook et al. 2007]

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

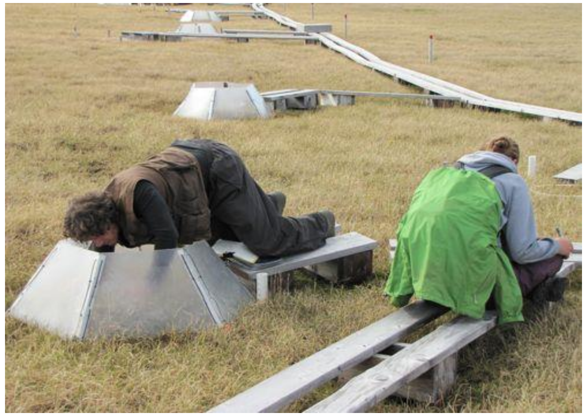
Video courtesy to Neil Bromhall on Youtube: Sycamore seedling growing time lapse

Render the Possibilities
SIGGRAPH2016

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

Charactering Plant Growth (1)

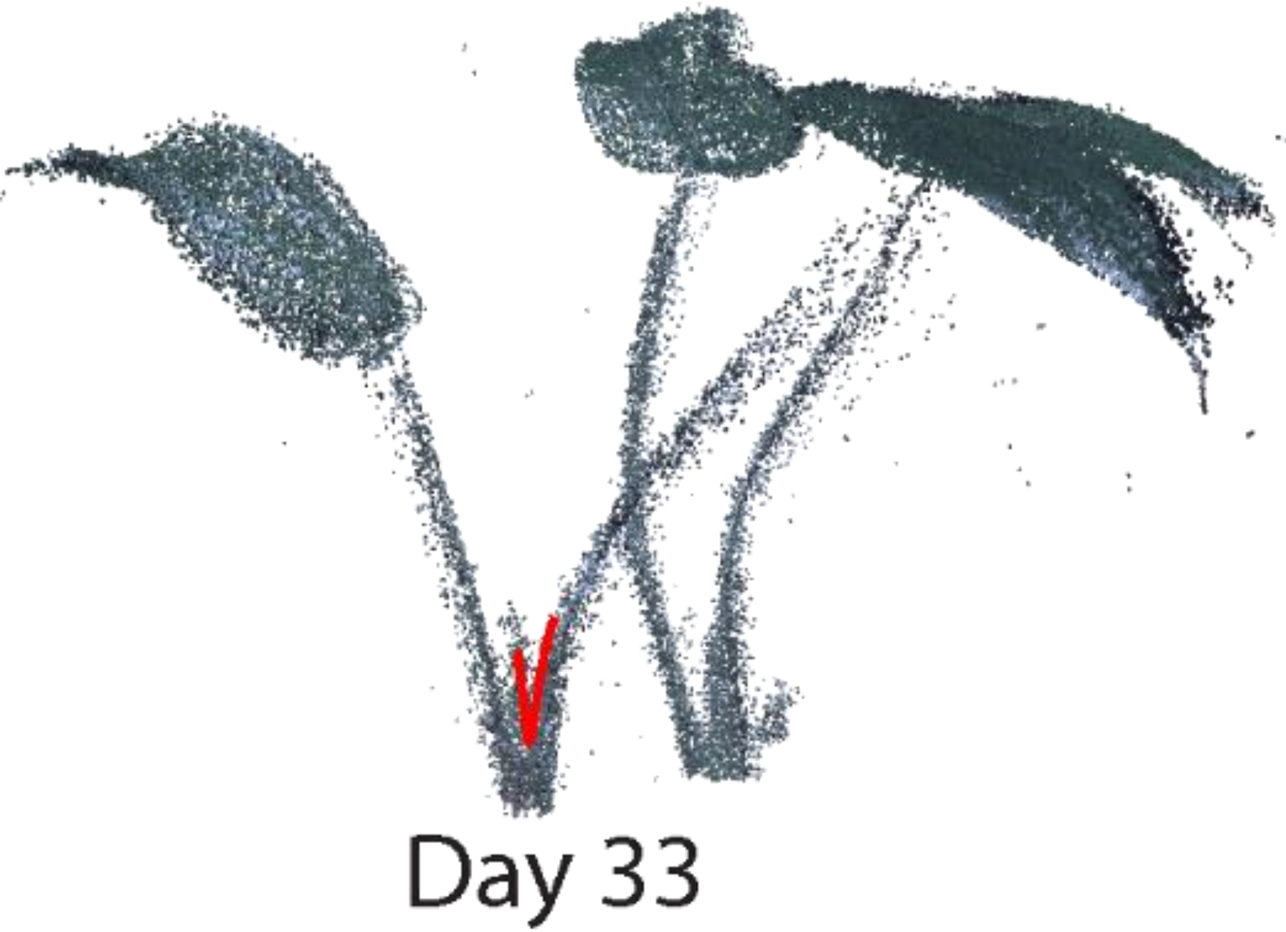
- Quantitative properties
  - Area, volume, etc.
  - Better in organ level




Huge amount of work!!!

Charactering Plant Growth (2)

- Growth events (qualitative changes)



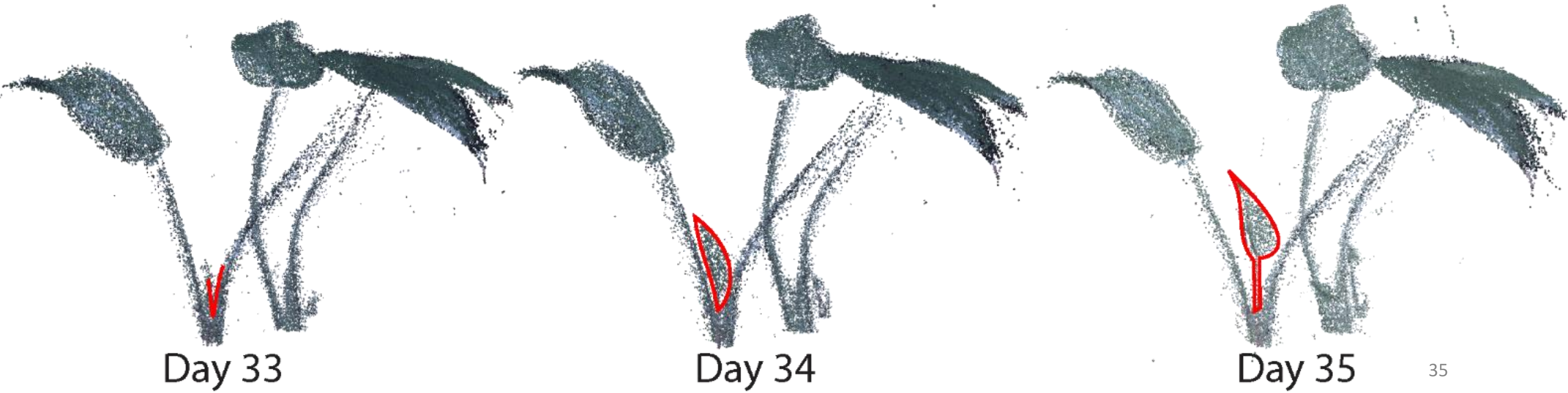
Bifurcation

Budding

Challenges

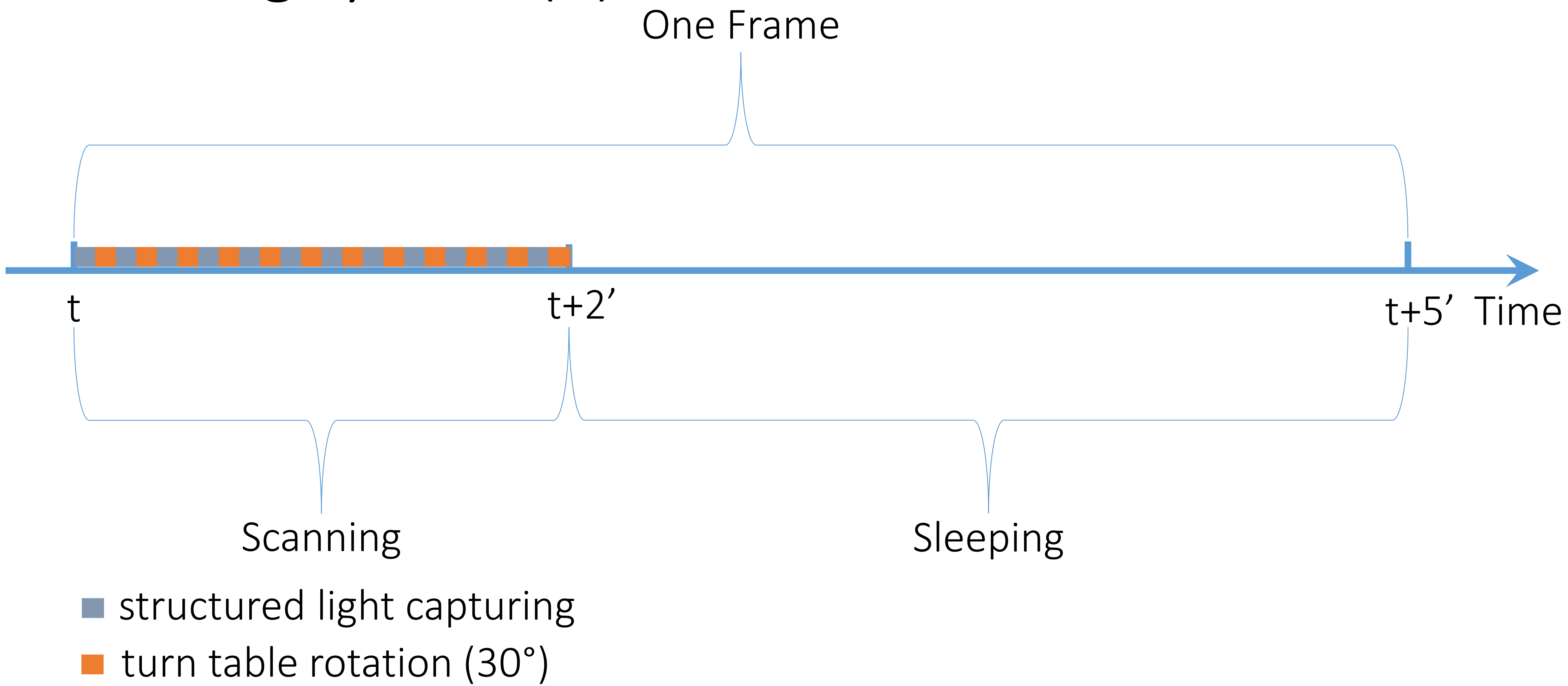
- Large deformation (violating incompressibility assumption)
- Large topology change
- No shape template

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



Scanning system (1)

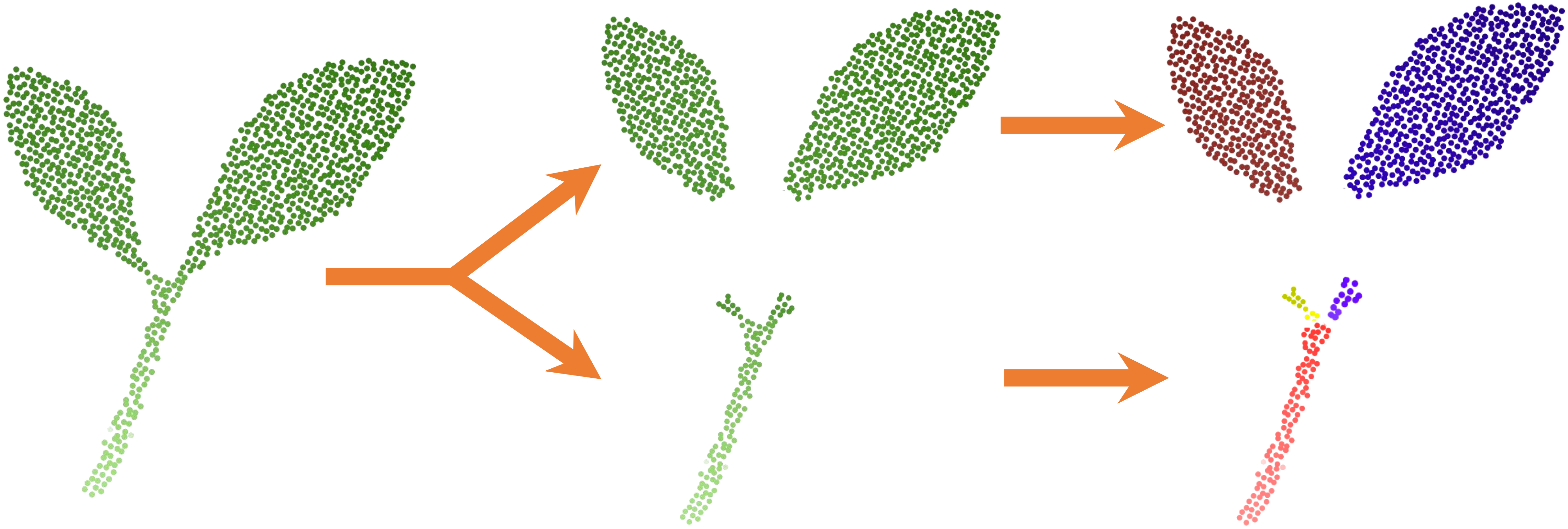
Scanning system (2)



Detecting growth events → counting organ number

Counting organ number → point cloud segmentation

Algorithm pipeline: Two-stage Segmentation



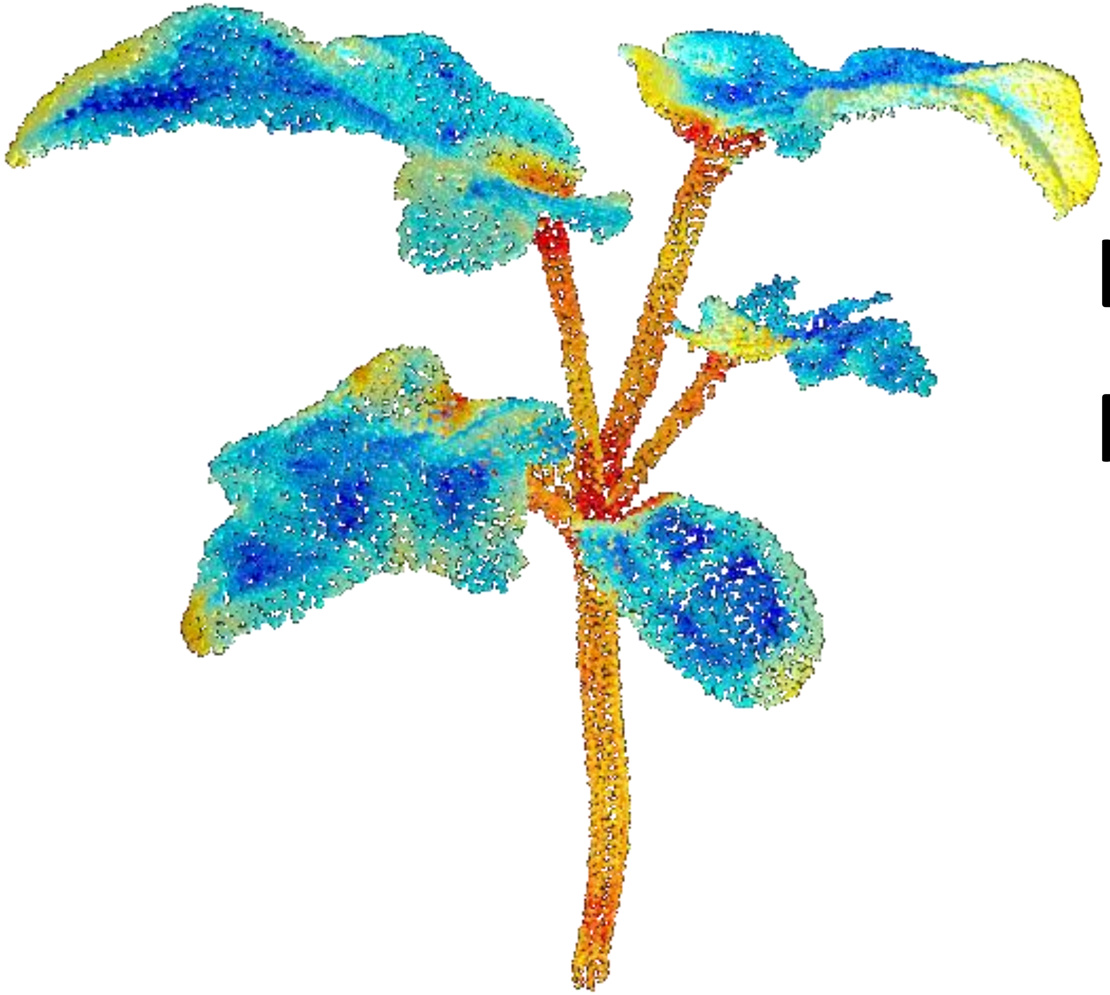
Leaf-stem classification

Binary labelling problem

Individual organ segmentation

Multi-labelling problem

Leaf-stem classification: discriminative feature



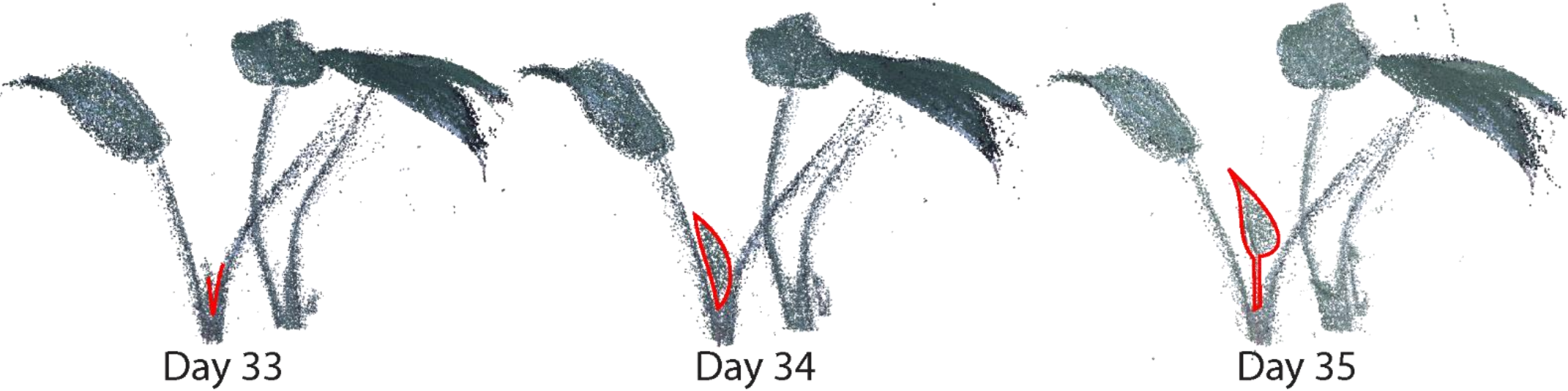
Curvature $C(p^t)$ of Plant Points

Leaves are more "flat"!

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

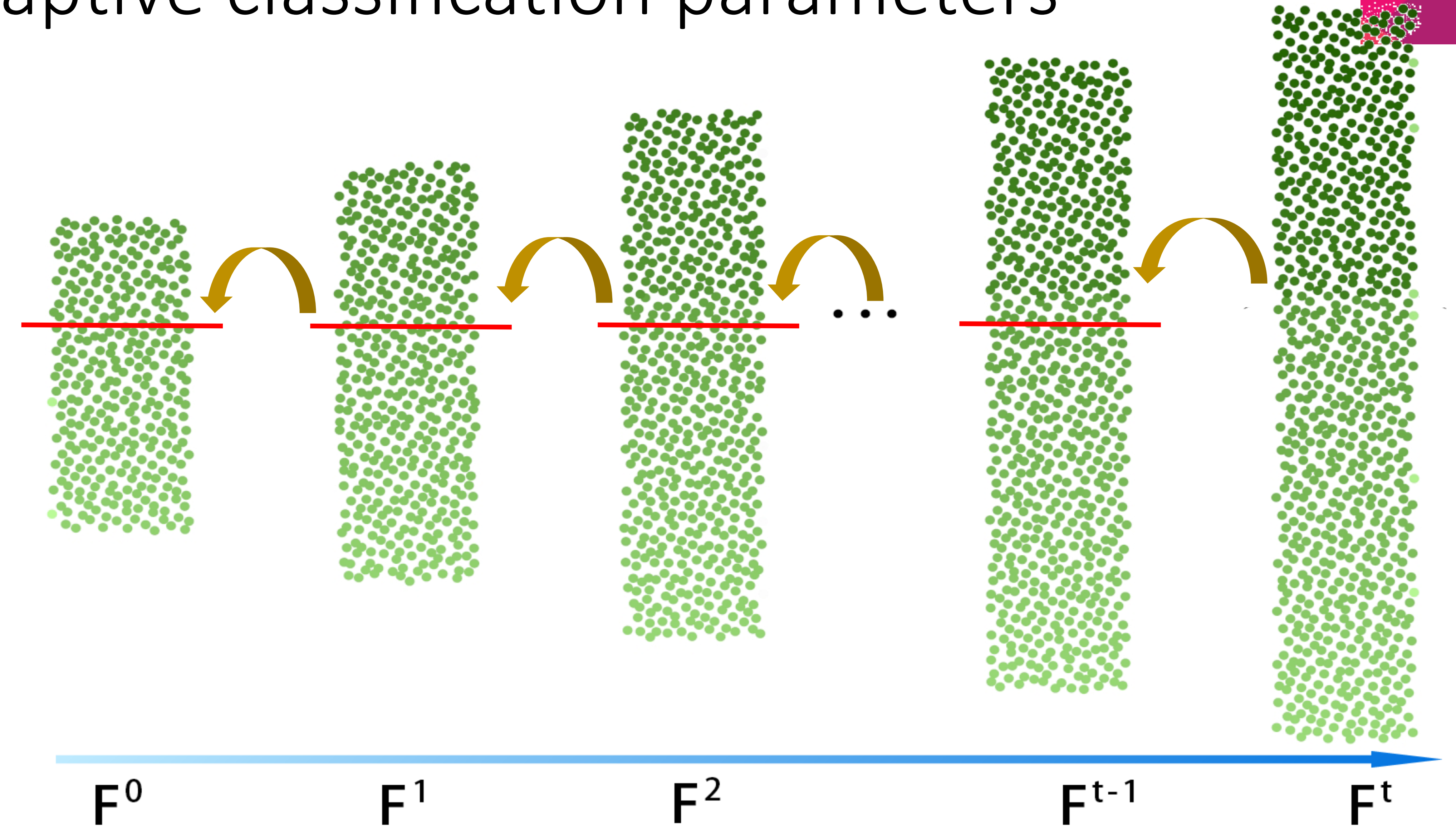
$$f_B(p^t) = \begin{cases} \mathrm{S, if}\ C(p^t) > t \\ \mathrm{L, if}\ C(p^t) \leq t \end{cases}$$

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



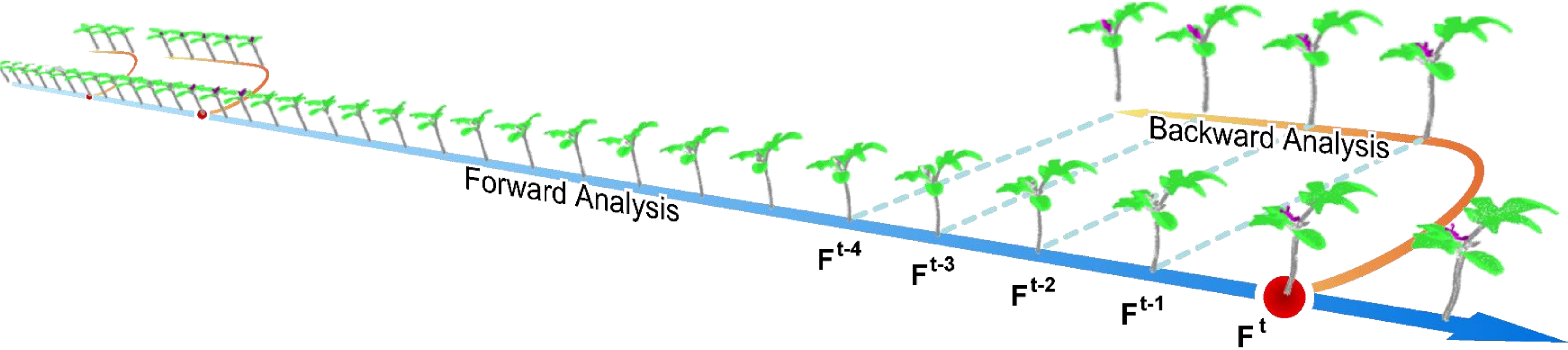
$$f_B(p^t) = \begin{cases} S, \text{if } C(p^t) > t \\ \mathrm{L}, \text{if } C(p^t) \le t \end{cases}, \text{t has to be adaptive!}$$

Adaptive classification parameters



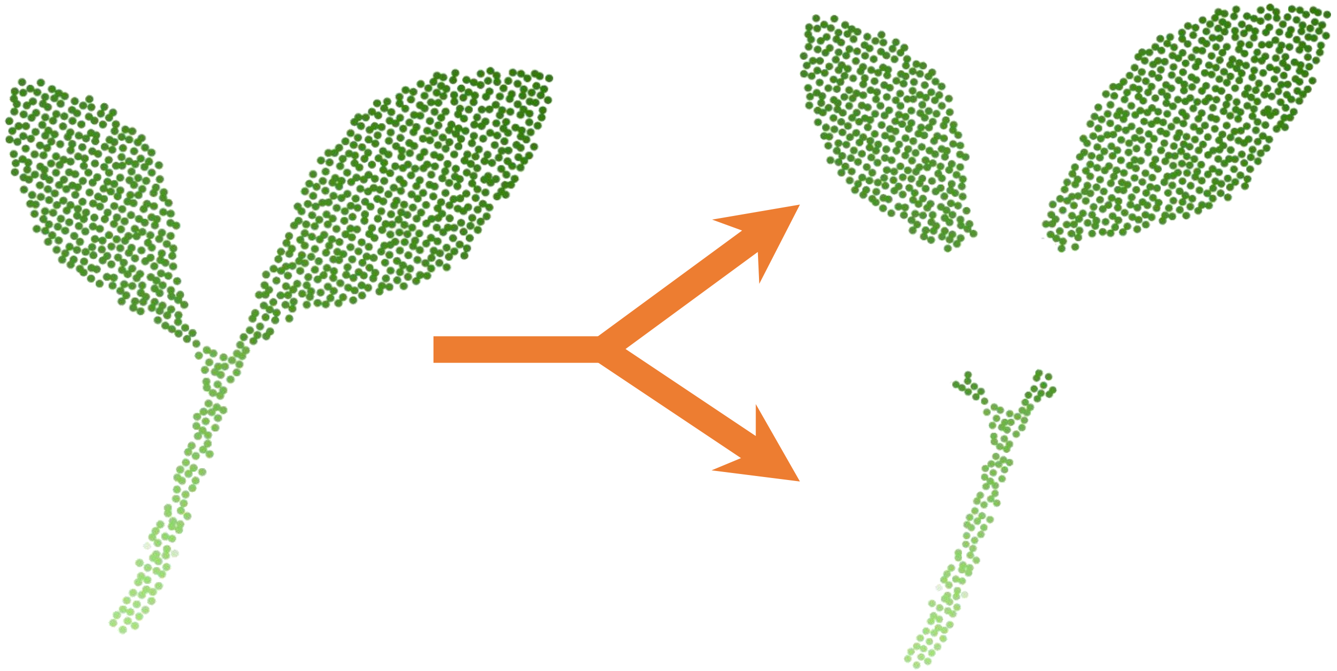
Growing leaf and stem in the feature space

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

Leaf-stem classification: data term (1)

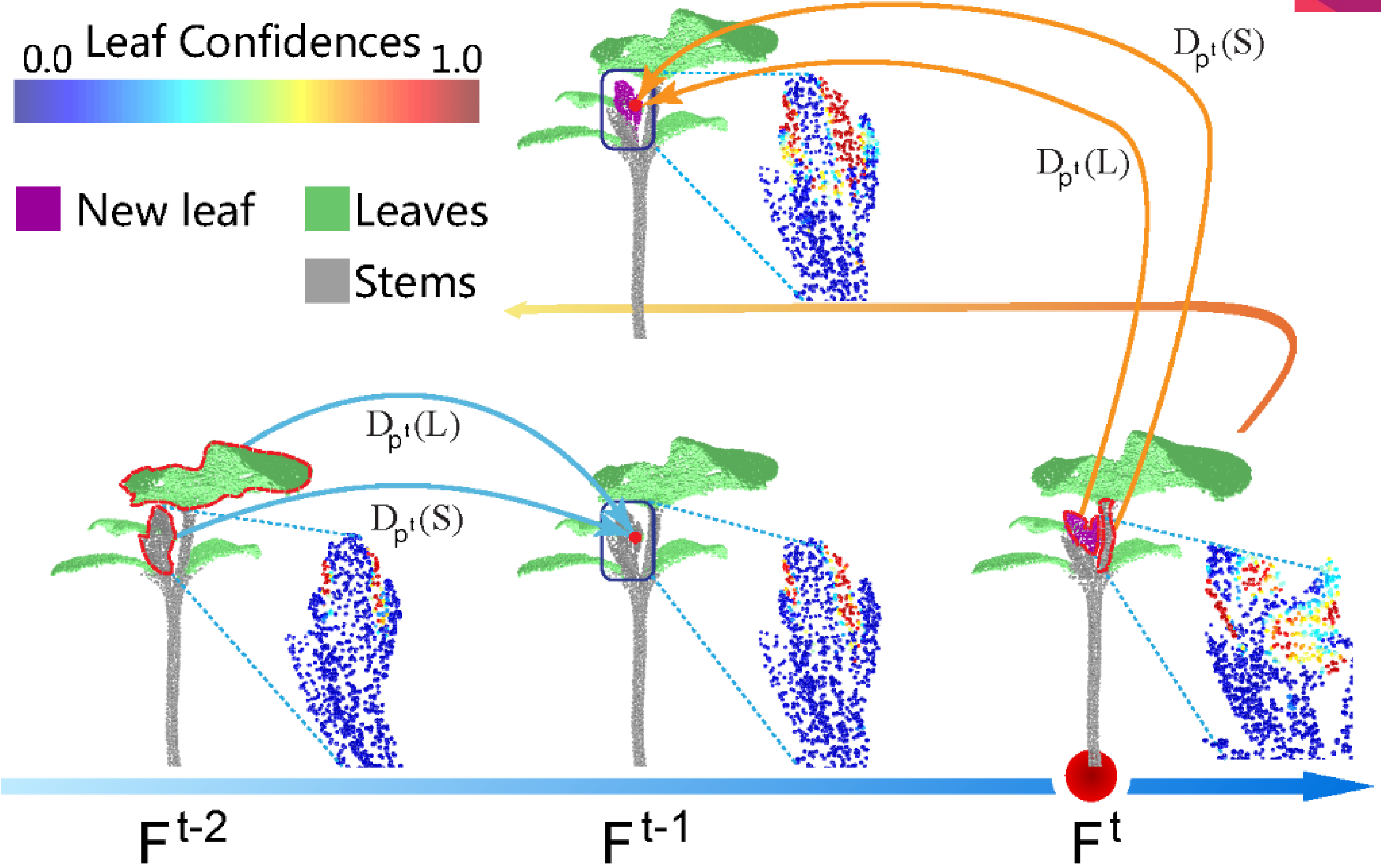
$$D_{p^t}(L) = \begin{cases} max\left(R(p^t) - R\left(L_{l*}^{t\pm1}\right), 0\right), if\ \Phi > 0 \\ R(p^t) - \boxed{\Re_L} \qquad\qquad if\ \Phi = 0 \end{cases},$$

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

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

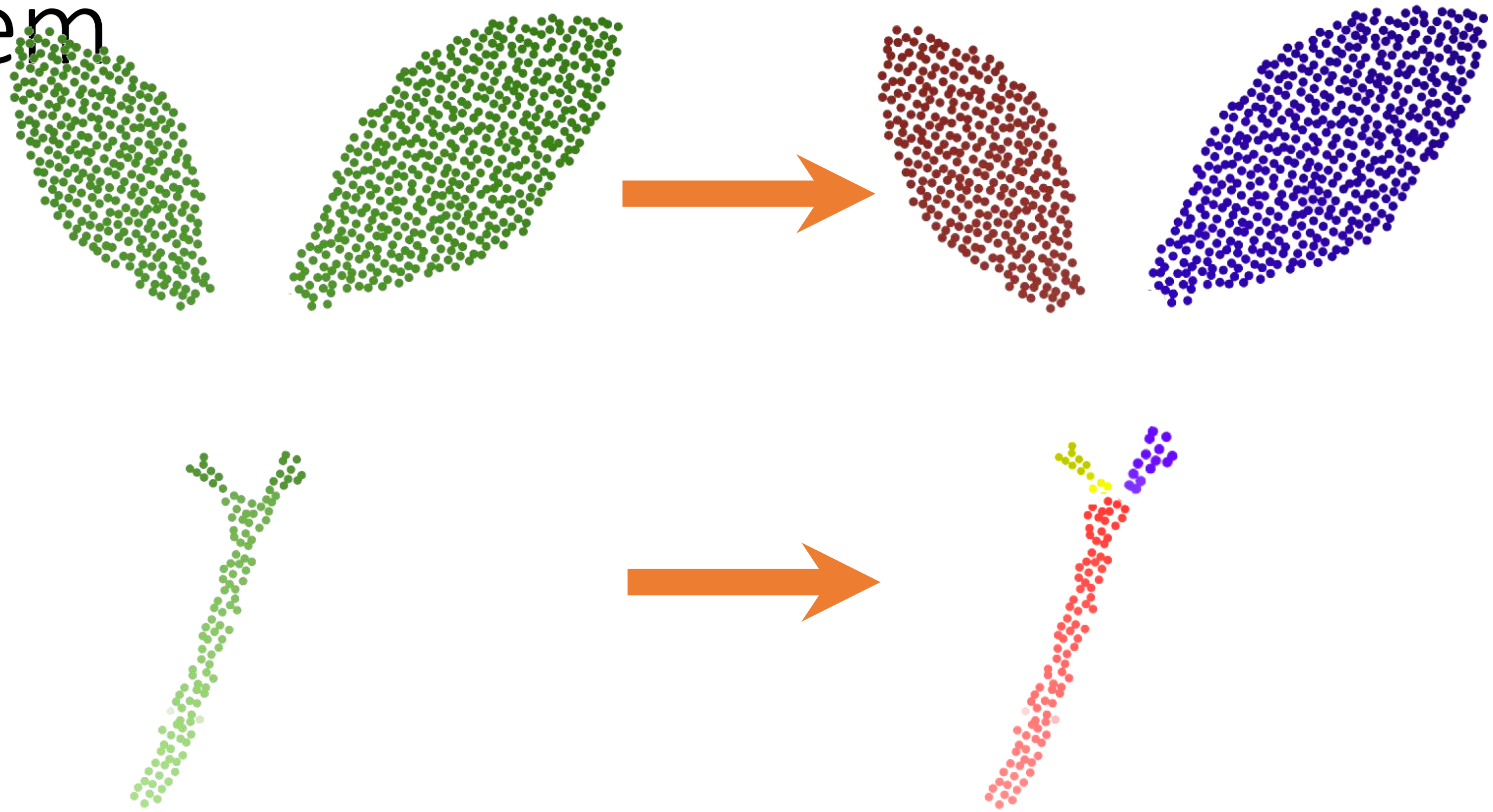
- **Spatial** and **temporal** adaption.
- Rarely relies on **global parameters**.

Leaf-stem classification: data term (2)



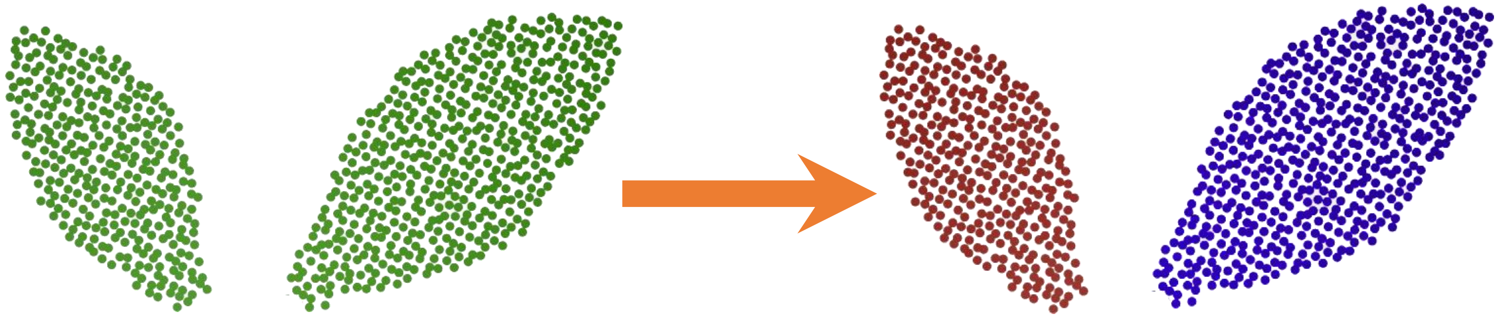
backward taking hints extractable only from future sequences

Individual organ segmentation: Multi-labelling problem



Label hypothesis generation + MRF optimization

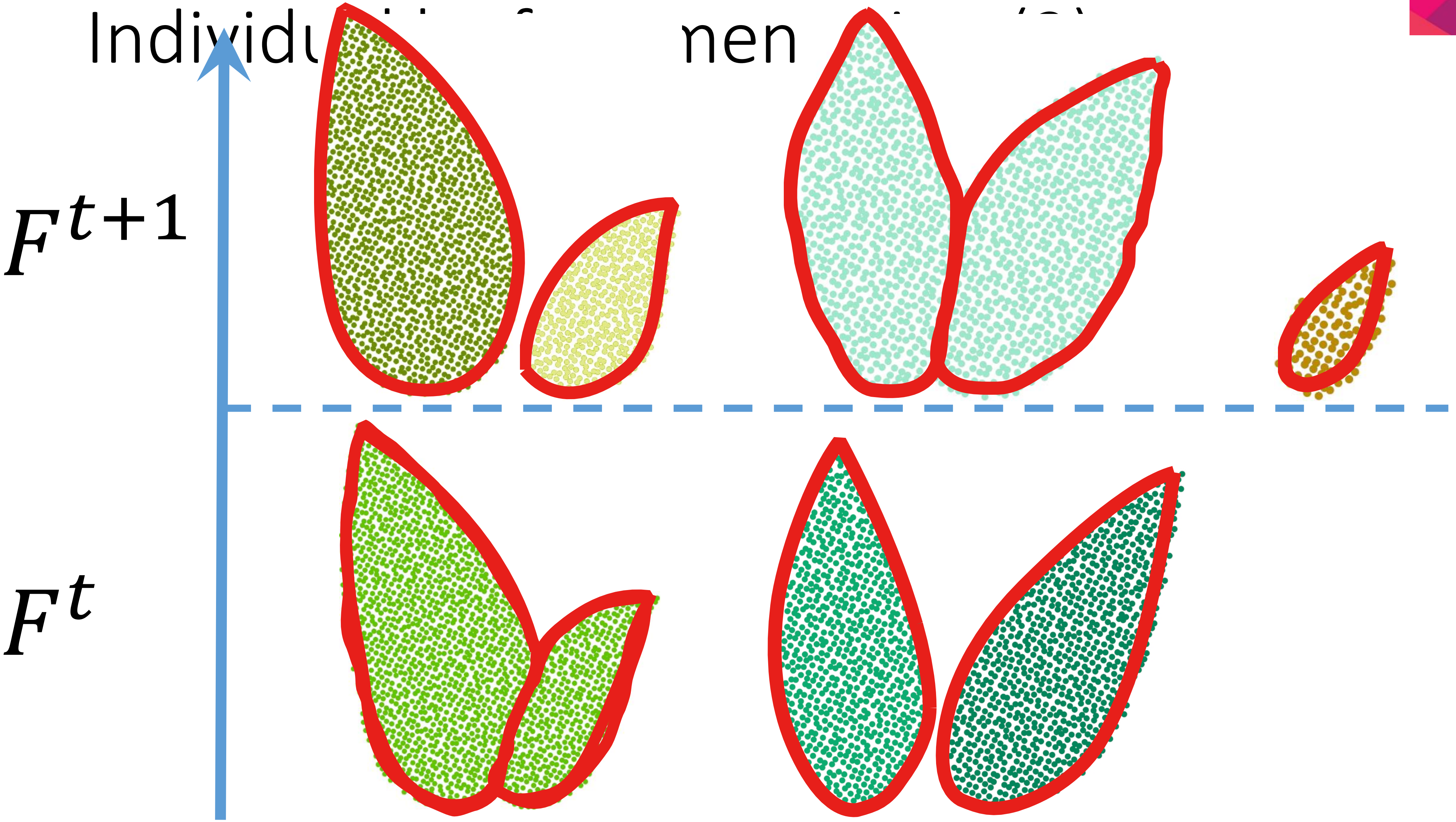
Individual leaf segmentation (1)



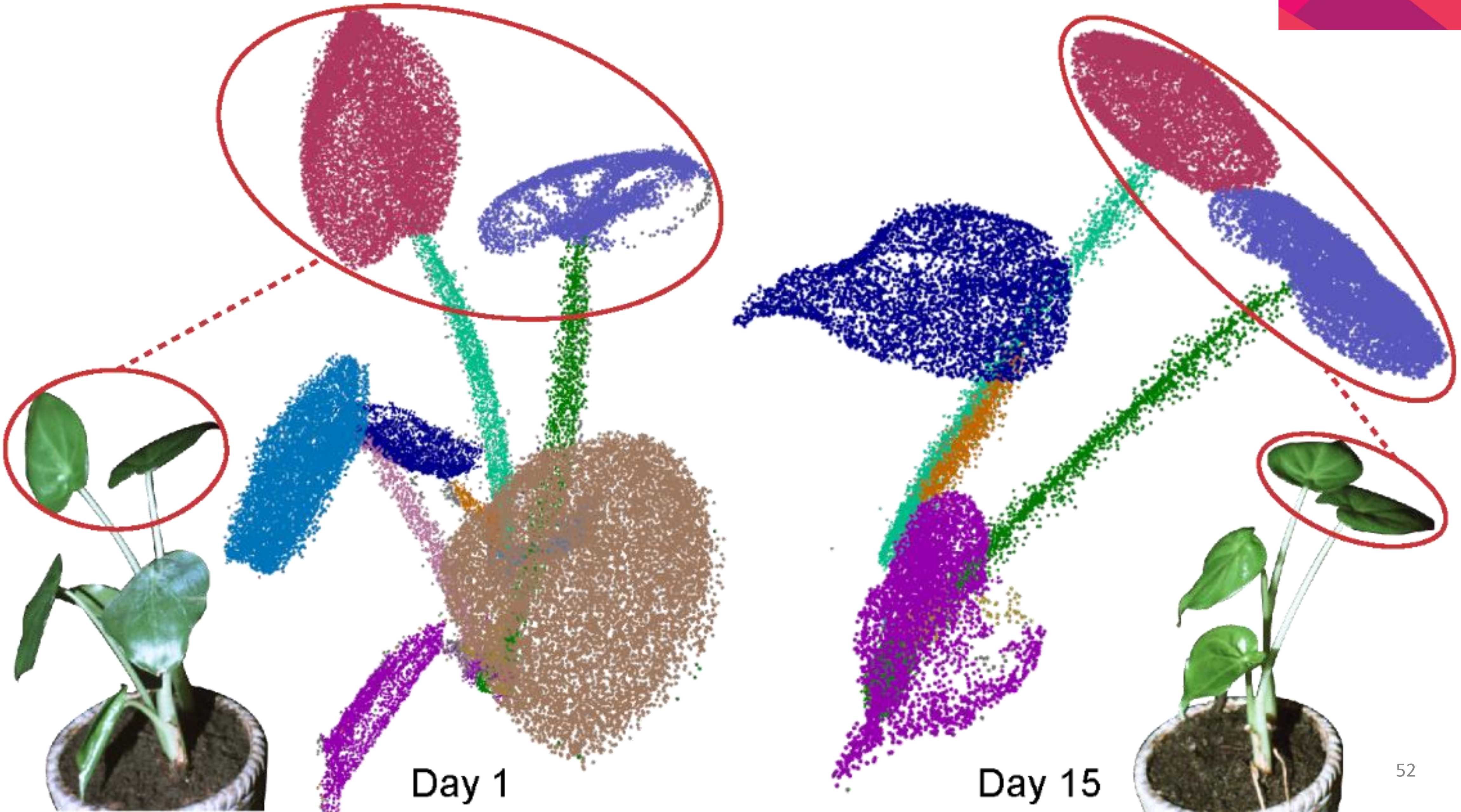
Individual leaf = one connected component

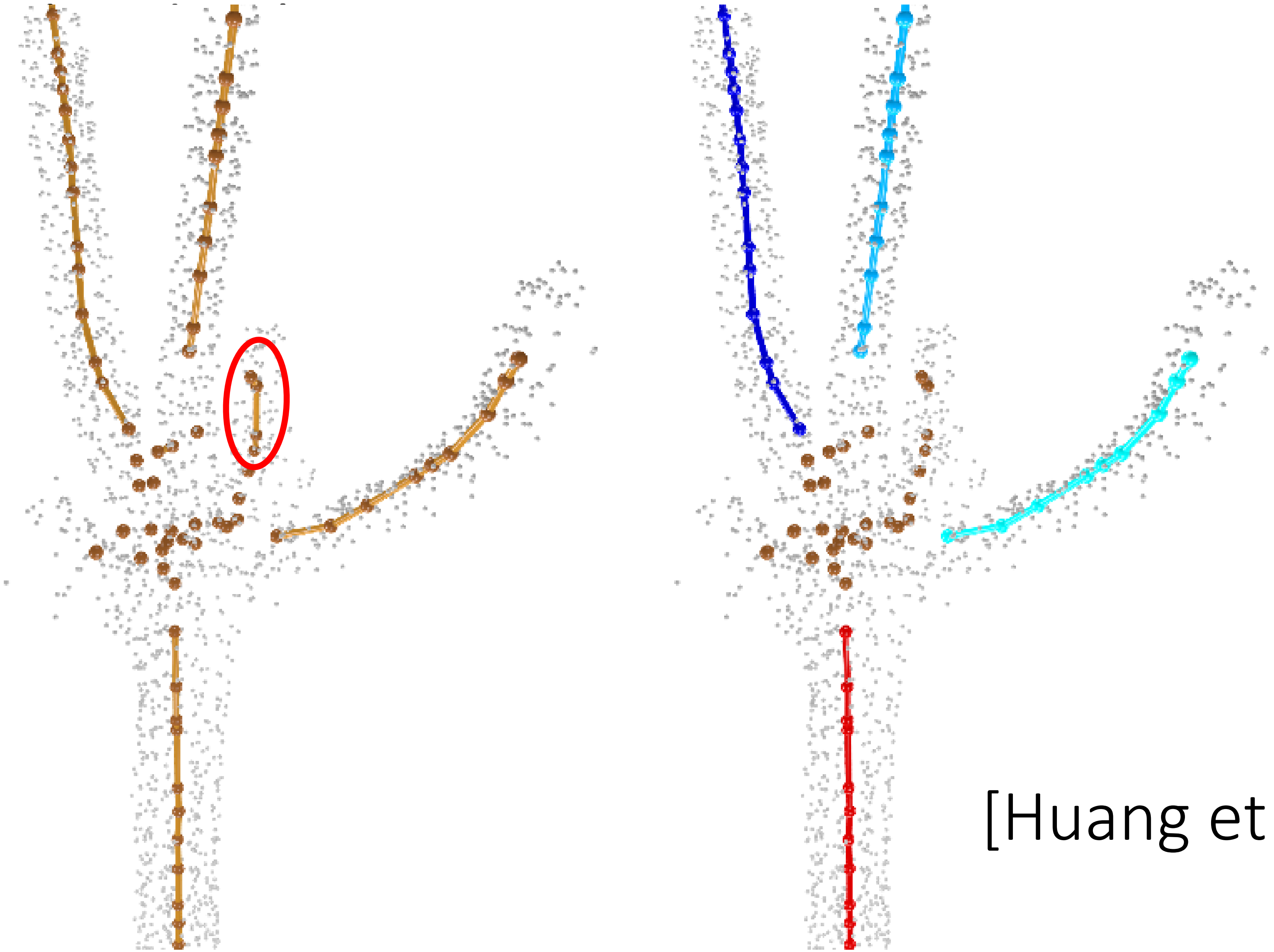
(true, if the leaves don't touch each other)

Individu nen



Transfer leaf information over time





[Huang et al. 2013]

[Dishlia]

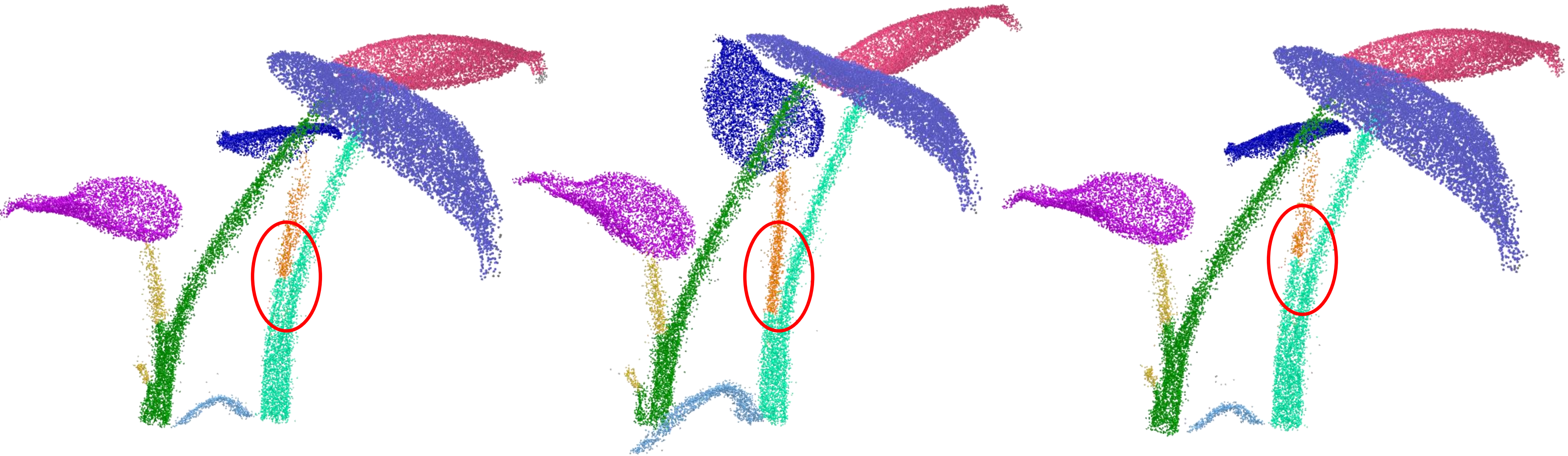
Day 1

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

[Organ Properties for Simulation]

[Synthesizing Live Plants]

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).

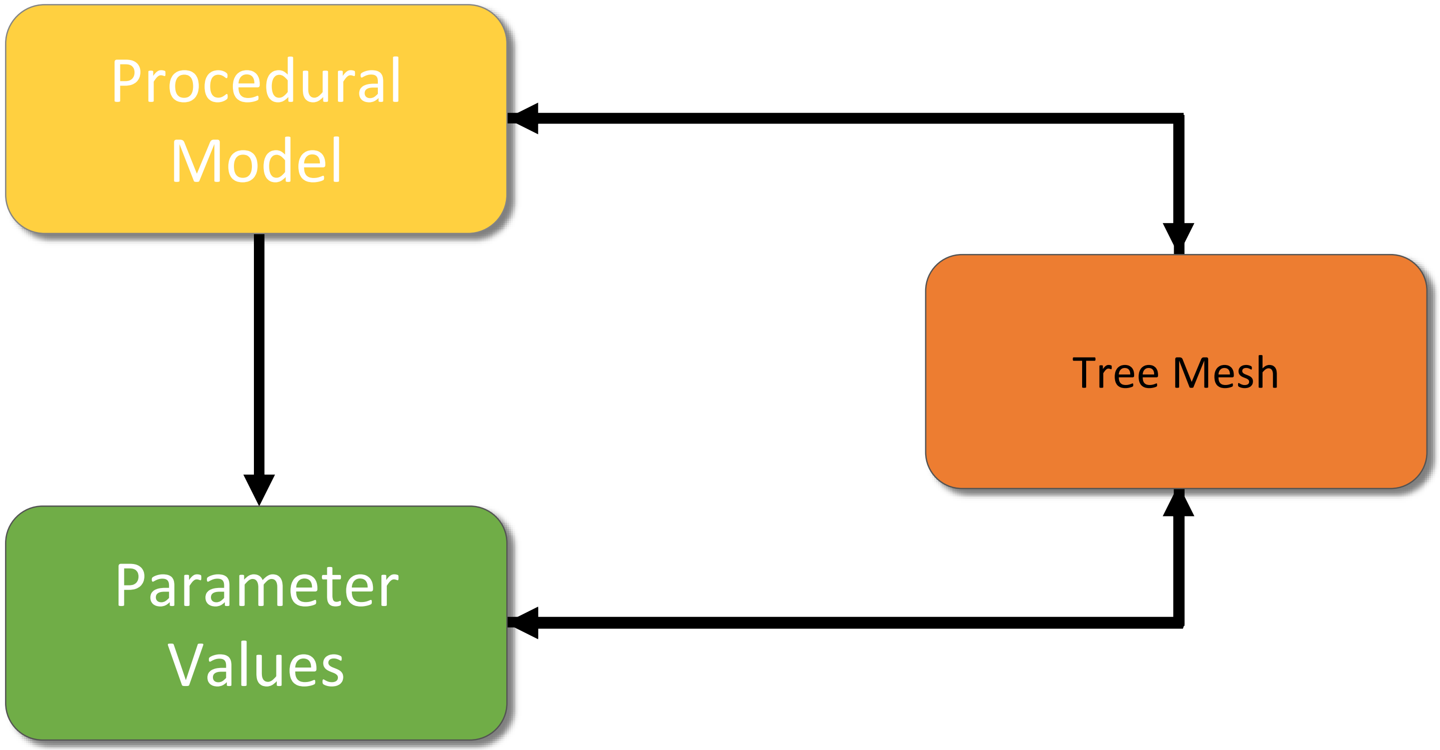
Procedural Modeling

?

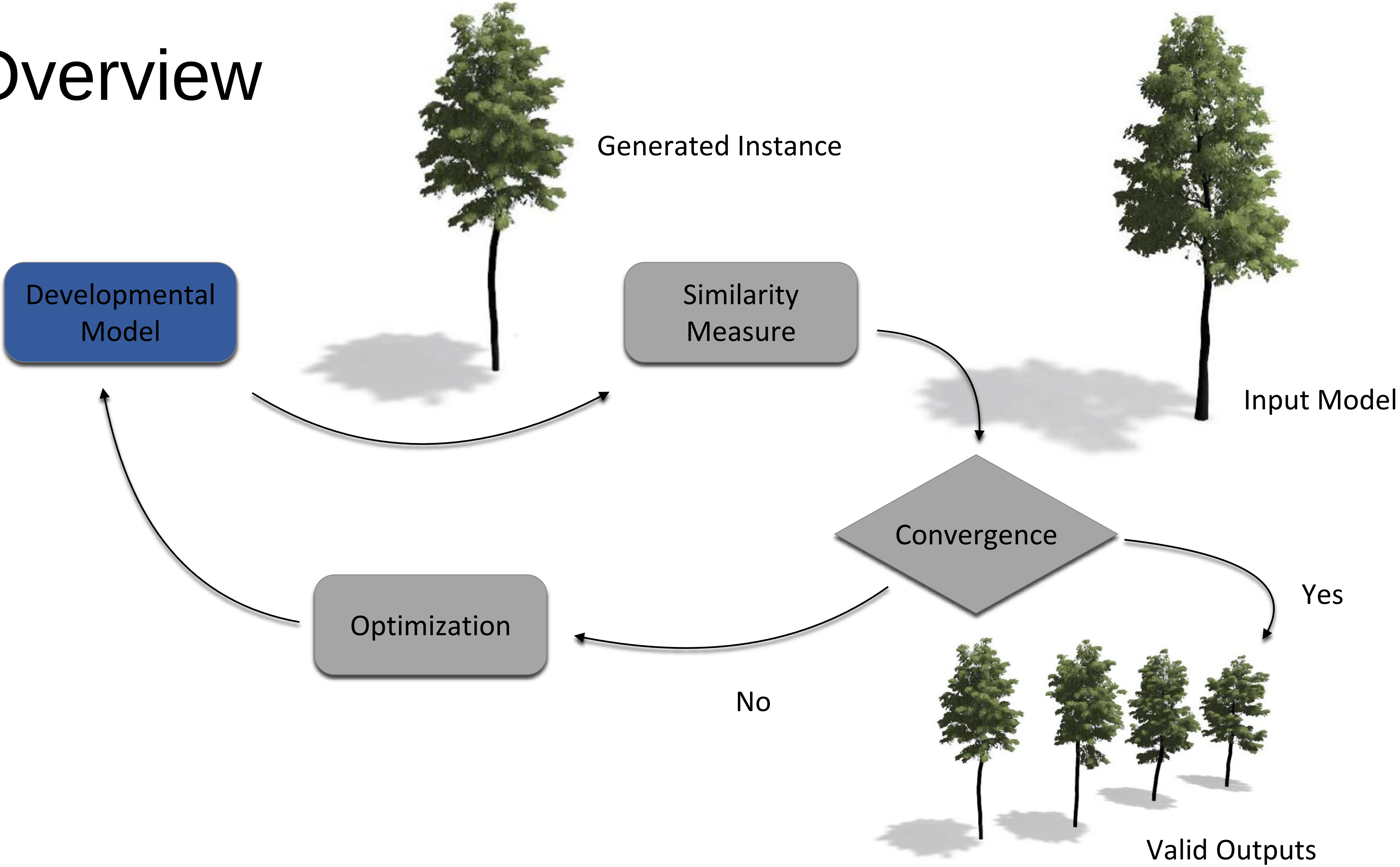
```
Angle={COUNT} : set angle used by '+' and '-' below to 360/{COUNT}
Angle {COUNT} : set angle used by '+' and '-' below to 360/{COUNT}

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

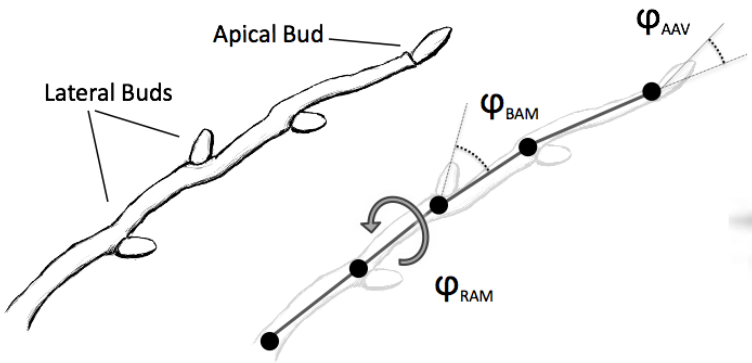


Overview


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

Growth Rate
Internode Length
Internode Angle Factor
Apical Control Level
Apical Dominance Factor
...

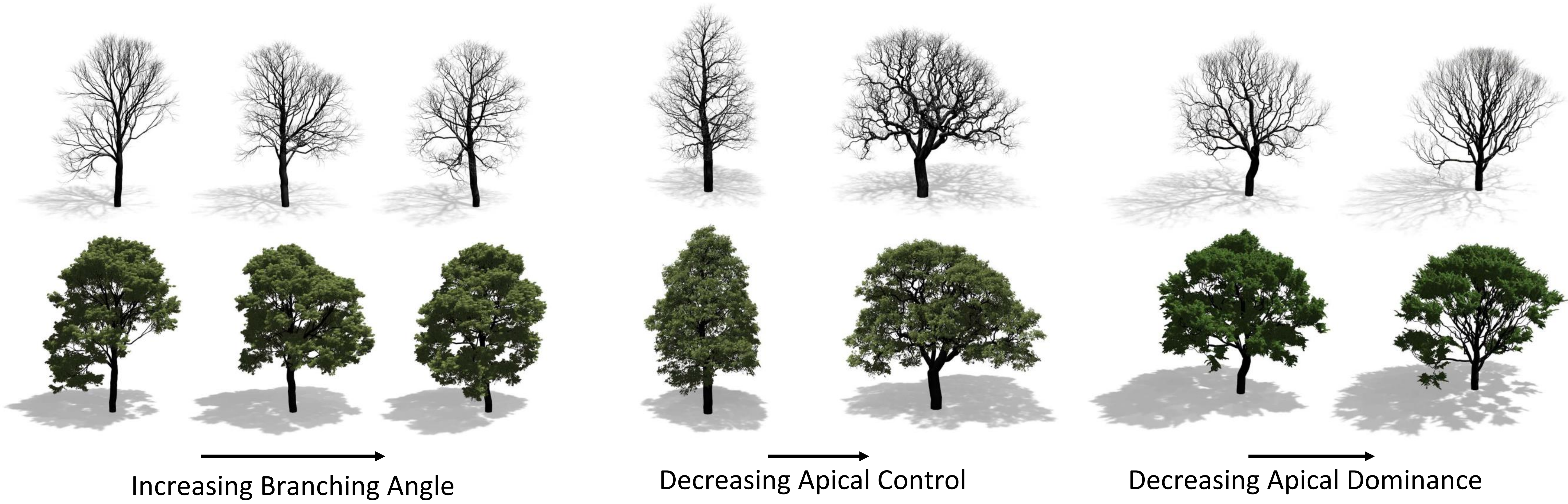
Environment Params

Gravitropism
Phototropism
Pruning Factor
Low Branch Pruning Factor
Gravity-bending Strength
...

Bud Fate Params

Apical Angle Variance
Number of Lateral Buds
Branching Angle Mean and Variance
Roll Angle and Variance
Apical and Lateral Light Factor
...

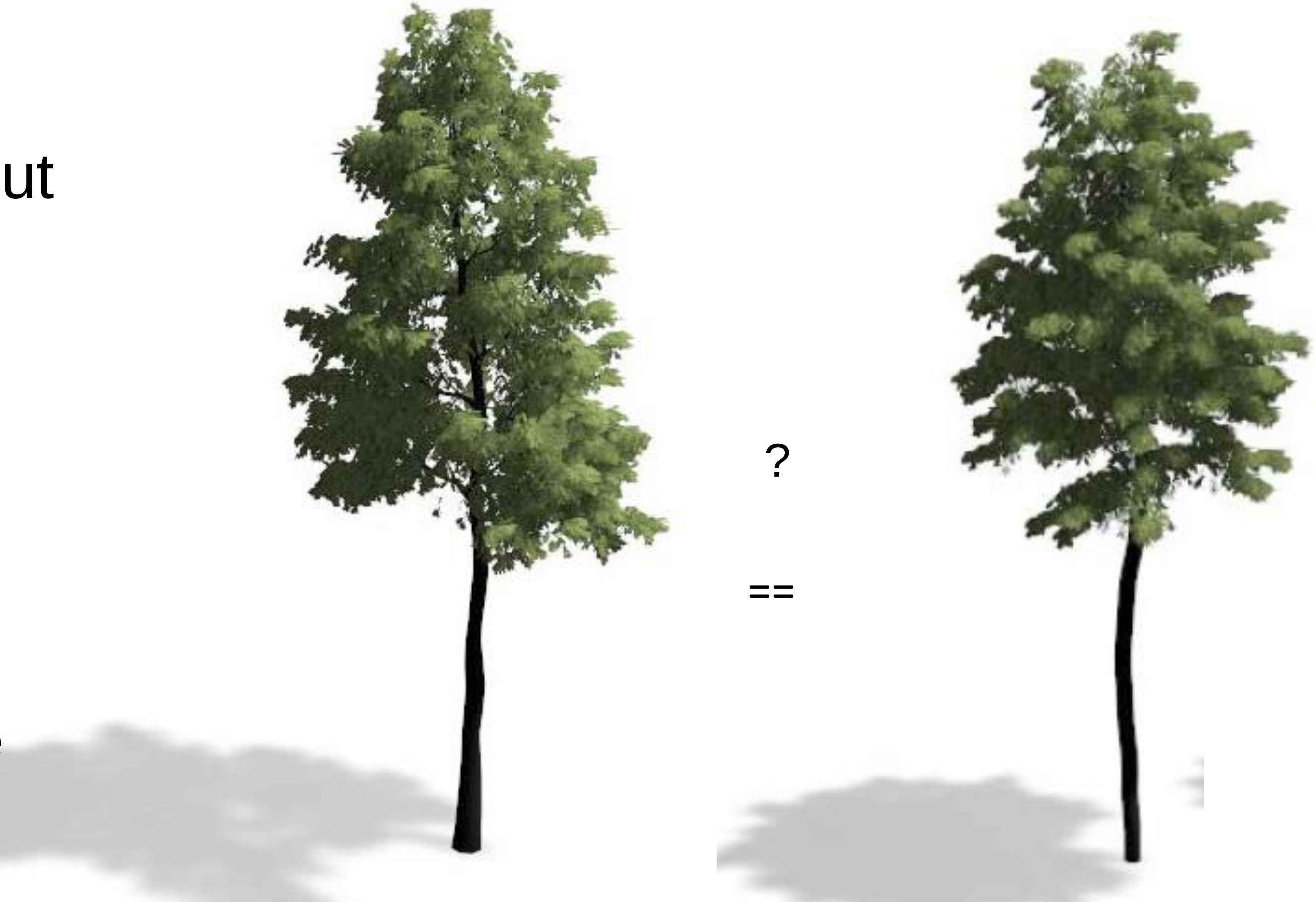
Developmental Model



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



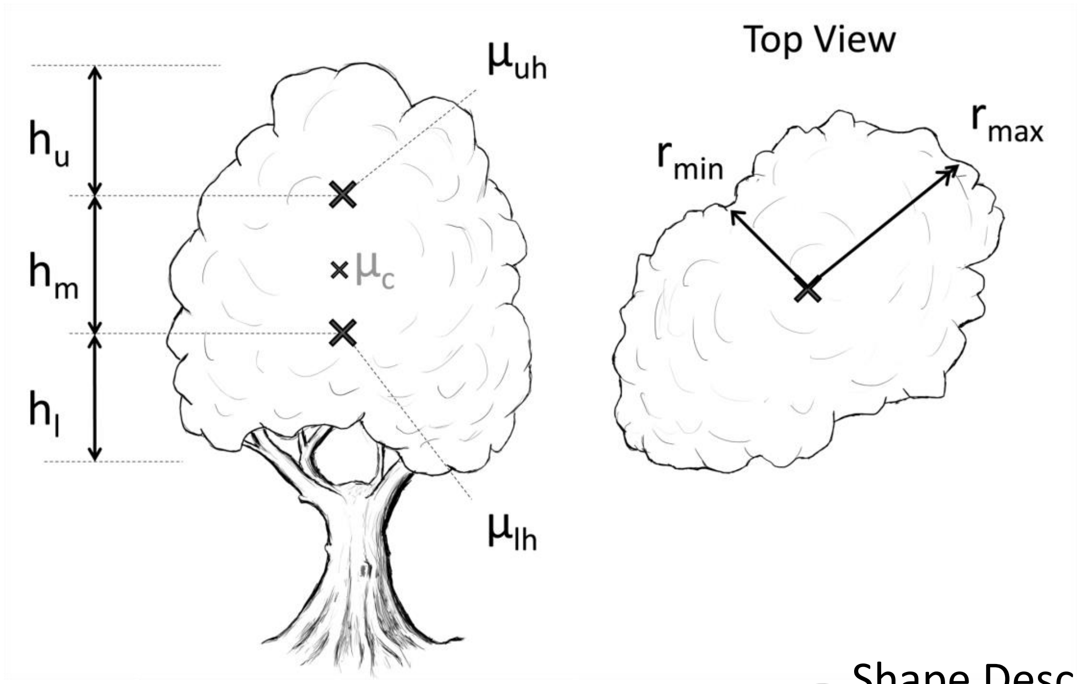
Input Mesh

Generated Output

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

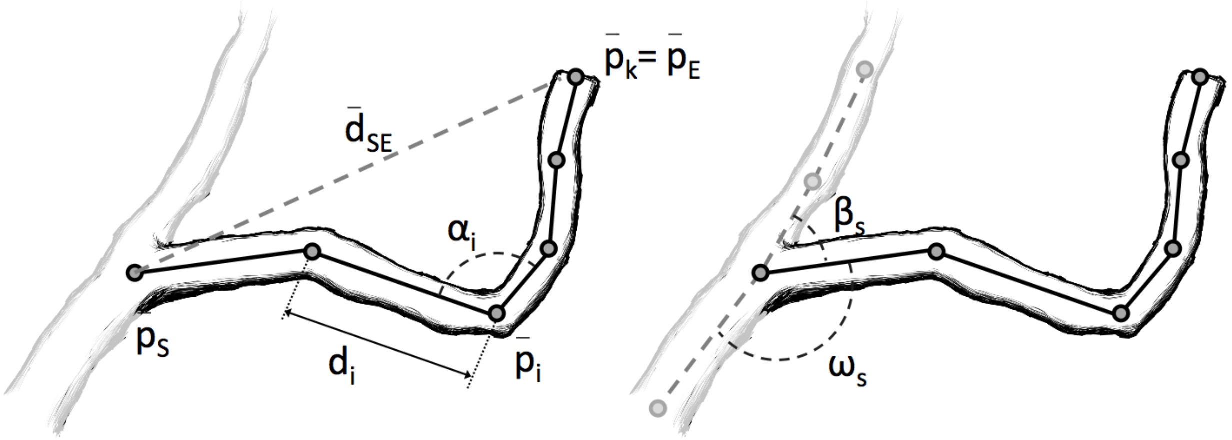
$$\delta_{\lambda_{S,i}} = 1 - \exp\left(-\frac{\left(\lambda_{S,i}(\tau_1) - \lambda_{S,i}(\tau_2)\right)^2}{2\sigma^2_{\lambda_{S,i}}}\right)$$

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

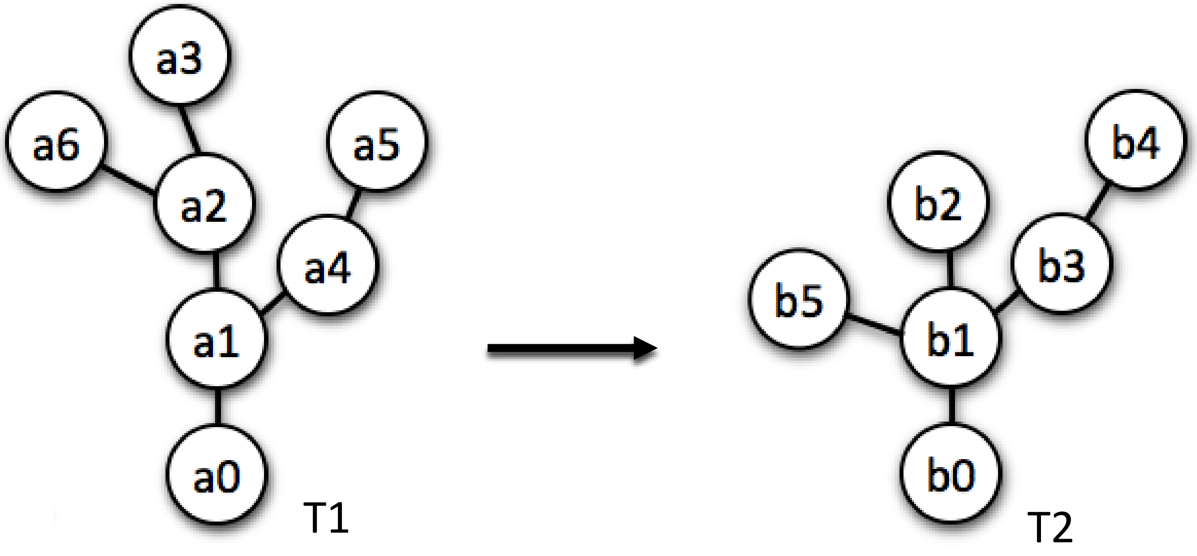
Name	Formula
Length	$\sum_{i=1}^{k} d_i$
Thickness	$\max_{\forall d_i} t_i$
Deformation	$\sum_{i=1}^{k-1} \alpha_i$
Straightness	$\frac{\lvert \bar{d}_{SE} \rvert}{b_L}$
Slope	$\angle \bar{d}_{SE}$
Sibling Angle	β_S
Parent Angle	ω_S



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

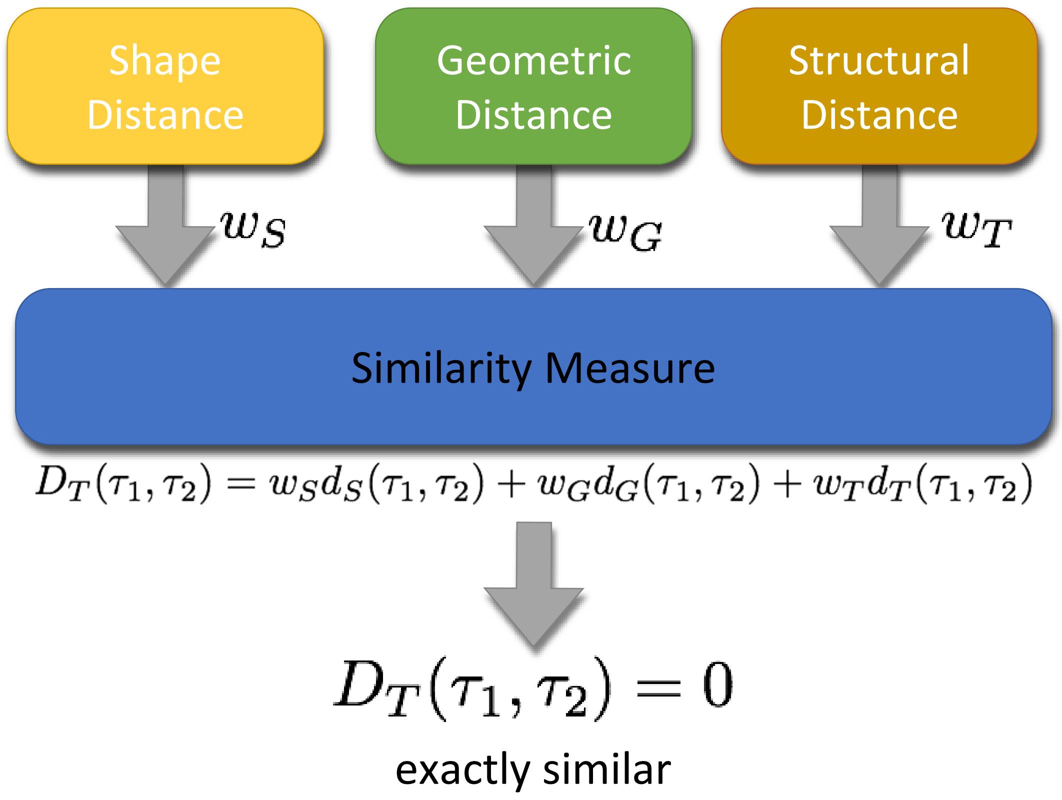
$$d_T(\tau_1, \tau_2) = \frac{d_N(t_1, t_2)}{2 \max \left(d_N(t_1, \varepsilon), d_N(\varepsilon, t_2) \right)}$$

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

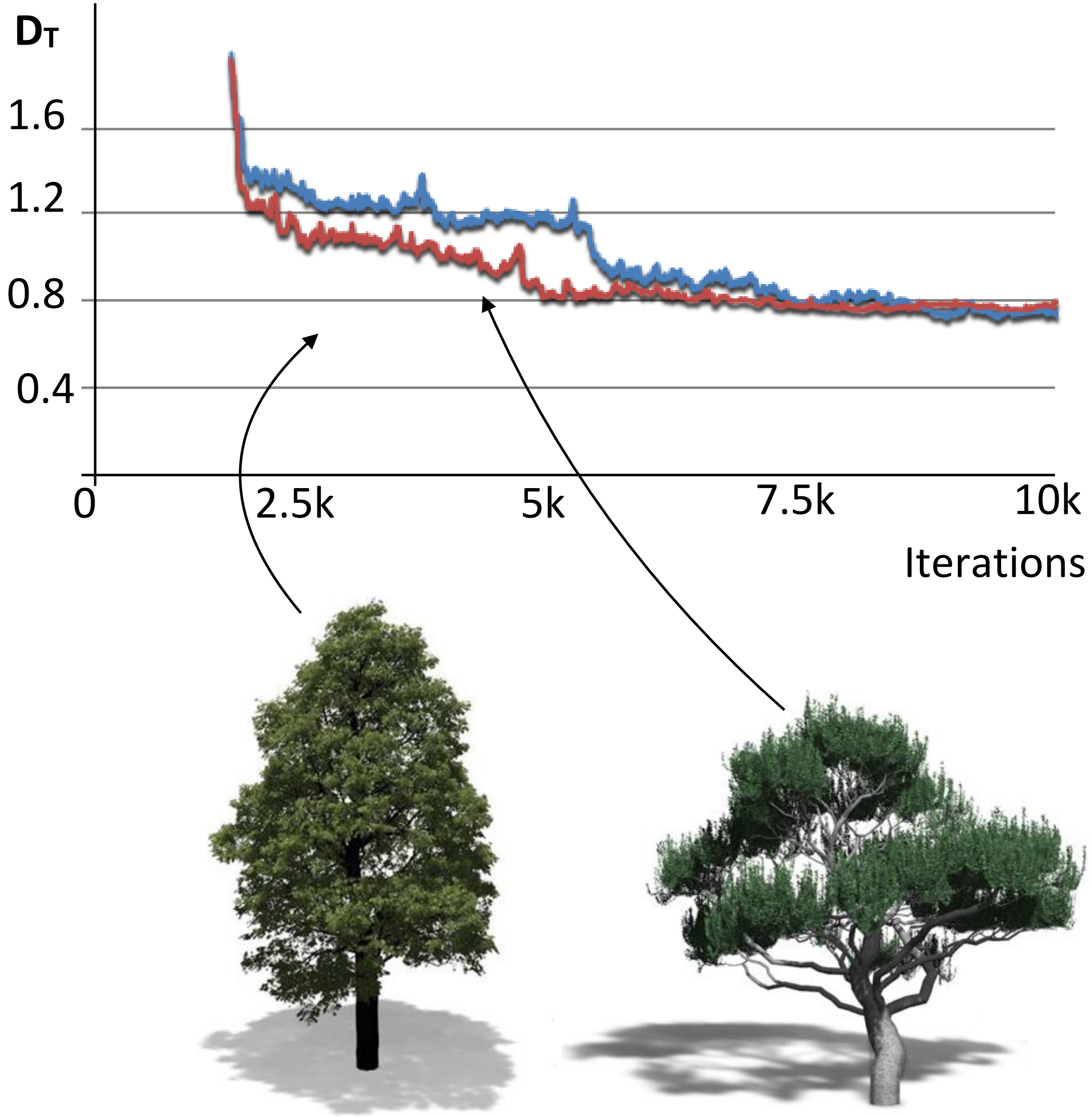


Optimization of Parameters

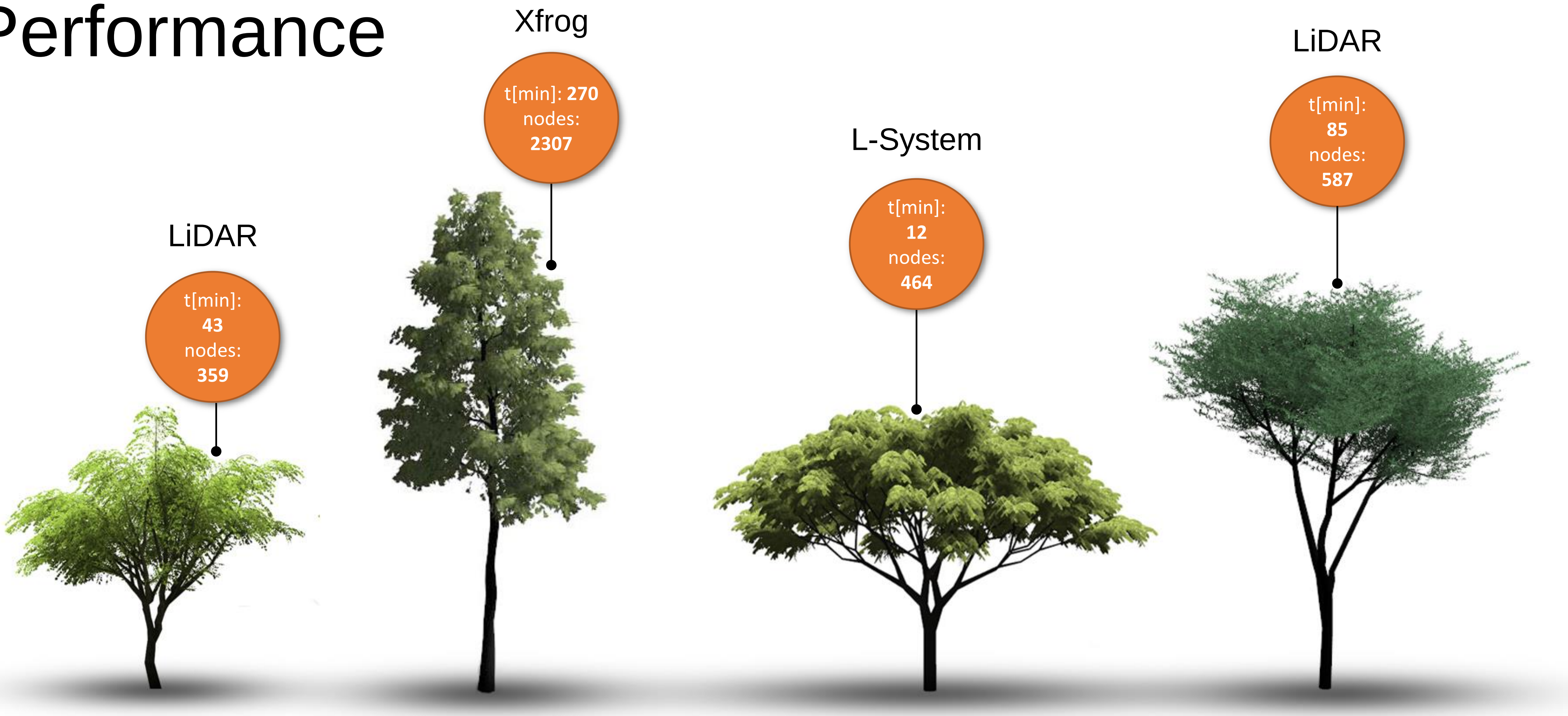
[Metropolis et al. 1953]

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

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



Performance



Results

Environment

Interpolation of Parameters

Different Species