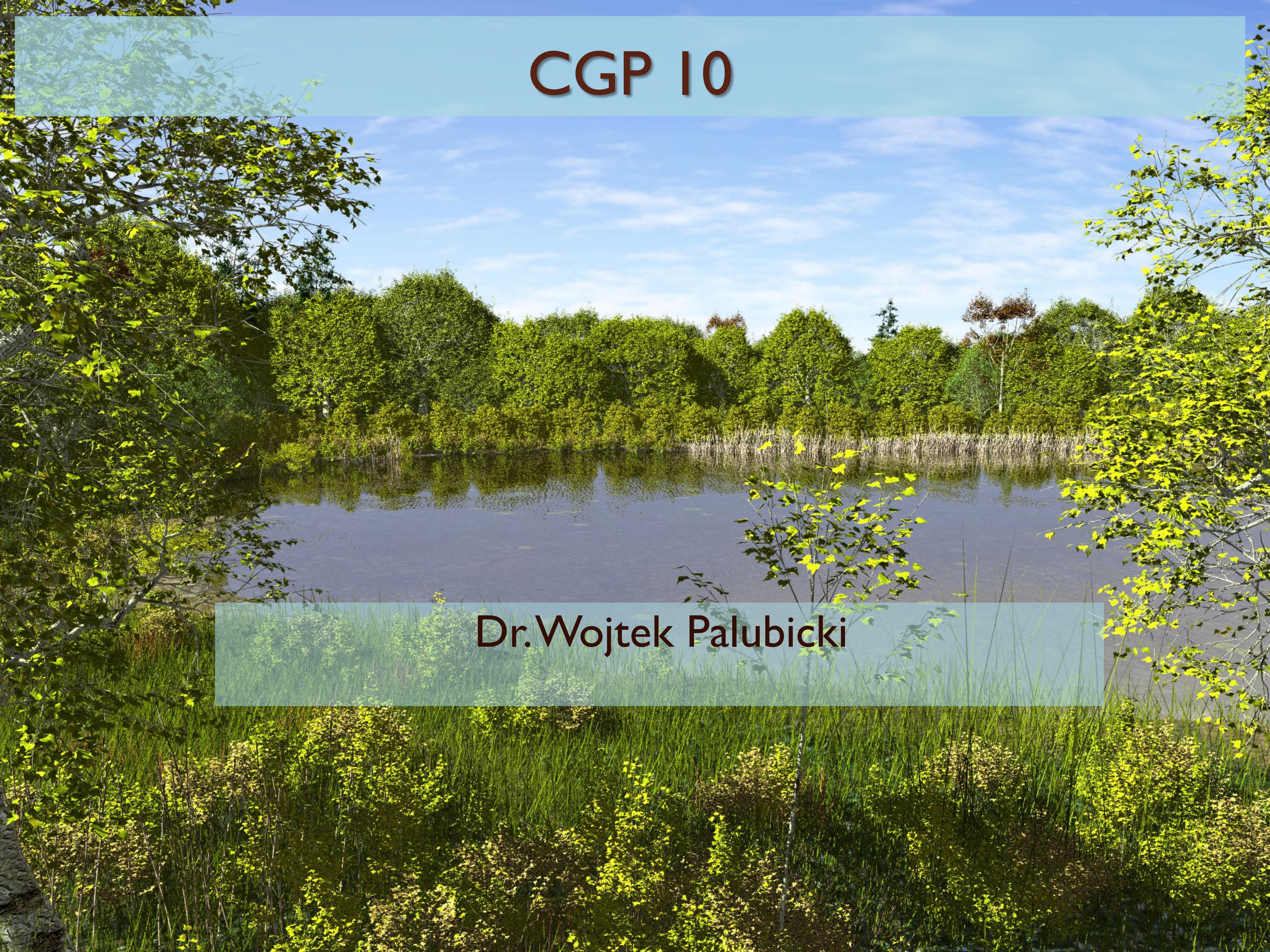


CGP 10

Dr. Wojtek Palubicki

Question

How do trees acquire their branching form?

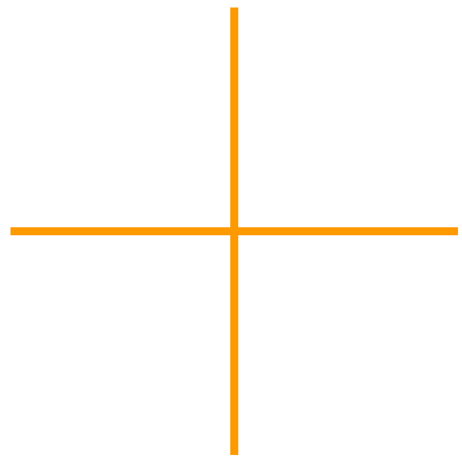
Thesis

Through hierarchical self-organization of branches

- Self-organization
  - Process in which global pattern and structure emerge from interactions among the lower-level components of the system.
- Database amplification
  - Simple mechanism (economically encoded in the genome) can generate complex patterns and structures
- Reason for modelling
  - The emergence of form through self-organization is difficult to comprehend without models

S. Camazine et al. (2001): Self-organization in biological systems, Princeton University Press.

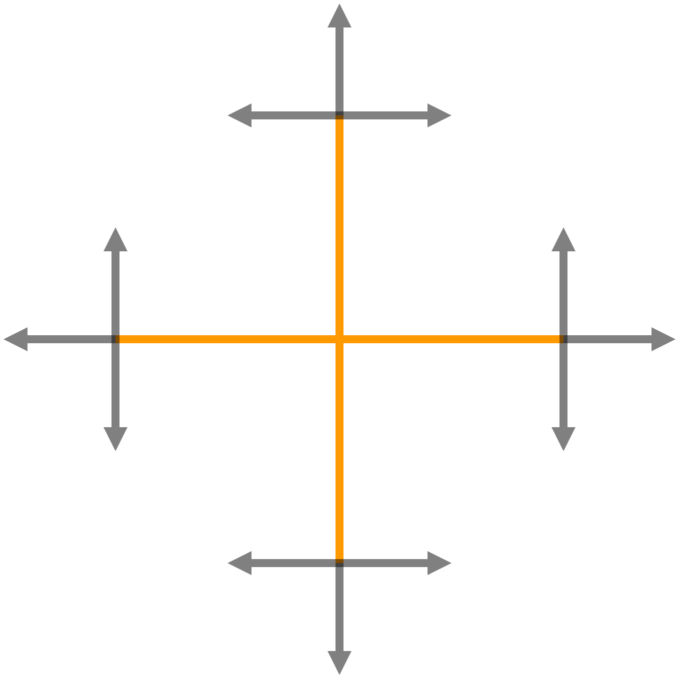
Example – Cellular Automaton



Consider a branching structure…

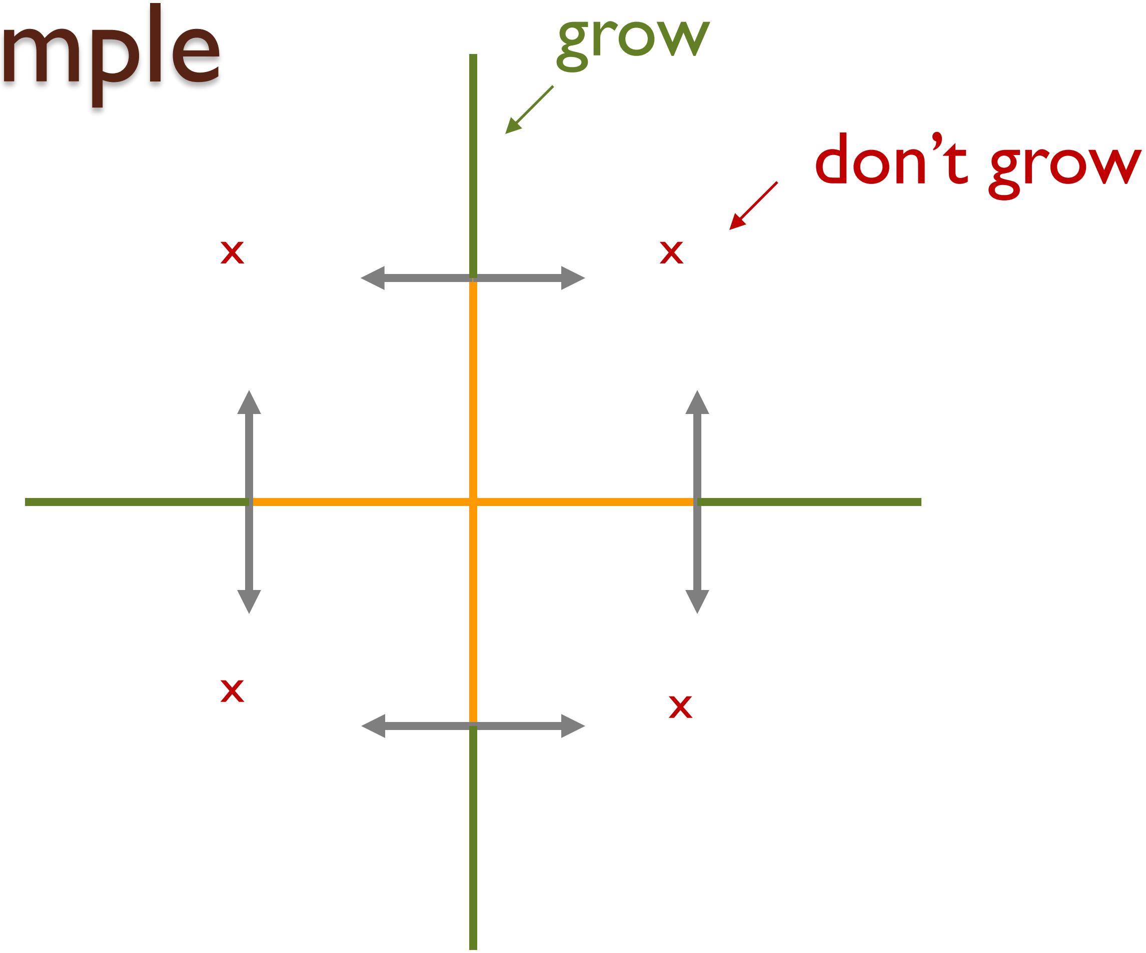
S. Ulam (1962): Patterns of growth of figures. *Proceedings of Symposia on Applied Mathematics* 14, 215-224.

Example



At the end of each branch there are 3 buds.

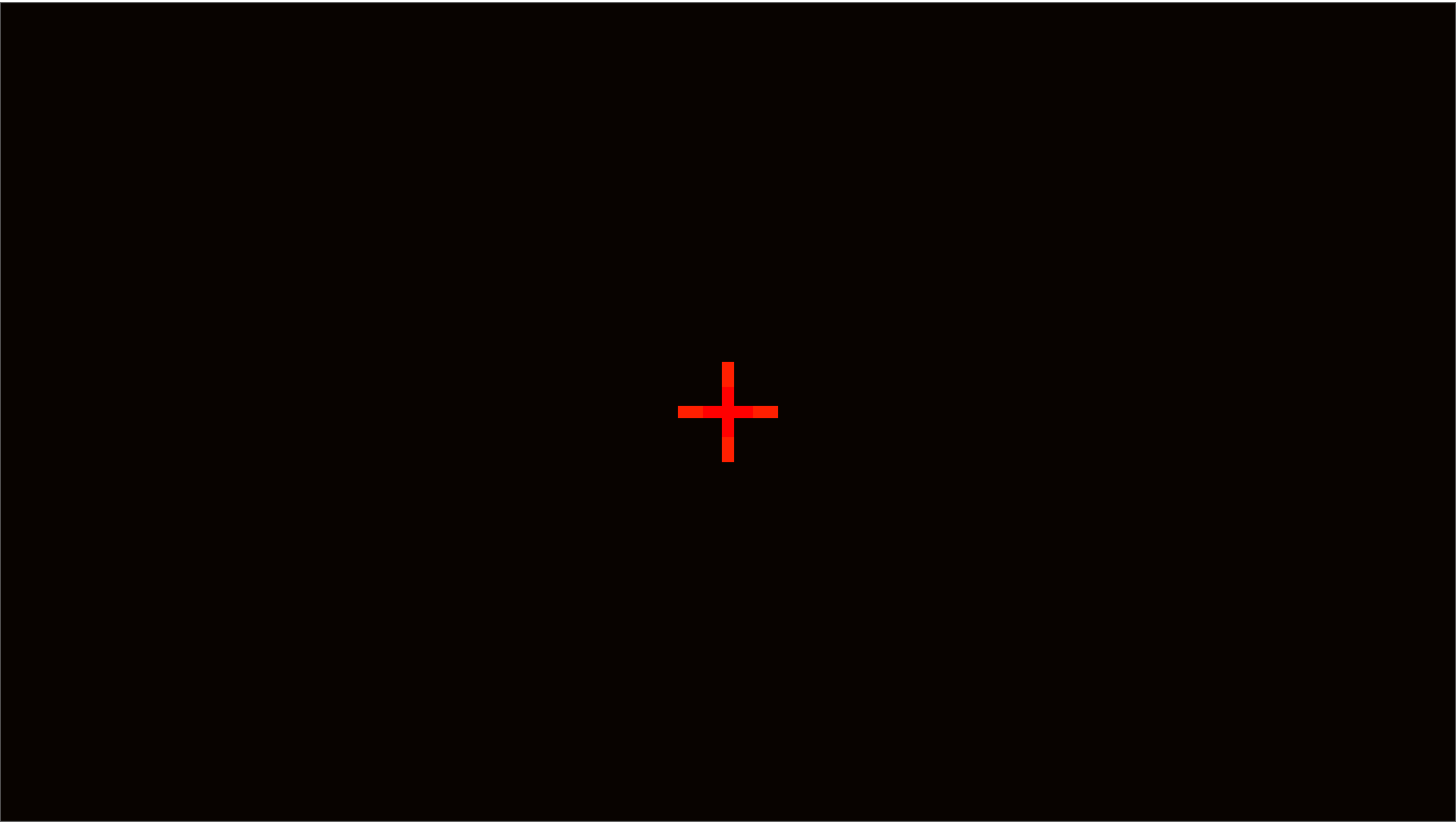
Example

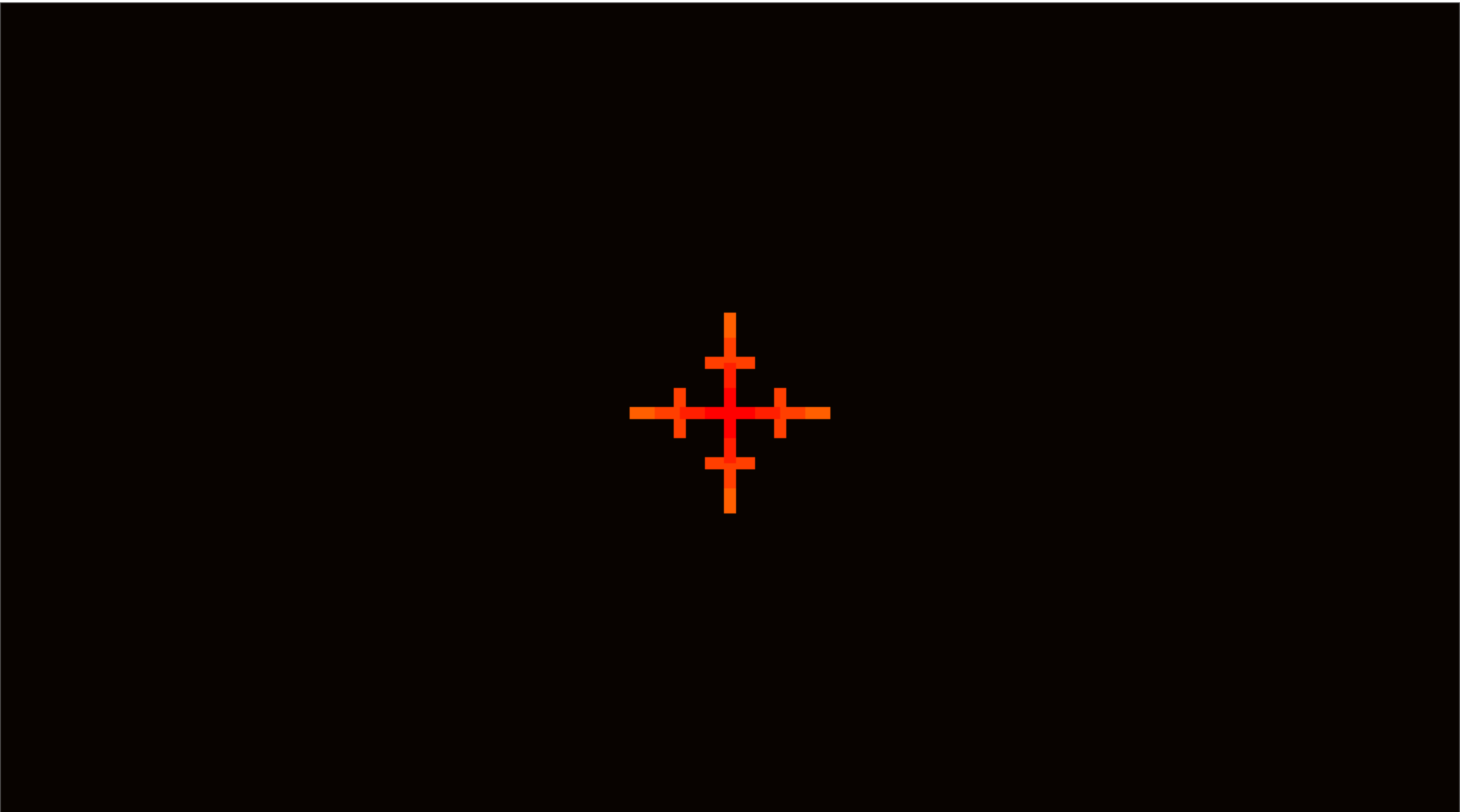


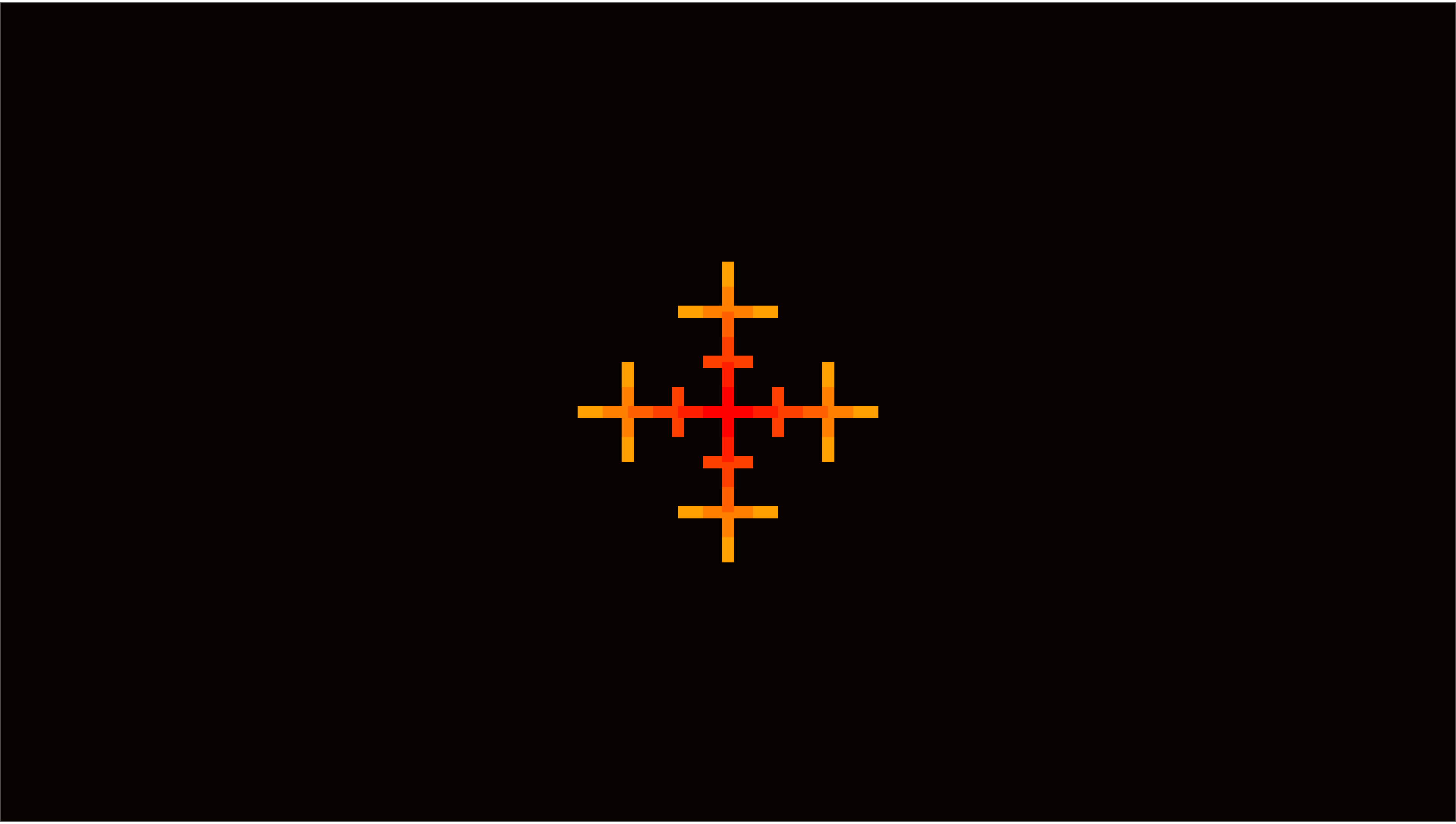
Rule 1: If there is enough space, grow.

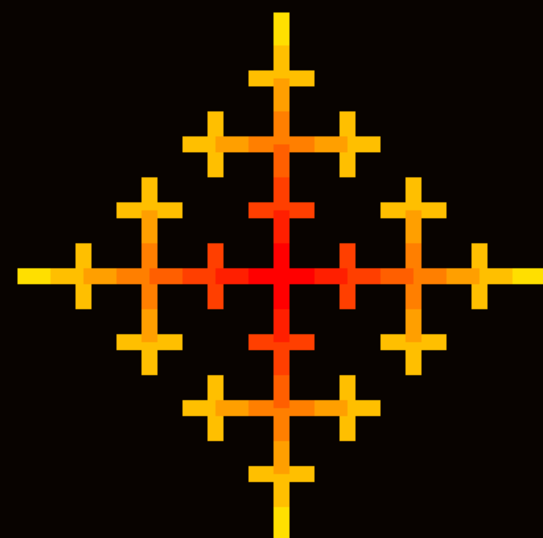
Rule 2: If there isn't enough space, don't grow.

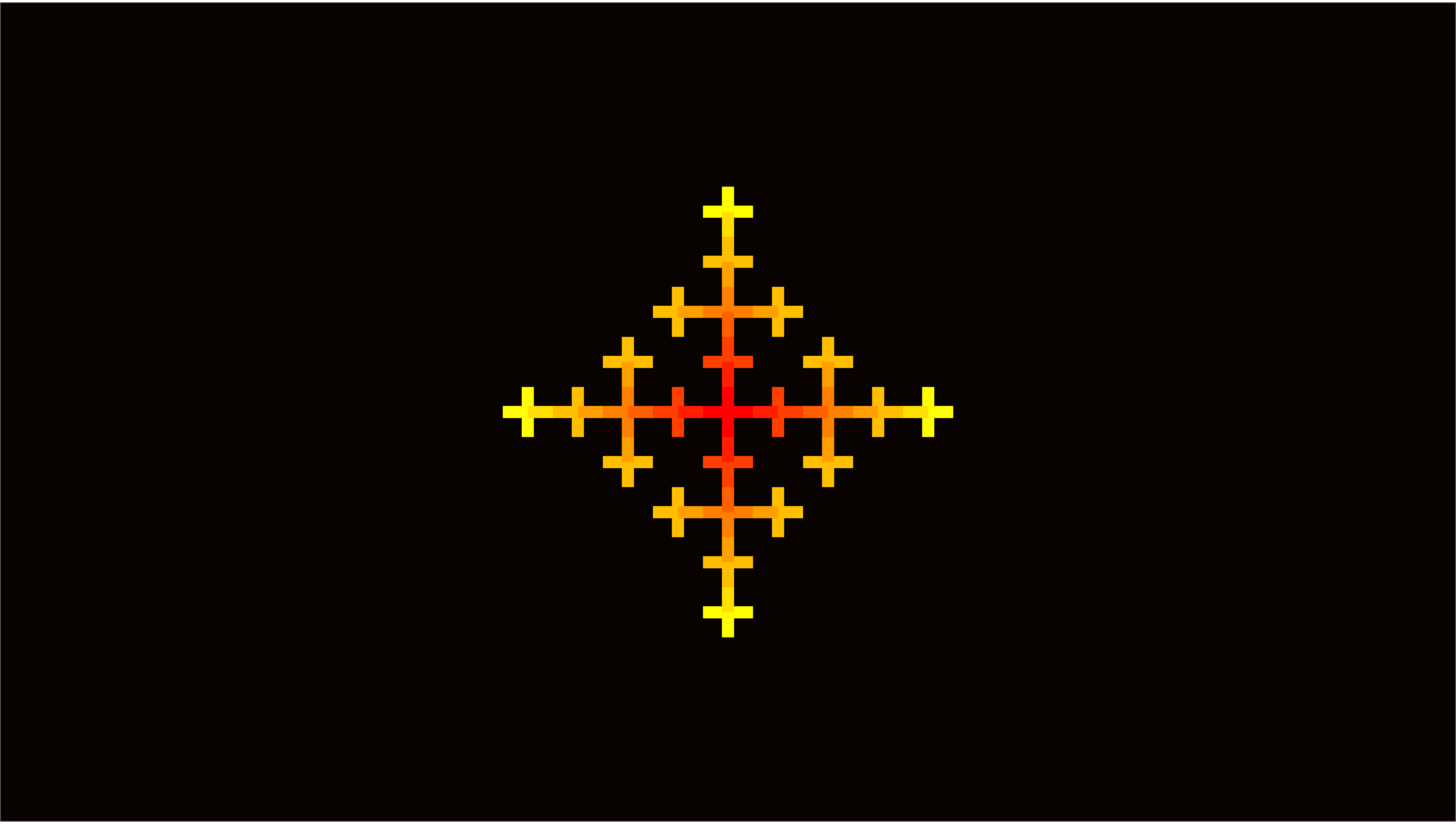
+

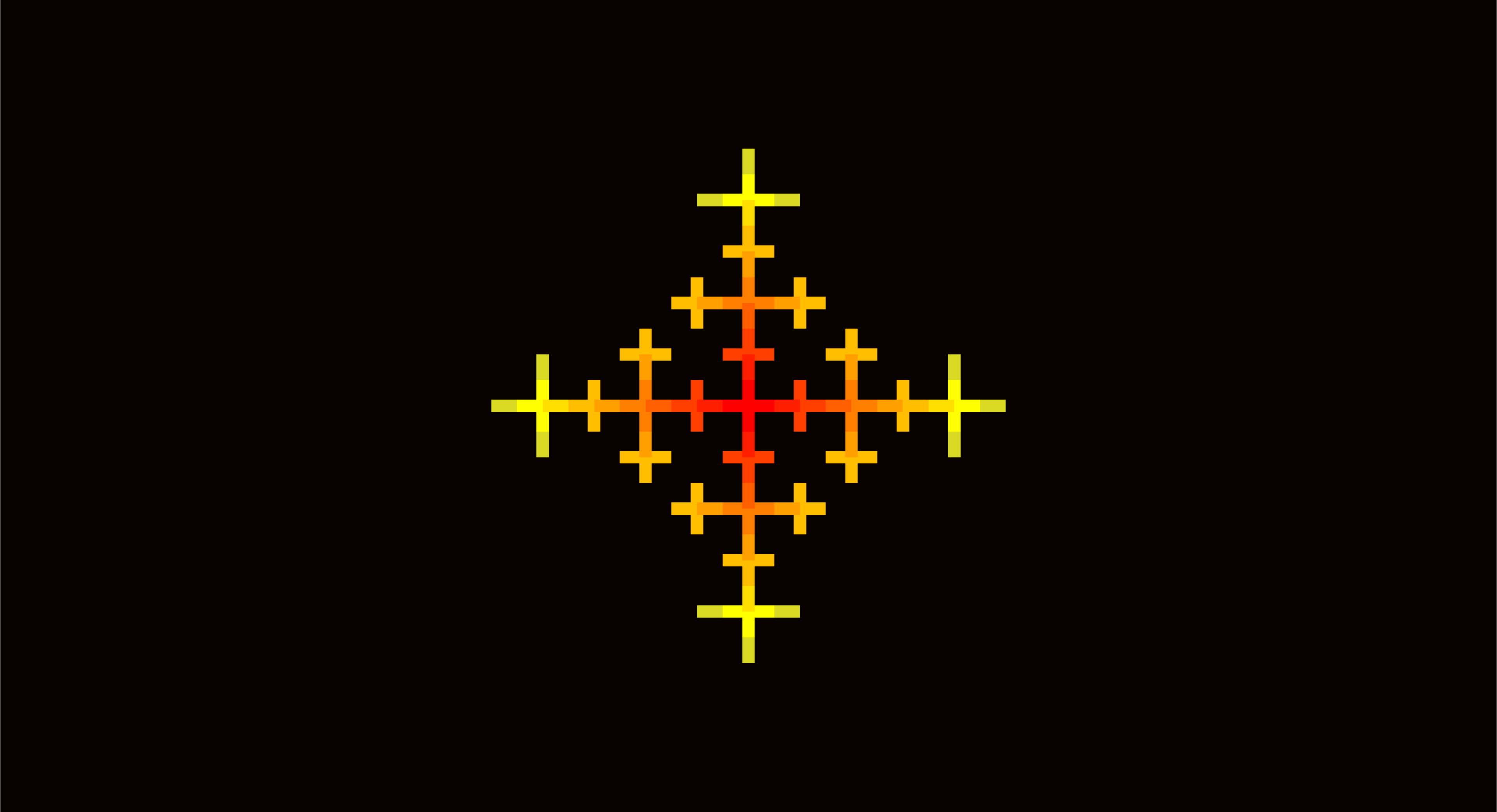


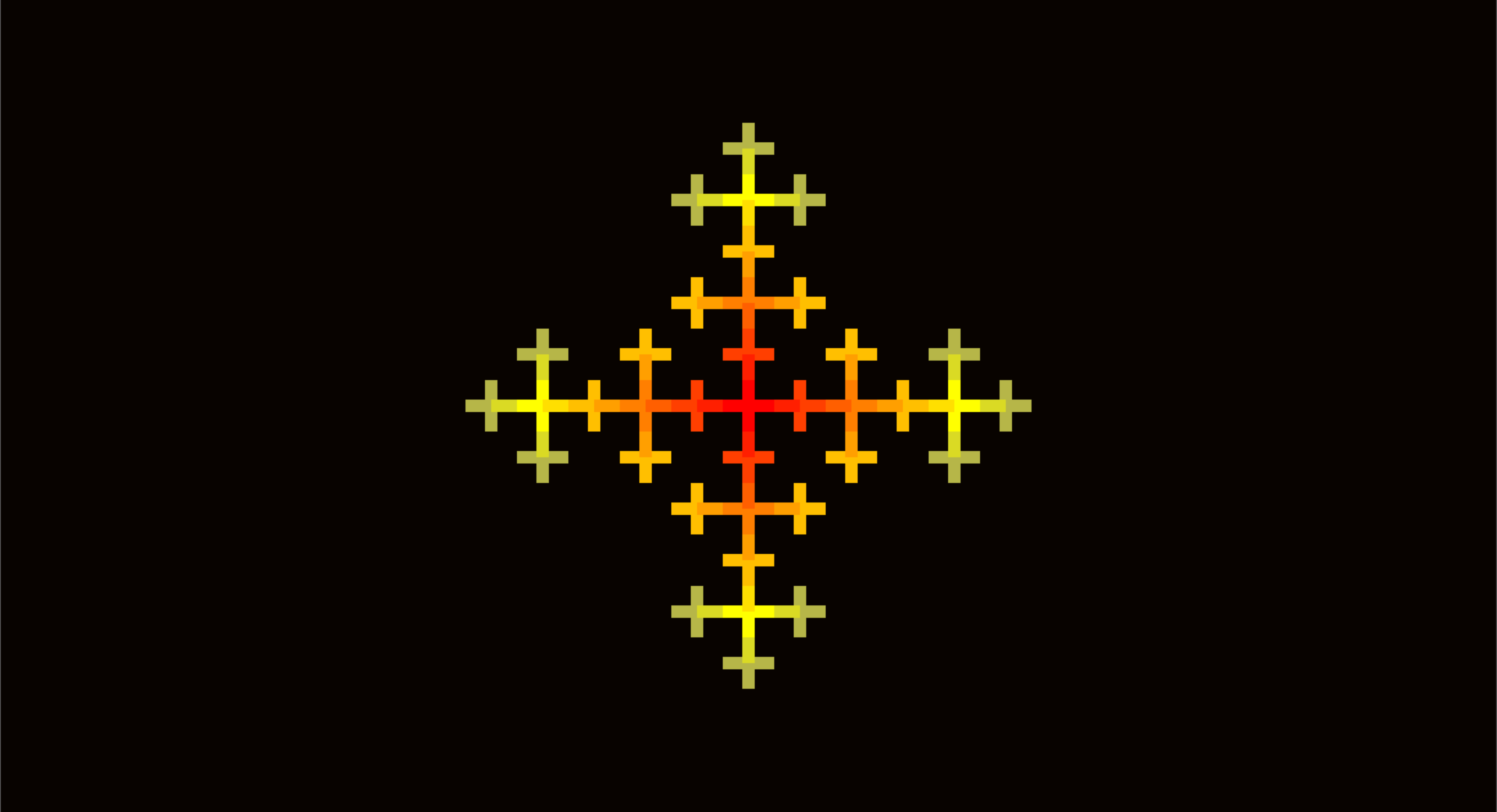


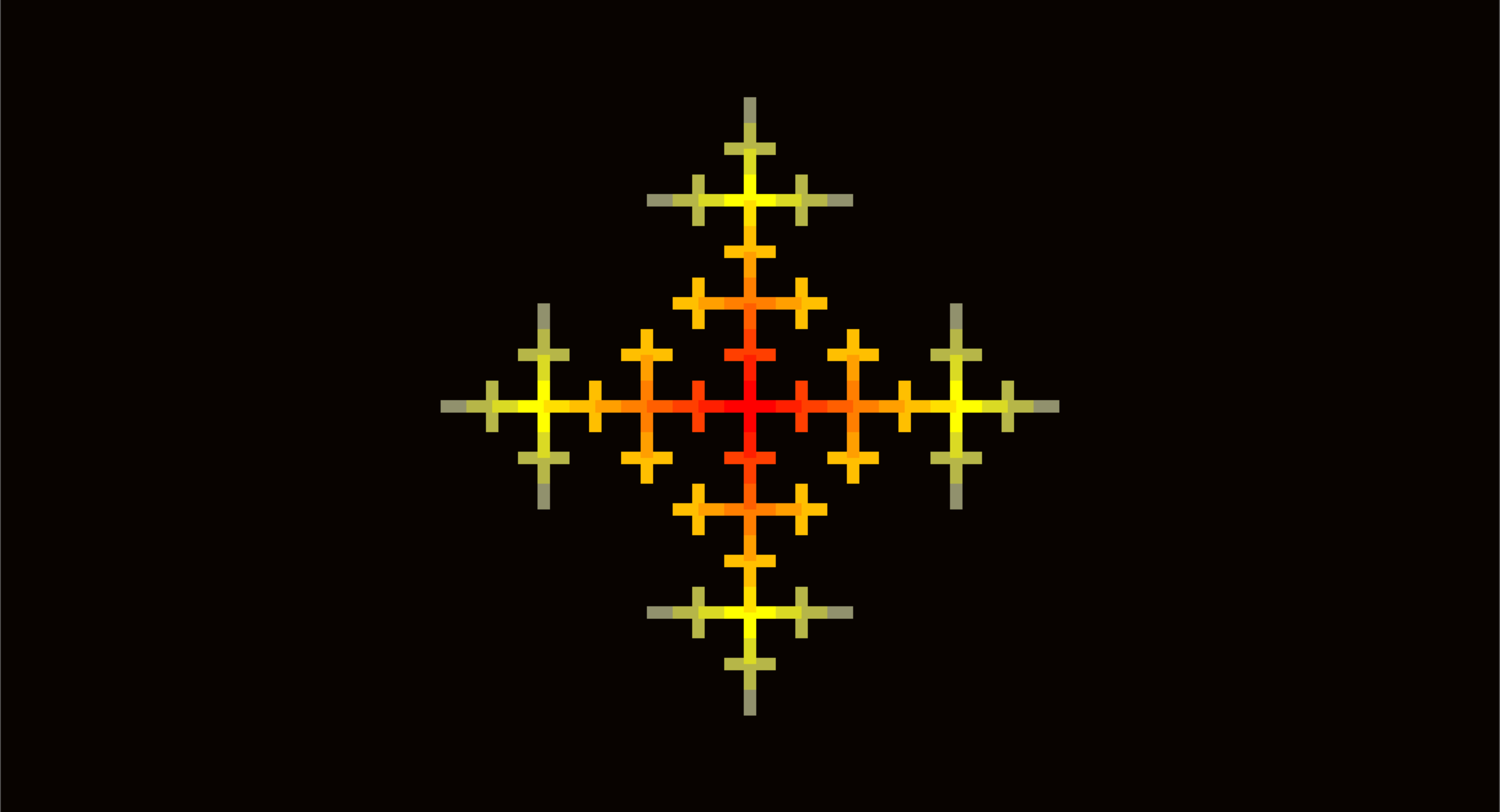


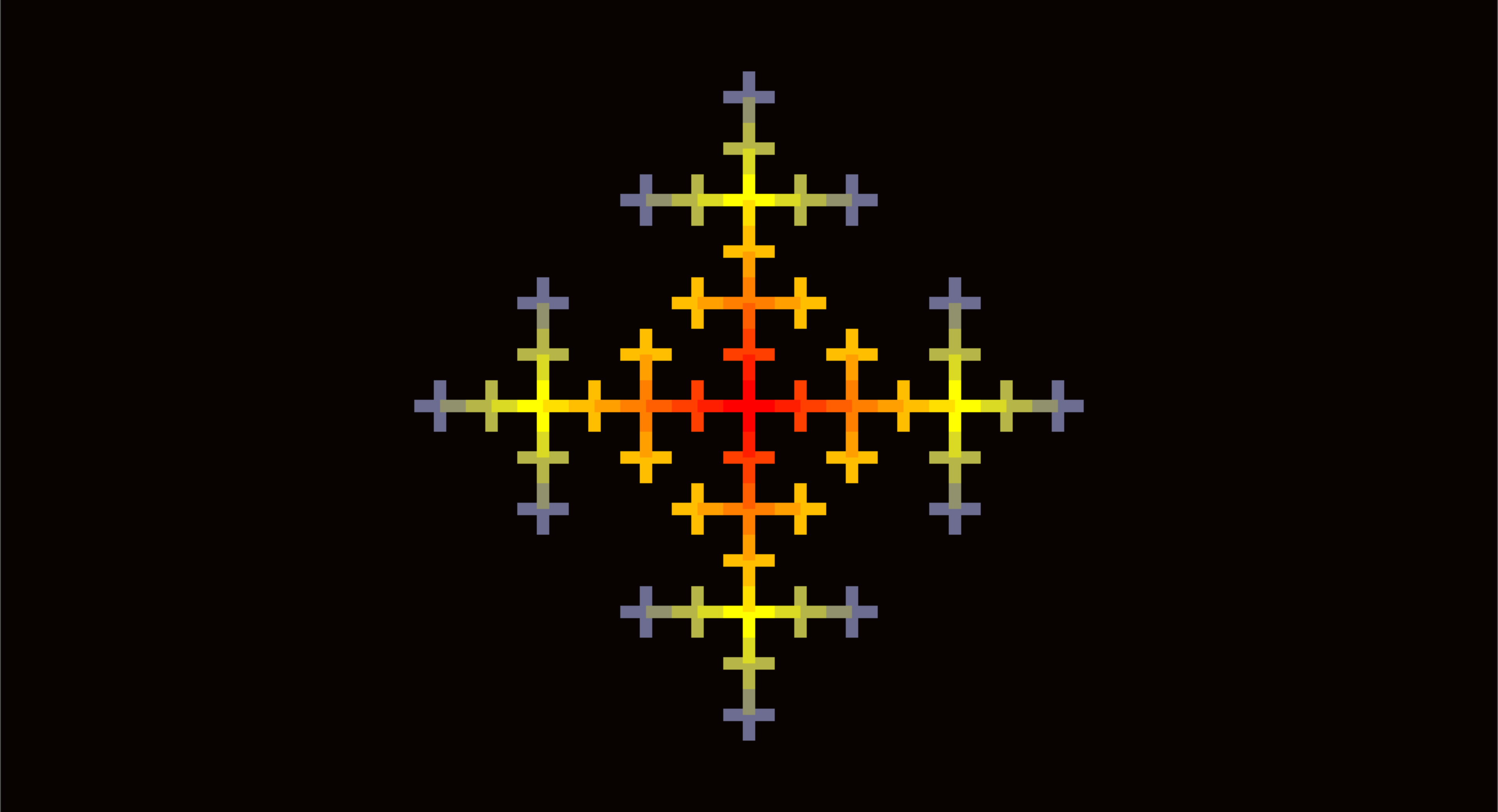


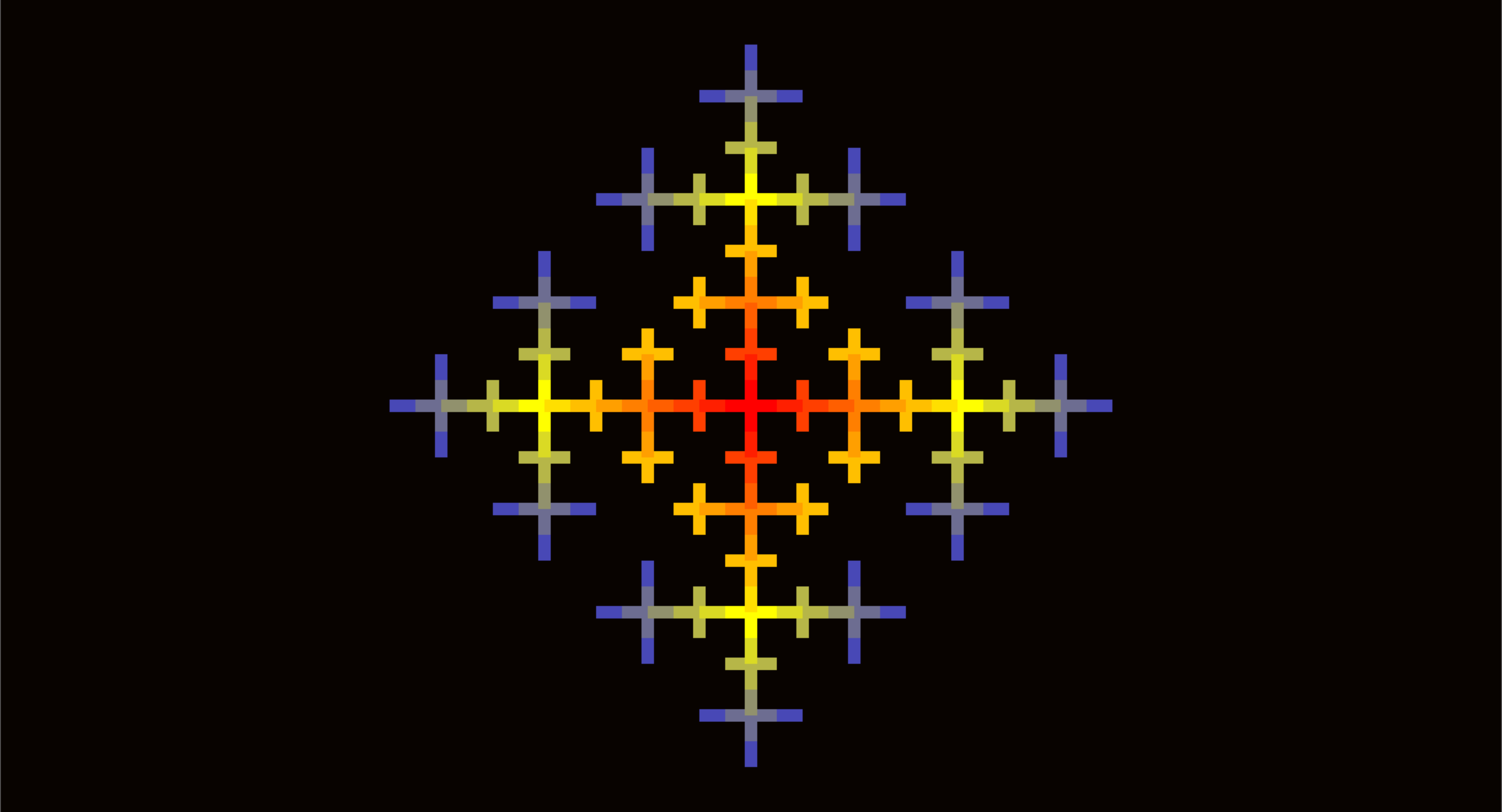


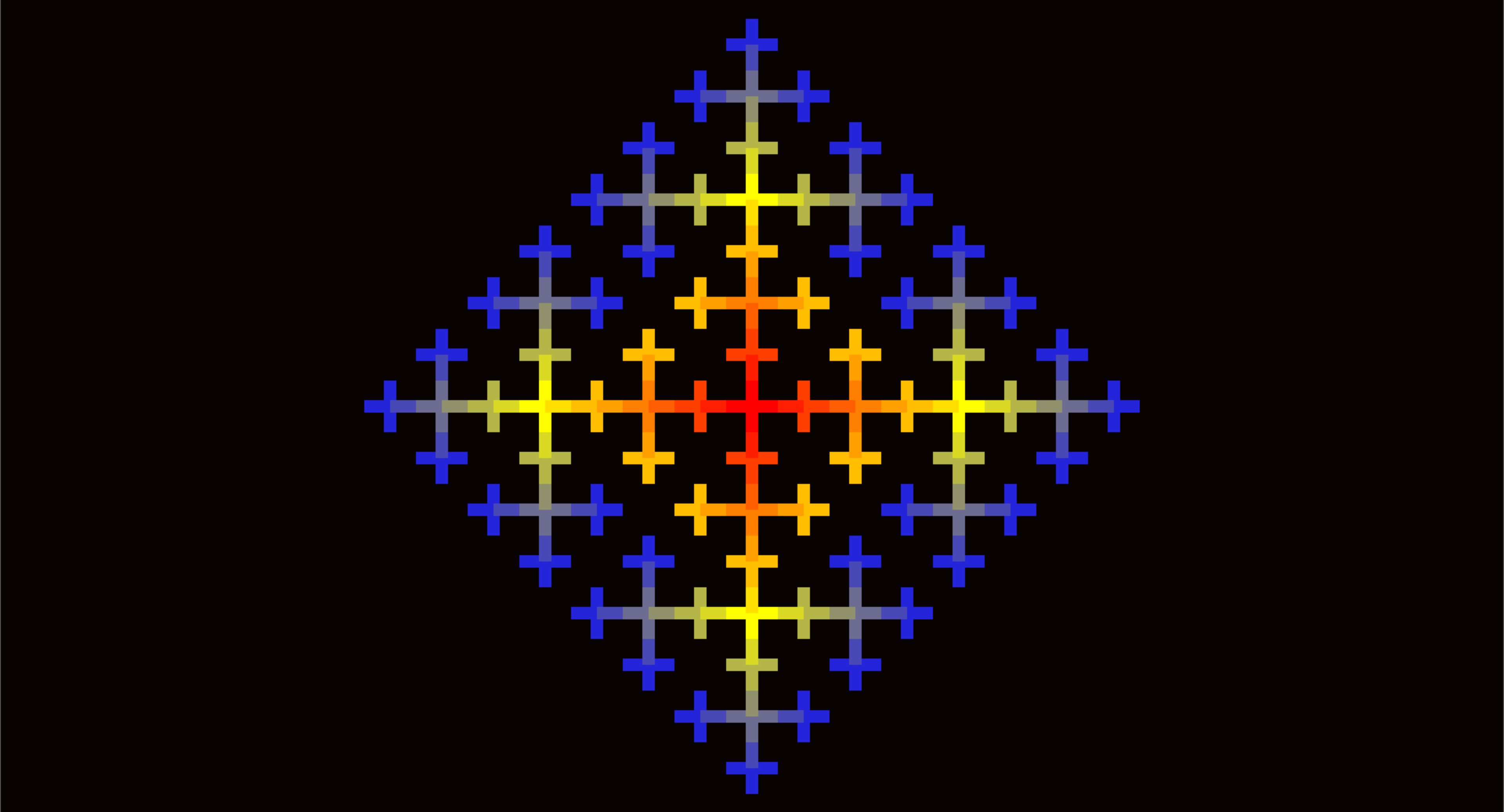






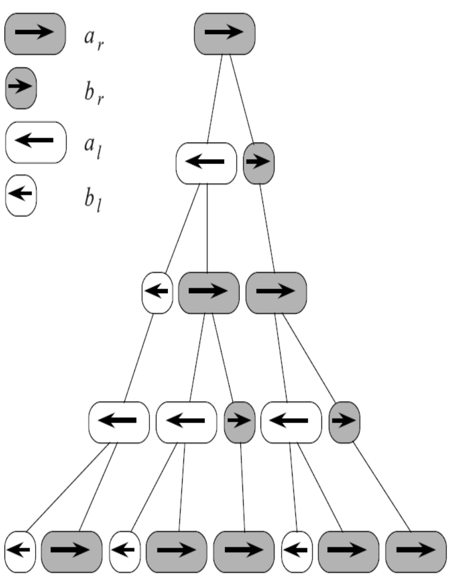




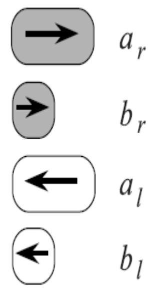


L-Systems

- Aristid Lindenmayer (1925-1989)
  - Anabaena Catenula
  - 1968 Lindenmayer systems – parallel string rewriting systems



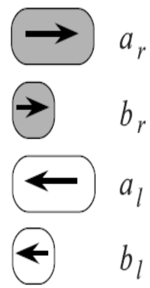
Anabaena Catenula: Model 1



Anabaena Catenula: Model 1

$$p_1 : a_r \rightarrow a_l b_r$$

$$p_2 : a_l \rightarrow b_l a_r$$



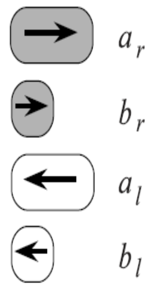
Anabaena Catenula: Model 1

$$p_1 : a_r \rightarrow a_l b_r$$

$$p_2 : a_l \rightarrow b_l a_r$$

$$p_3 : b_r \rightarrow a_r$$

$$p_4 : b_l \rightarrow a_l$$



Anabaena Catenula: Model 1

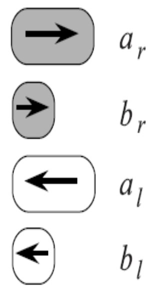
$$\omega : a_r$$

$$p_1 : a_r \rightarrow a_l b_r$$

$$p_2 : a_l \rightarrow b_l a_r$$

$$p_3 : b_r \rightarrow a_r$$

$$p_4 : b_l \rightarrow a_l$$



Anabaena Catenula: Model 1

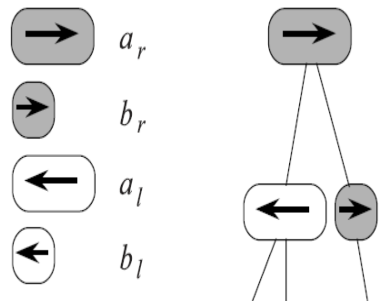
$\omega : a_r$

$p_1 : a_r \rightarrow a_l b_r$

$p_2 : a_l \rightarrow b_l a_r$

$p_3 : b_r \rightarrow a_r$

$p_4 : b_l \rightarrow a_l$



a_r

$a_l b_r$

Anabaena Catenula: Model 1

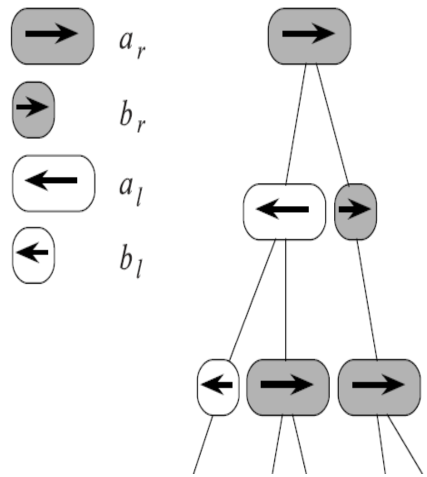
$\omega : a_r$

$p_1 : a_r \to a_l b_r$

$p_2 : a_l \to b_l a_r$

$p_3 : b_r \to a_r$

$p_4 : b_l \to a_l$



a_r

$a_l b_r$

$b_l a_r a_r$

Anabaena Catenula: Model 1

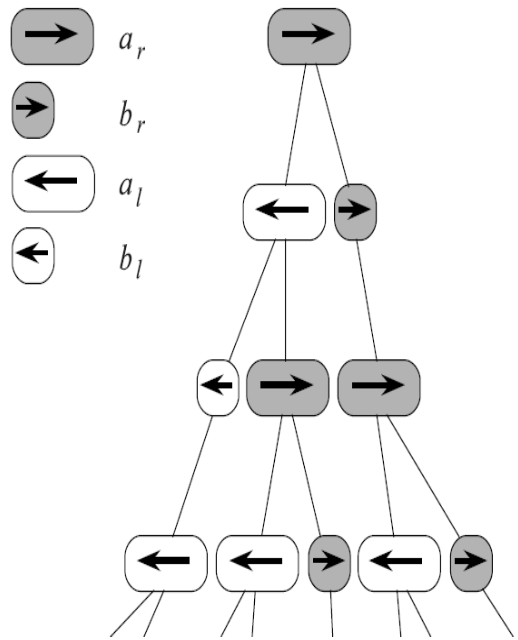
$\omega : a_r$

$p_1 : a_r \rightarrow a_l b_r$

$p_2 : a_l \rightarrow b_l a_r$

$p_3 : b_r \rightarrow a_r$

$p_4 : b_l \rightarrow a_l$



a_r

$a_l b_r$

$b_l a_r a_r$

$a_l a_l b_r a_l b_r$

Anabaena Catenula: Model 1

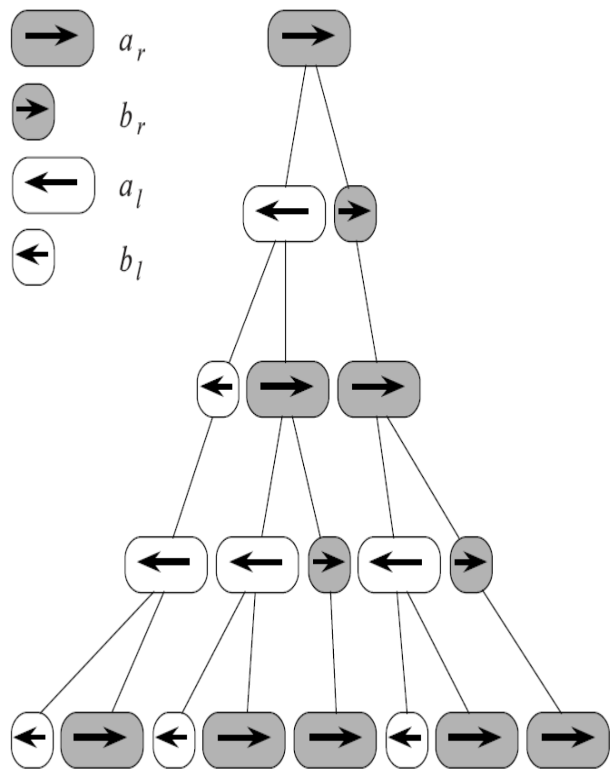
$\omega : a_r$

$p_1 : a_r \rightarrow a_l b_r$

$p_2 : a_l \rightarrow b_l a_r$

$p_3 : b_r \rightarrow a_r$

$p_4 : b_l \rightarrow a_l$



a_r

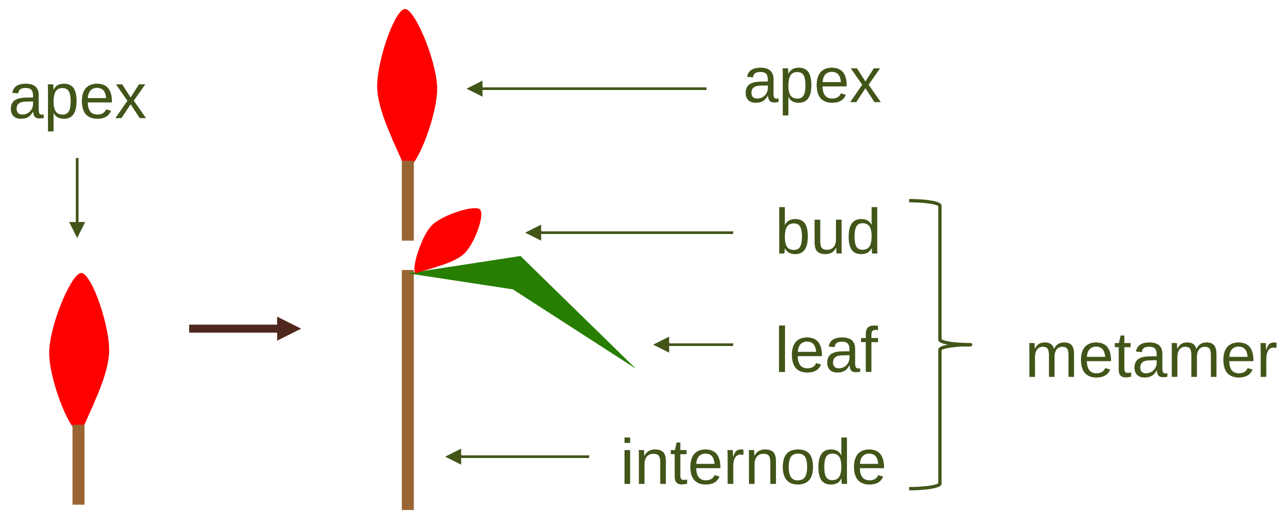
$a_l b_r$

$b_l a_r a_r$

$a_l a_l b_r a_l b_r$

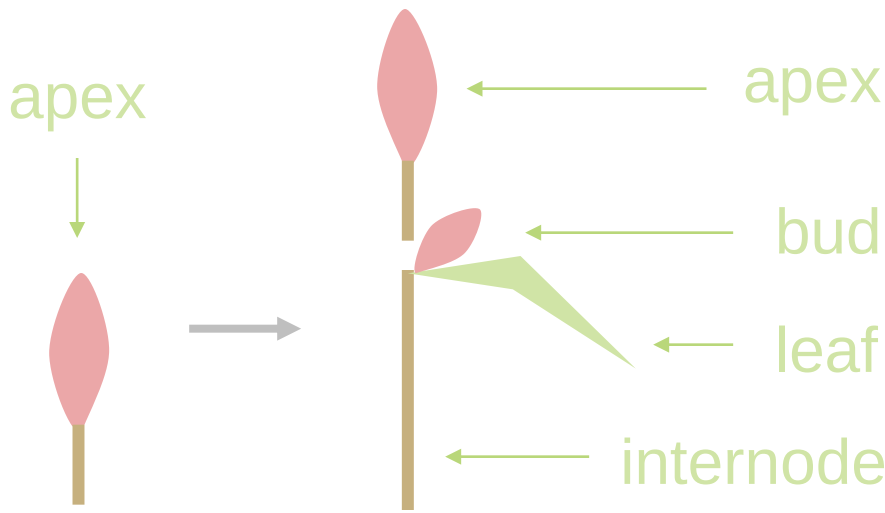
$b_l a_r b_l a_r a_r b_l a_r a_r$

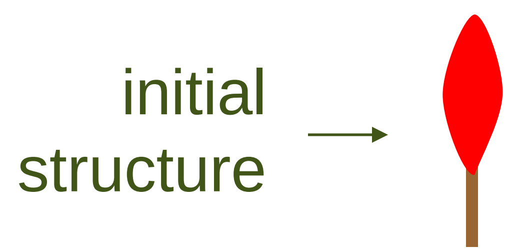
The fundamental developmental scheme



rule

The fundamental developmental scheme

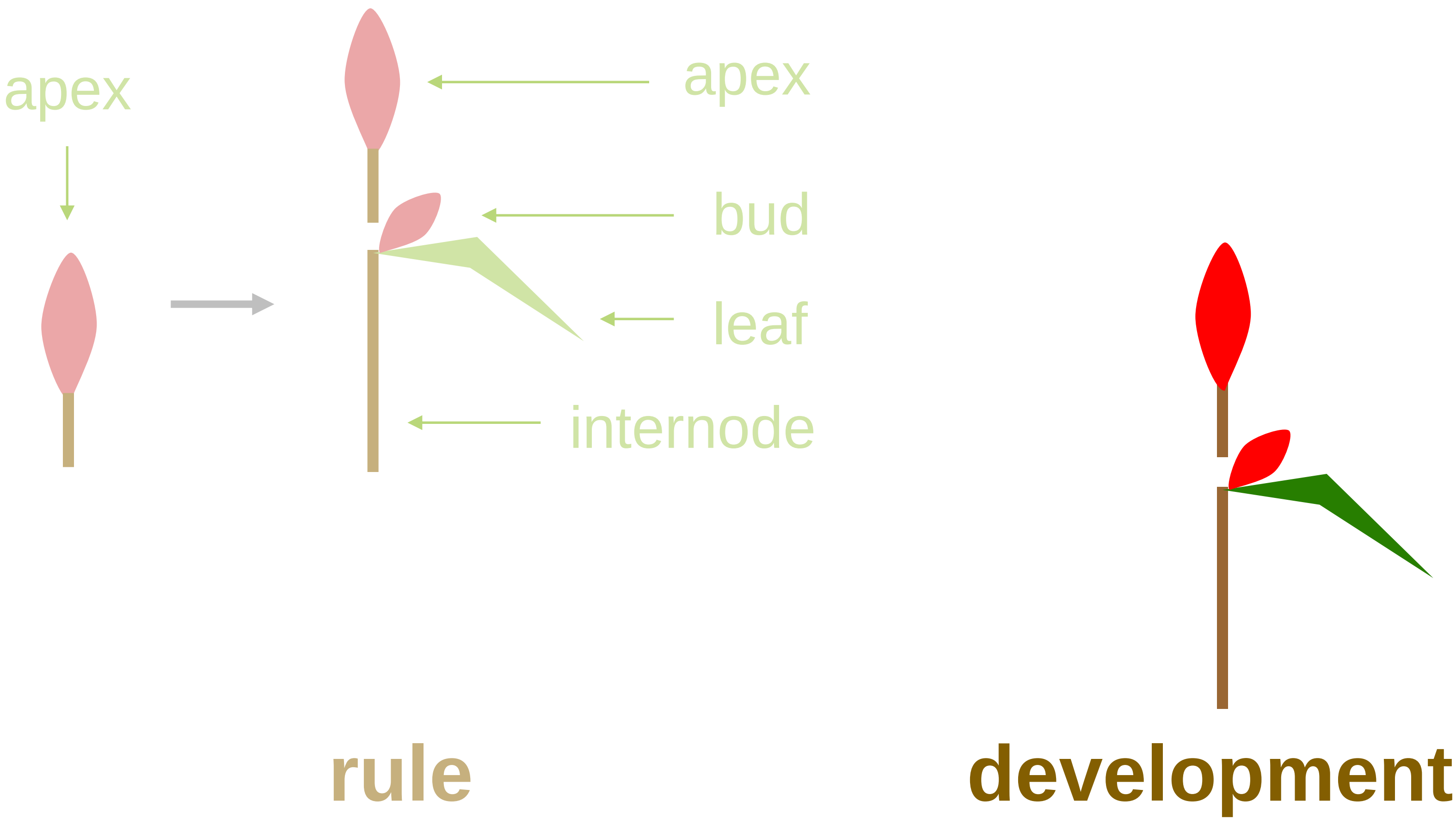




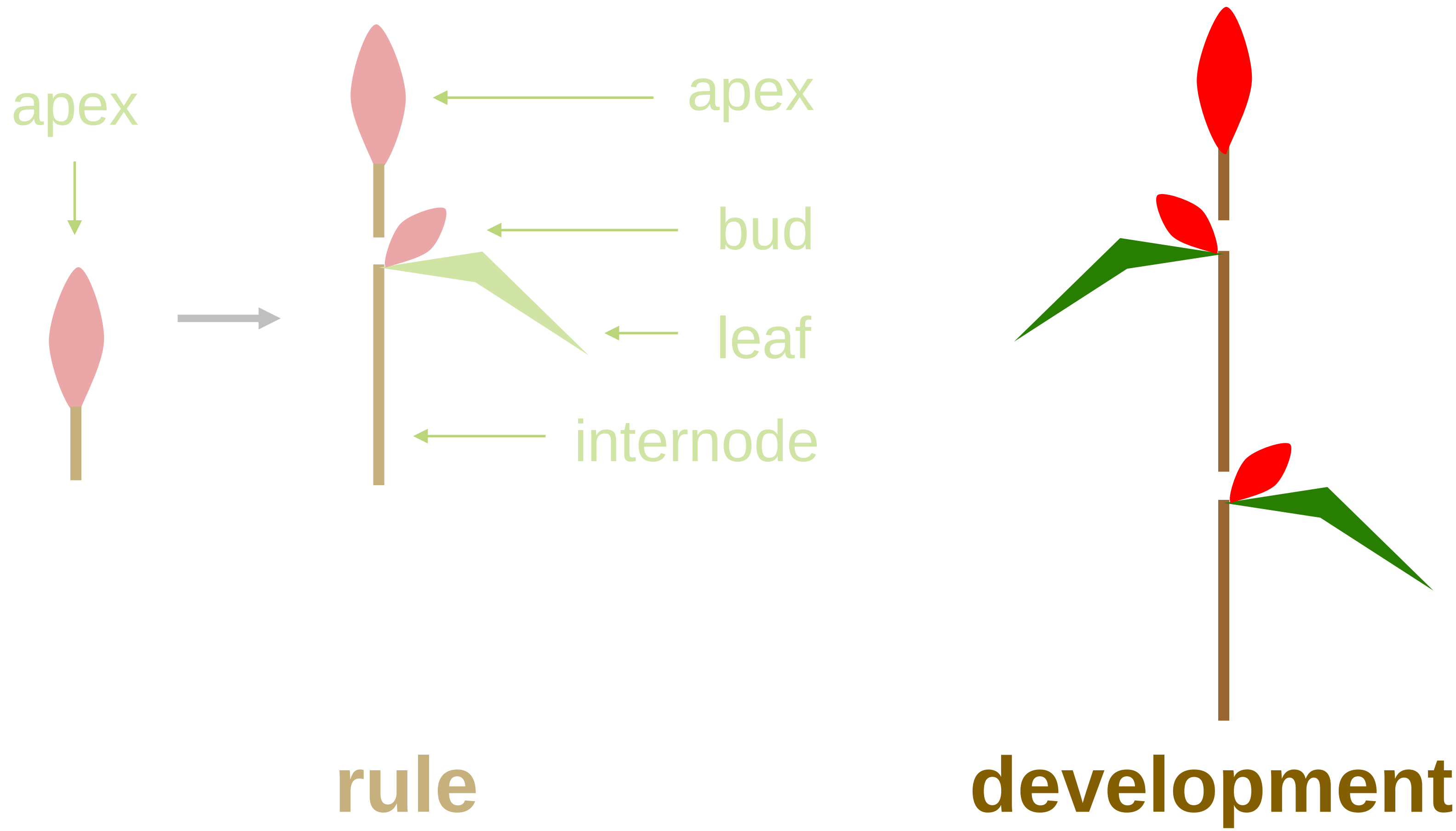
rule

development

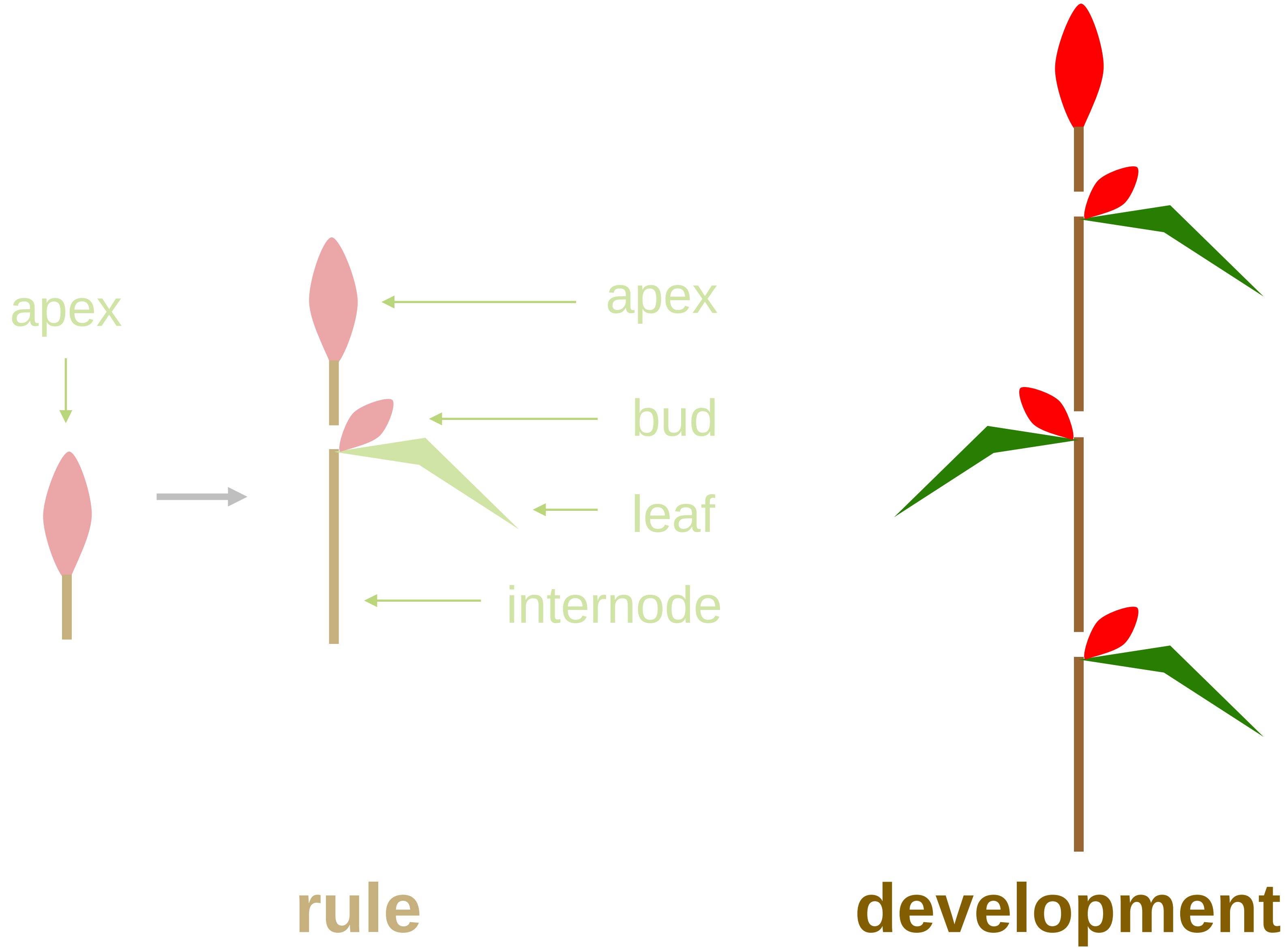
The fundamental developmental scheme



The fundamental developmental scheme



The fundamental developmental scheme



Defining plant architecture

1) Where are the buds?

(phyllotaxis, internode elongation, bud formation)

2) What the buds will do (and when)?

(the fate of buds)

3) Further actions

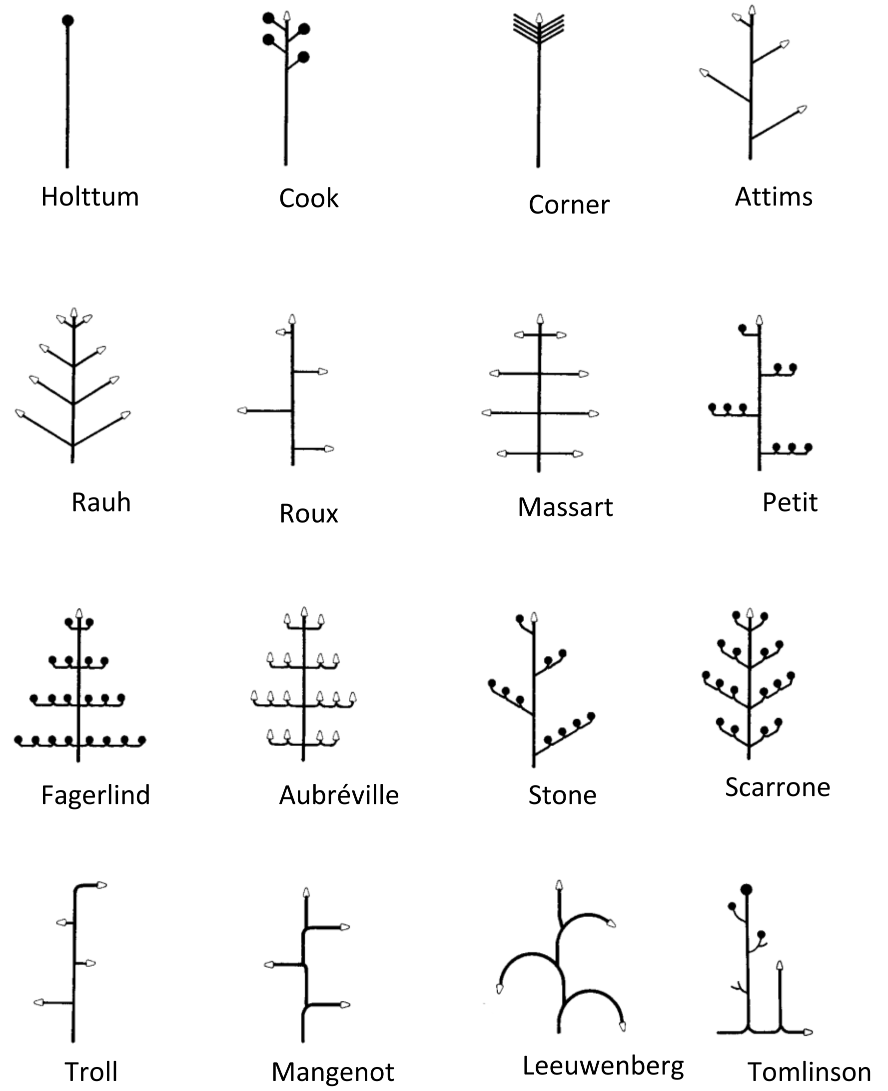
(reorientation, shedding)

Architectural models

Hallé, Oldeman, Tomlinson 1978

“Organization of trees reflects the precisely controlled genetic program which determines their development. [...]

This program is disrupted by environmental factors.”



F. Hallé, R.A.A Oldeman, P.B. Tomlinson:
Tropical trees and forests: An architectural analysis. Springer, Heidelberg 1978.

Architectural models do not suffice

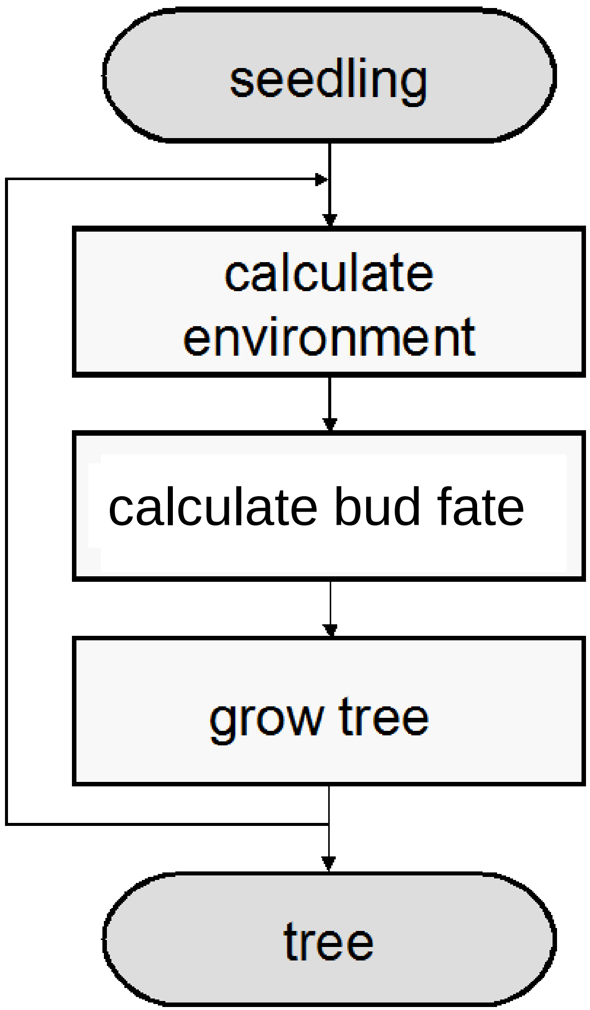
Sachs & Novoplansky 1995,
Sachs 2004

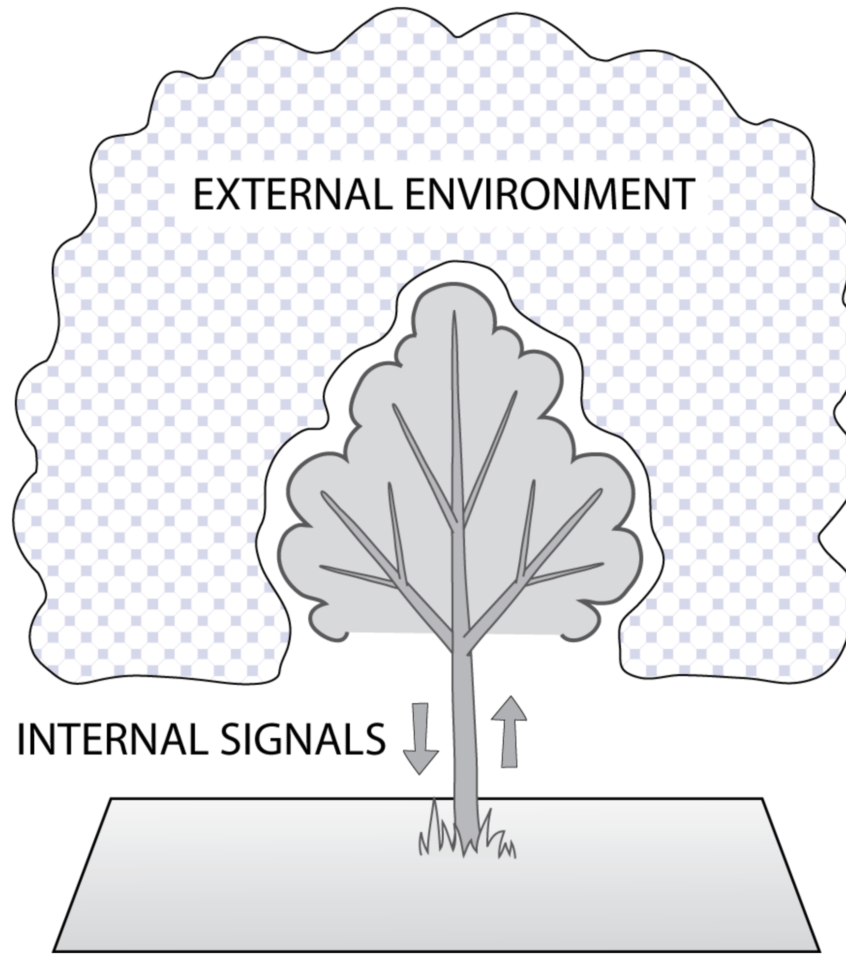
"The form of a tree is generated by self-organization in which alternative branches compete with one another, following no strict plan or pre-pattern."

T. Sachs and A. Novoplansky. Tree form: Architectural models do not suffice. *Israel Journal of Plant Sciences*, 43:203-212, 1995.

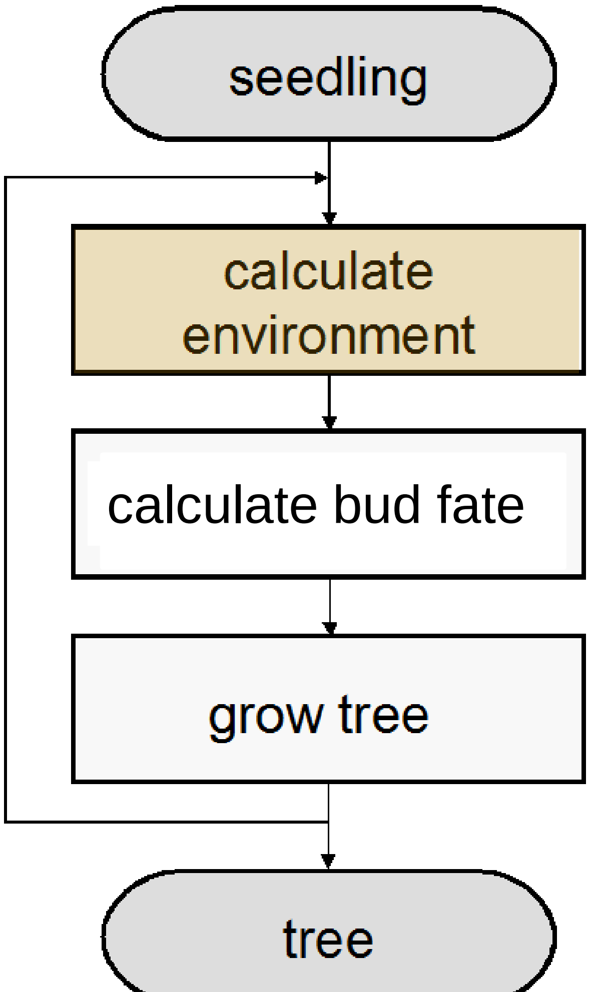
Combining Architectural and Self-organizing Models

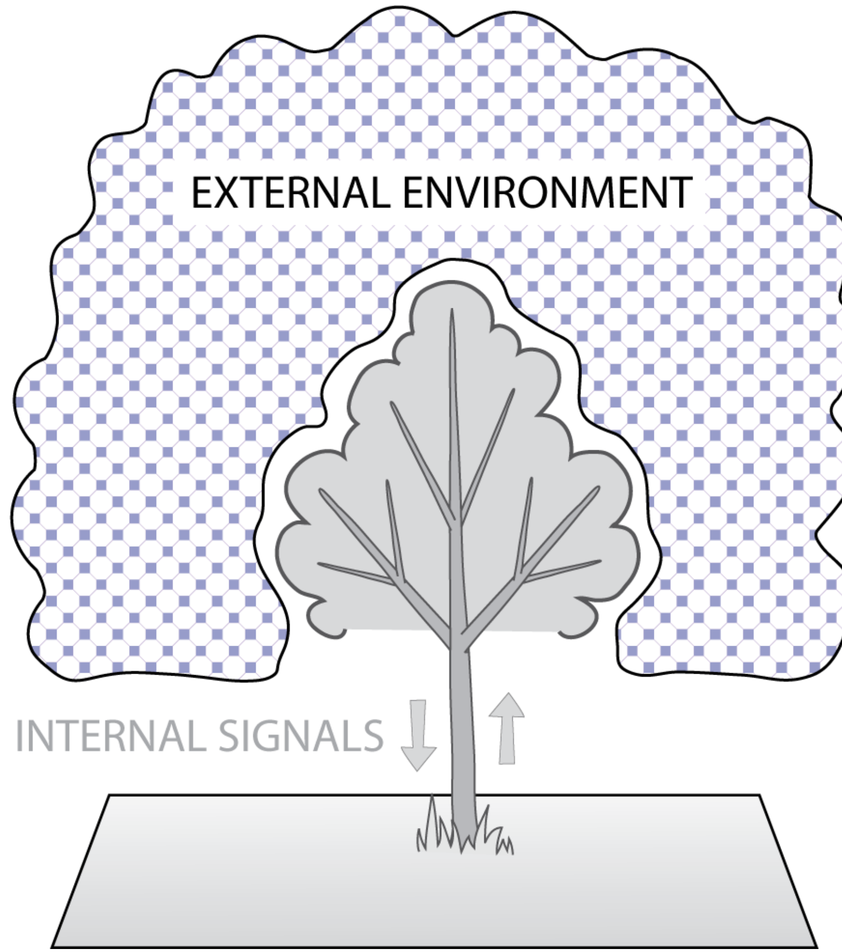
Simulation Overview



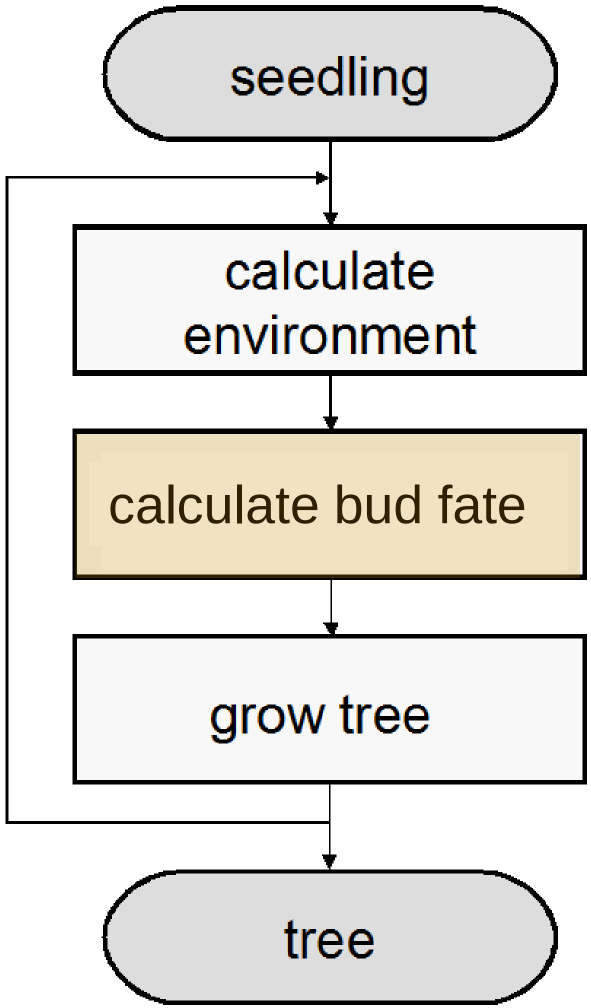


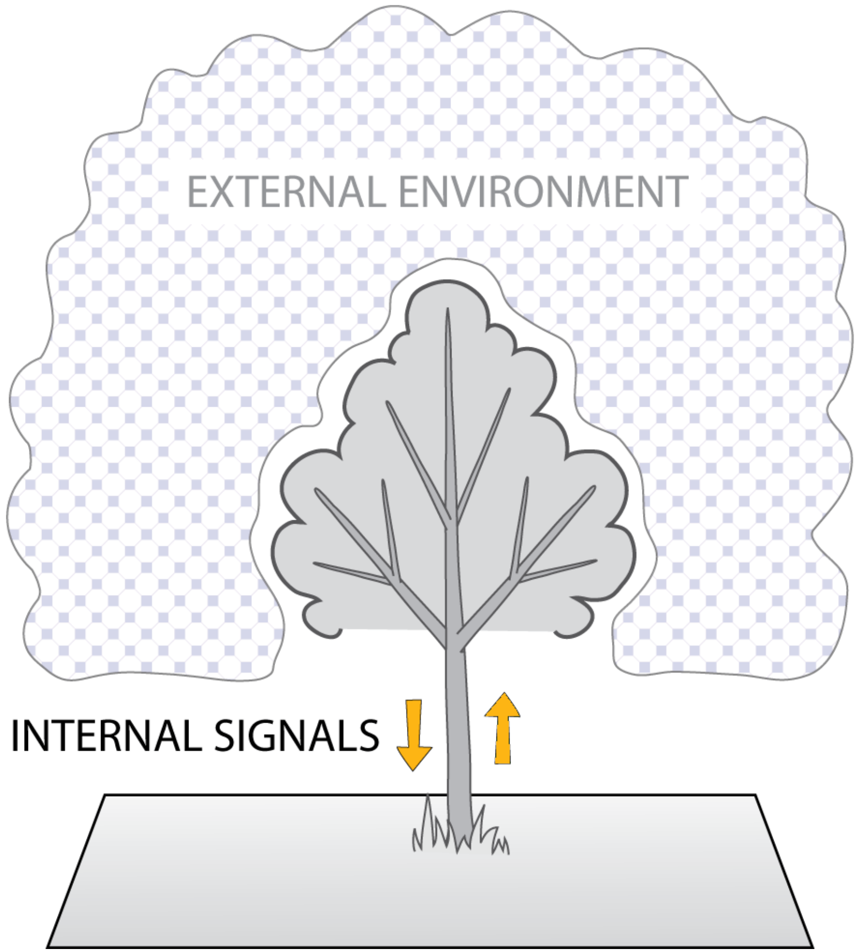
Simulation Overview



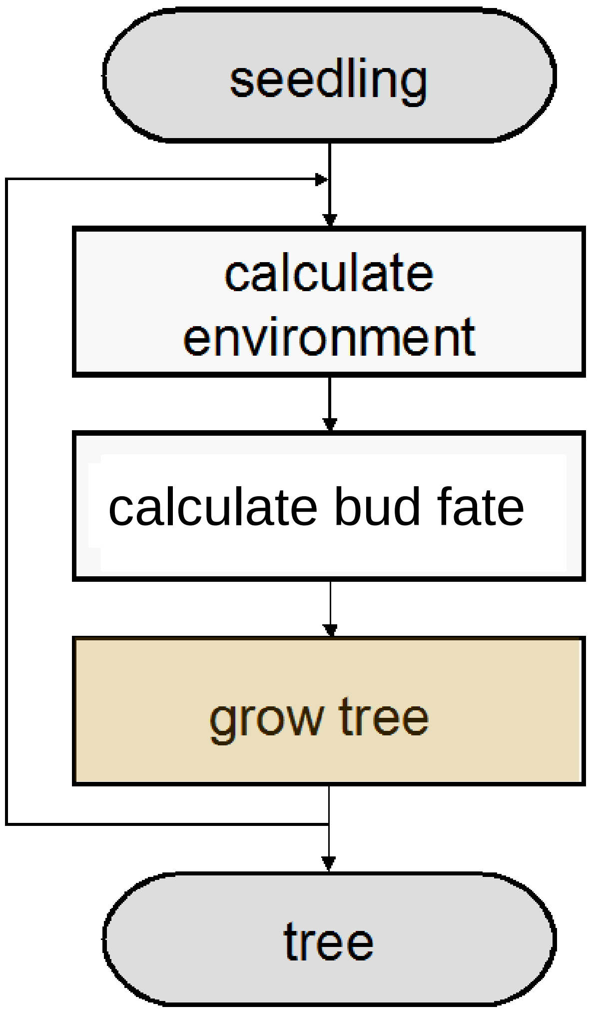


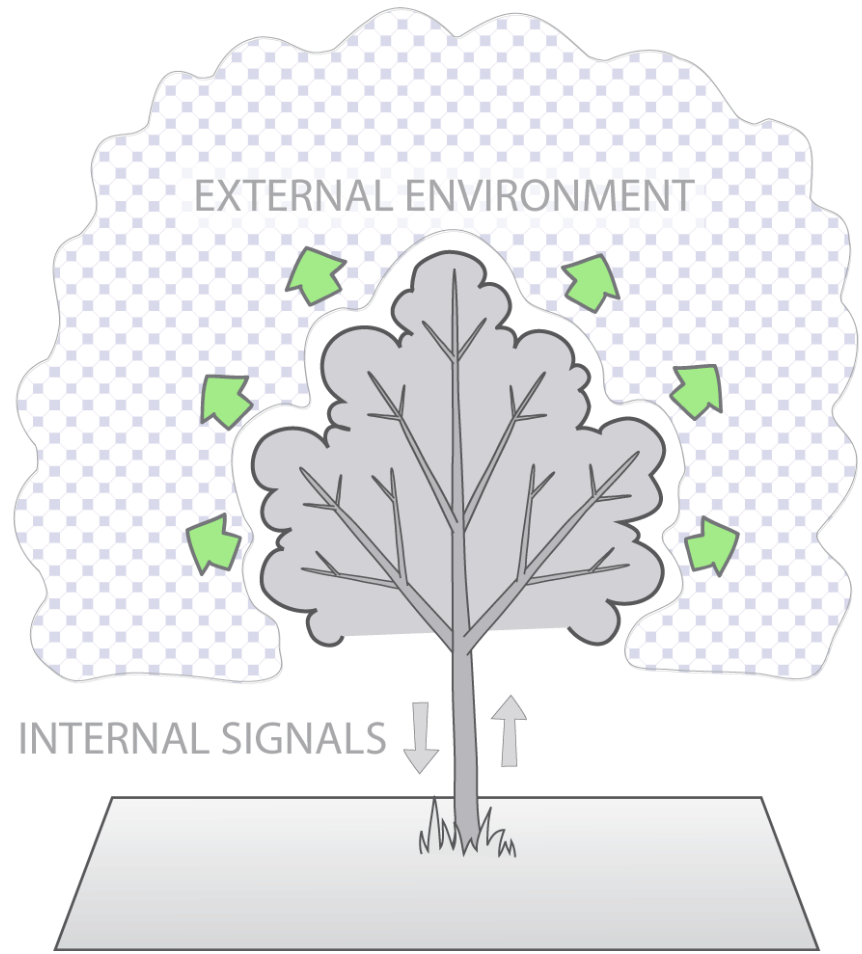
Simulation Overview



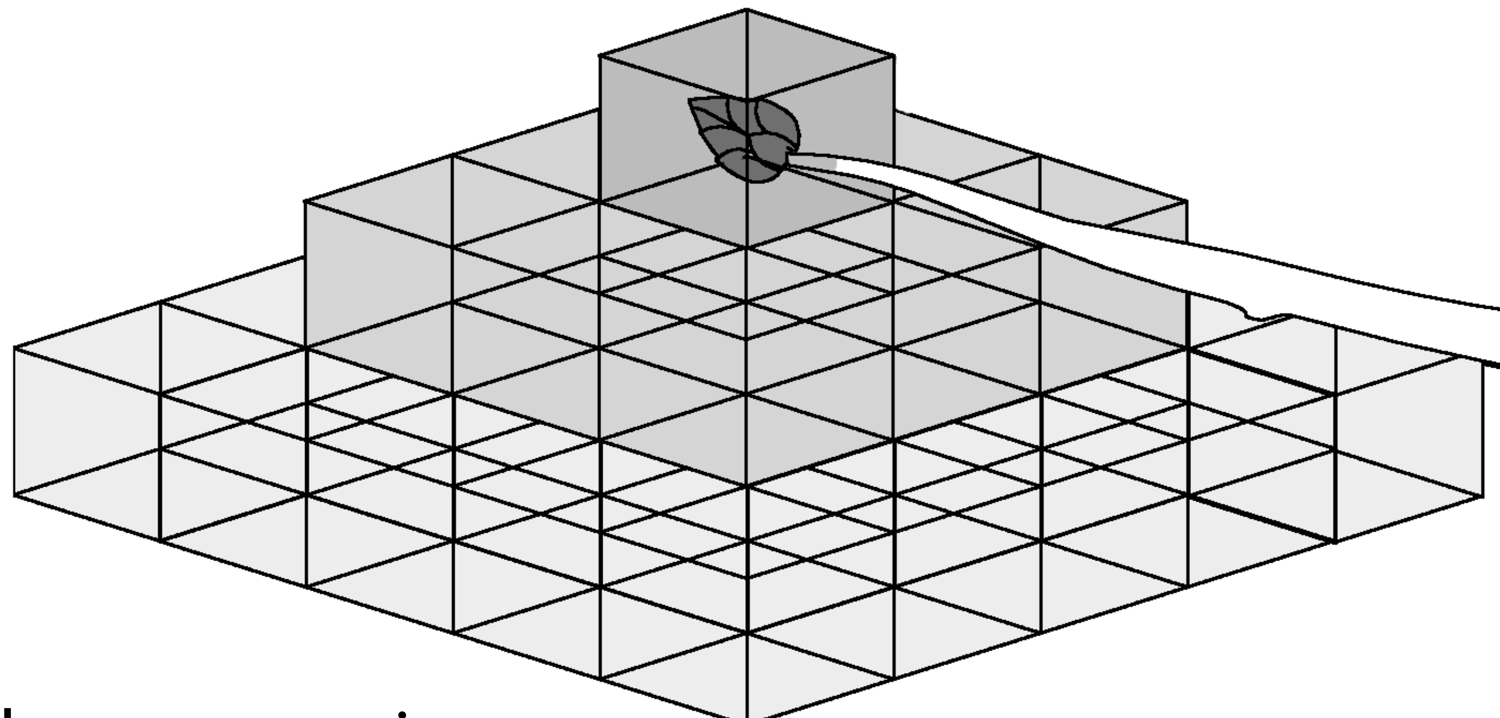


Simulation Overview





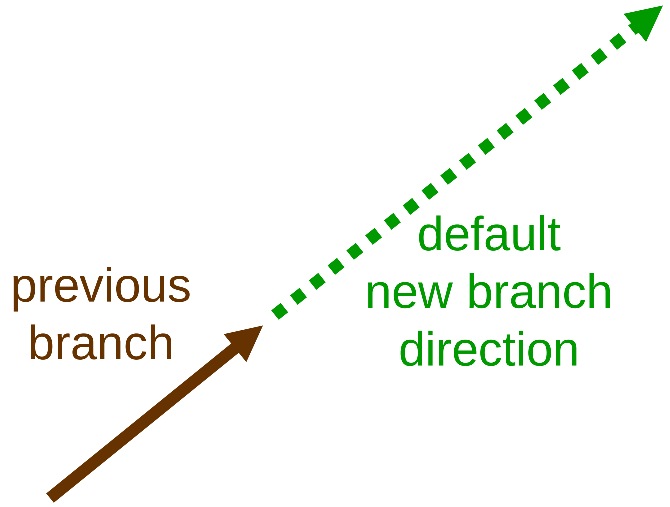
Calculating Environment



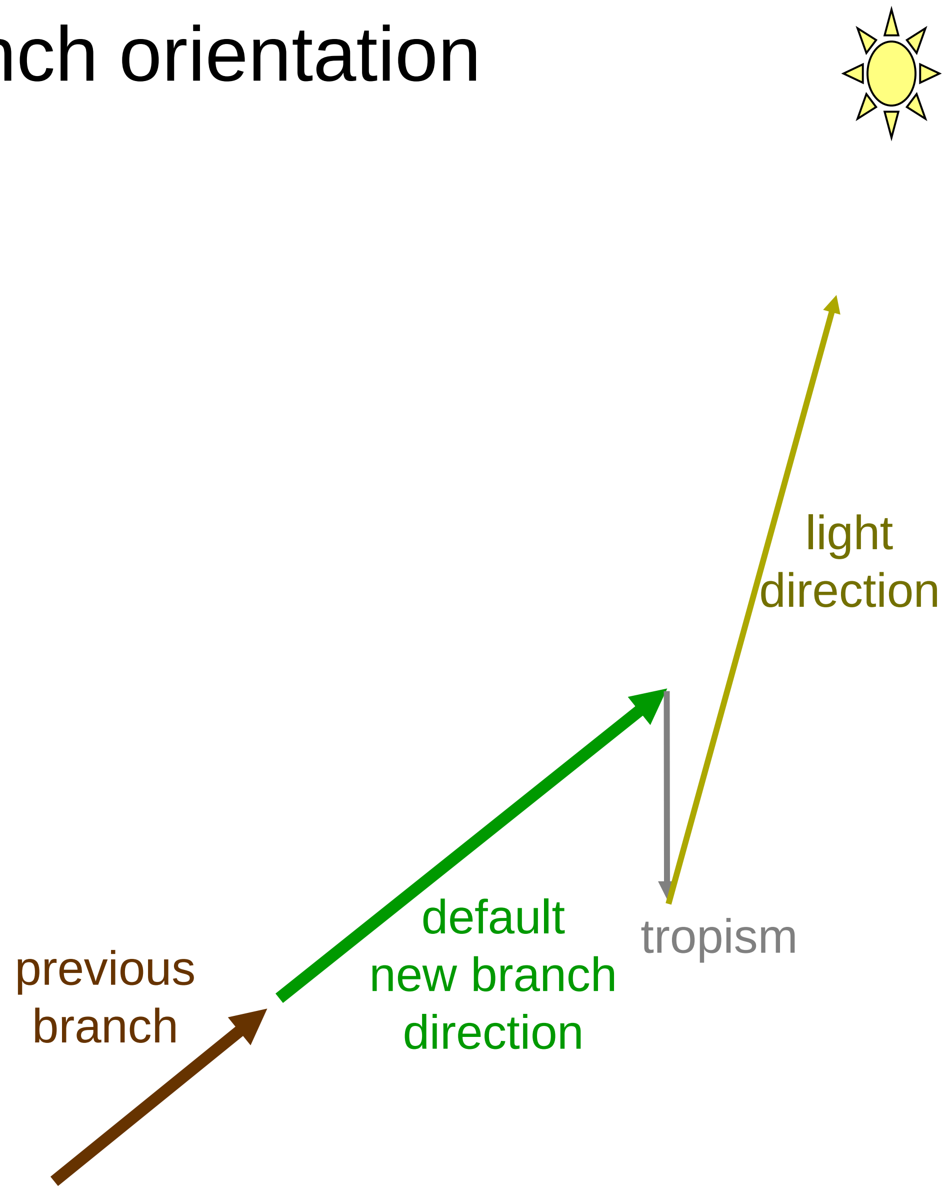
Shadow propagation

W. Palubicki (2007): Fuzzy Plant Modeling with OpenGL.
Vdm Verlag Dr. Mueller E K.

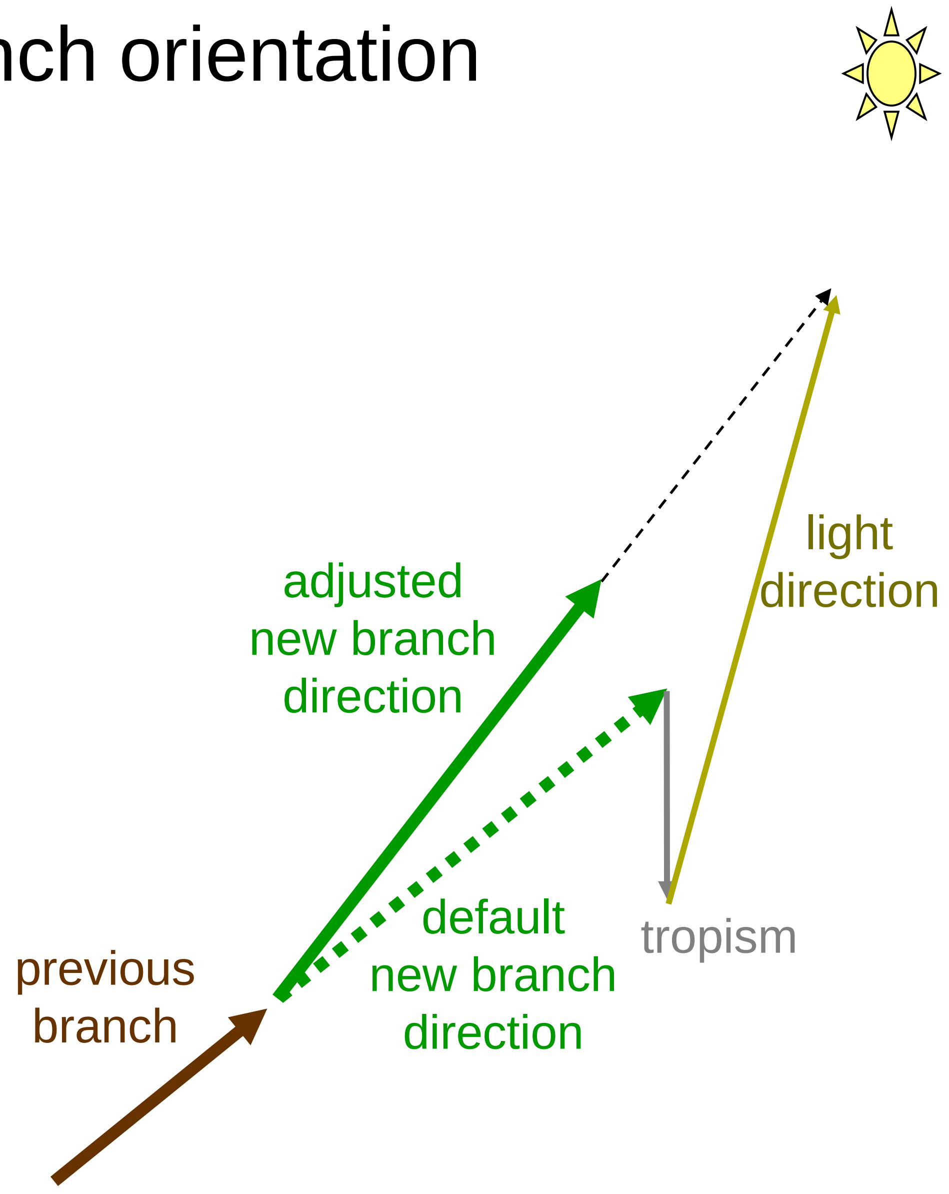
Branch orientation



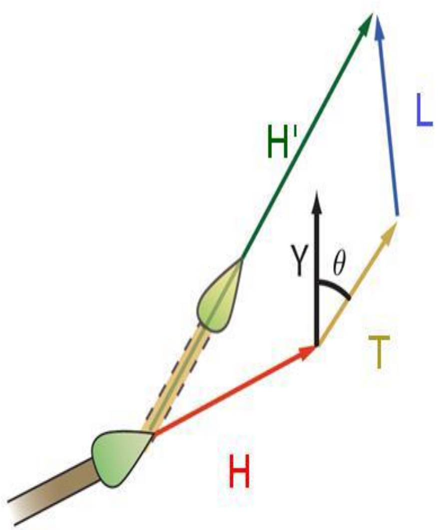
Branch orientation

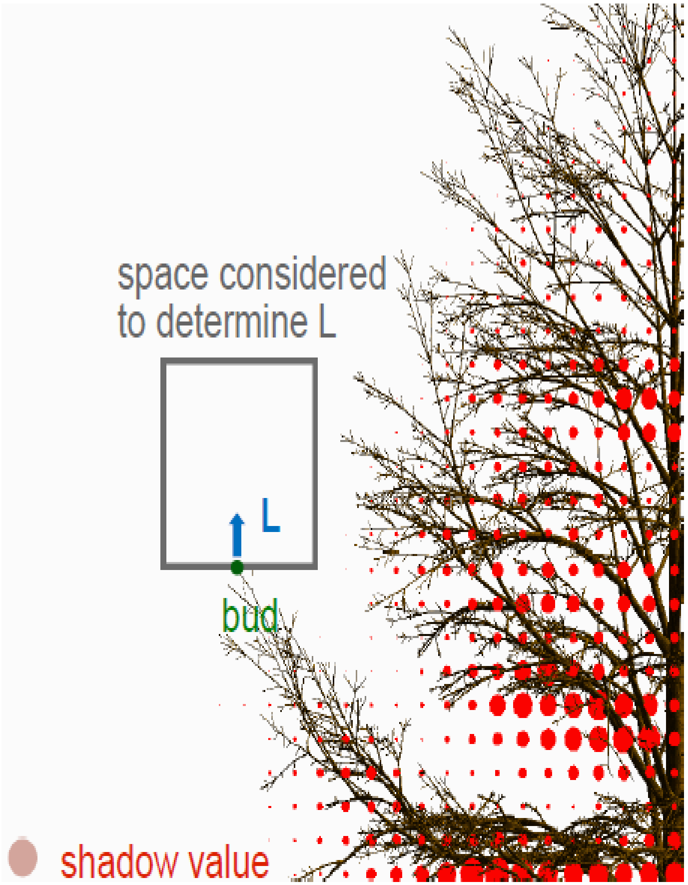


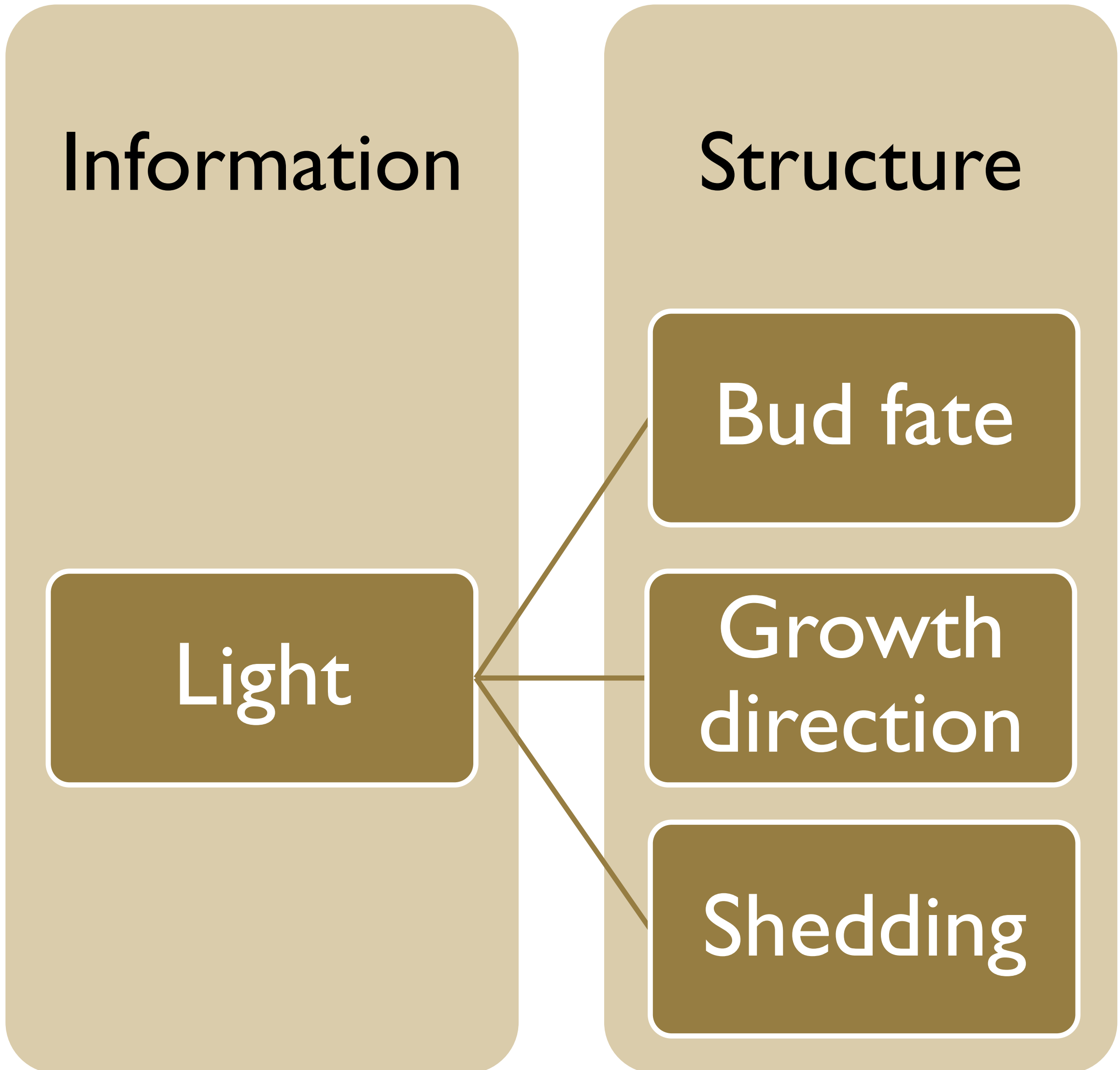
Branch orientation



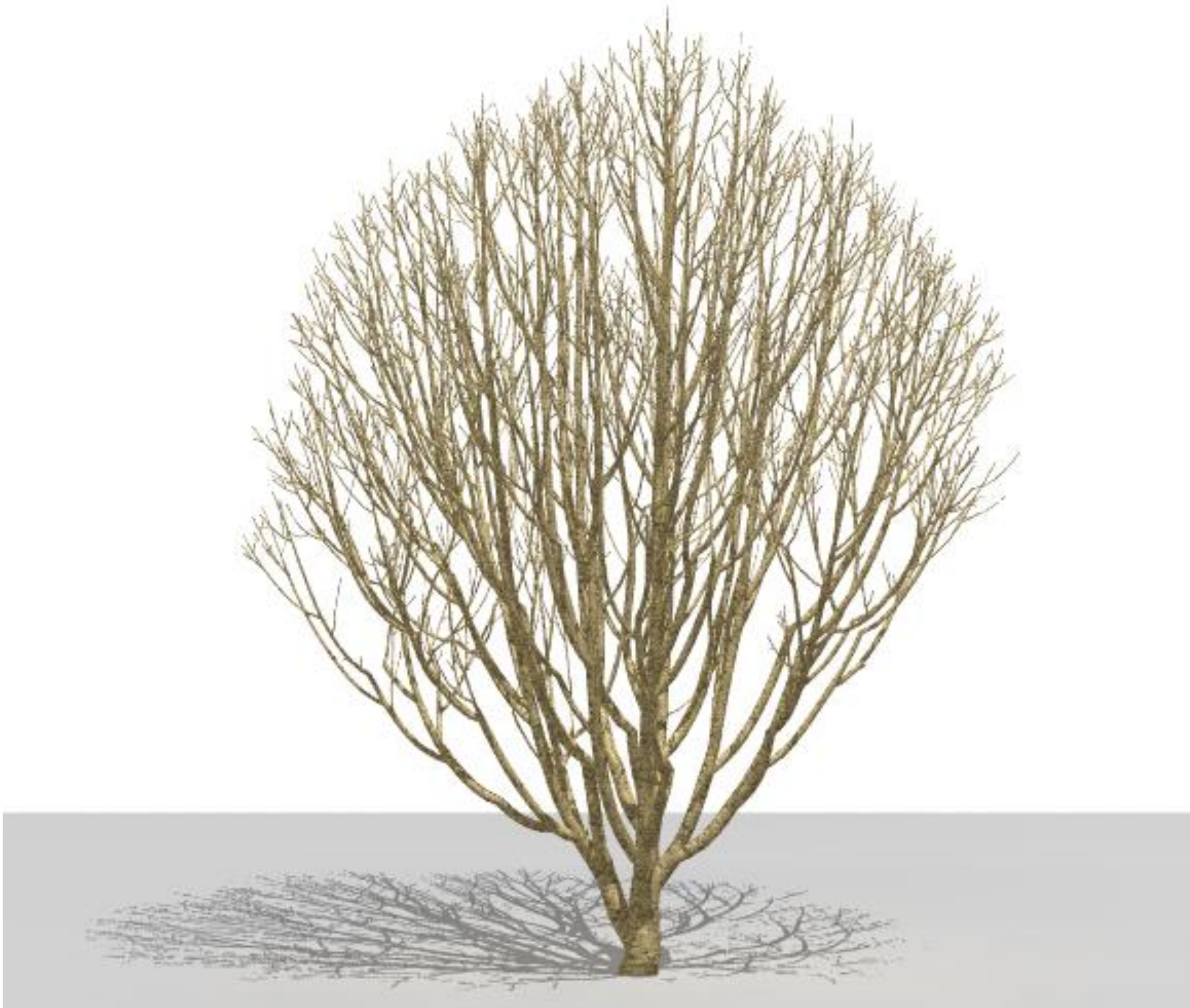
Calculating Growth Direction

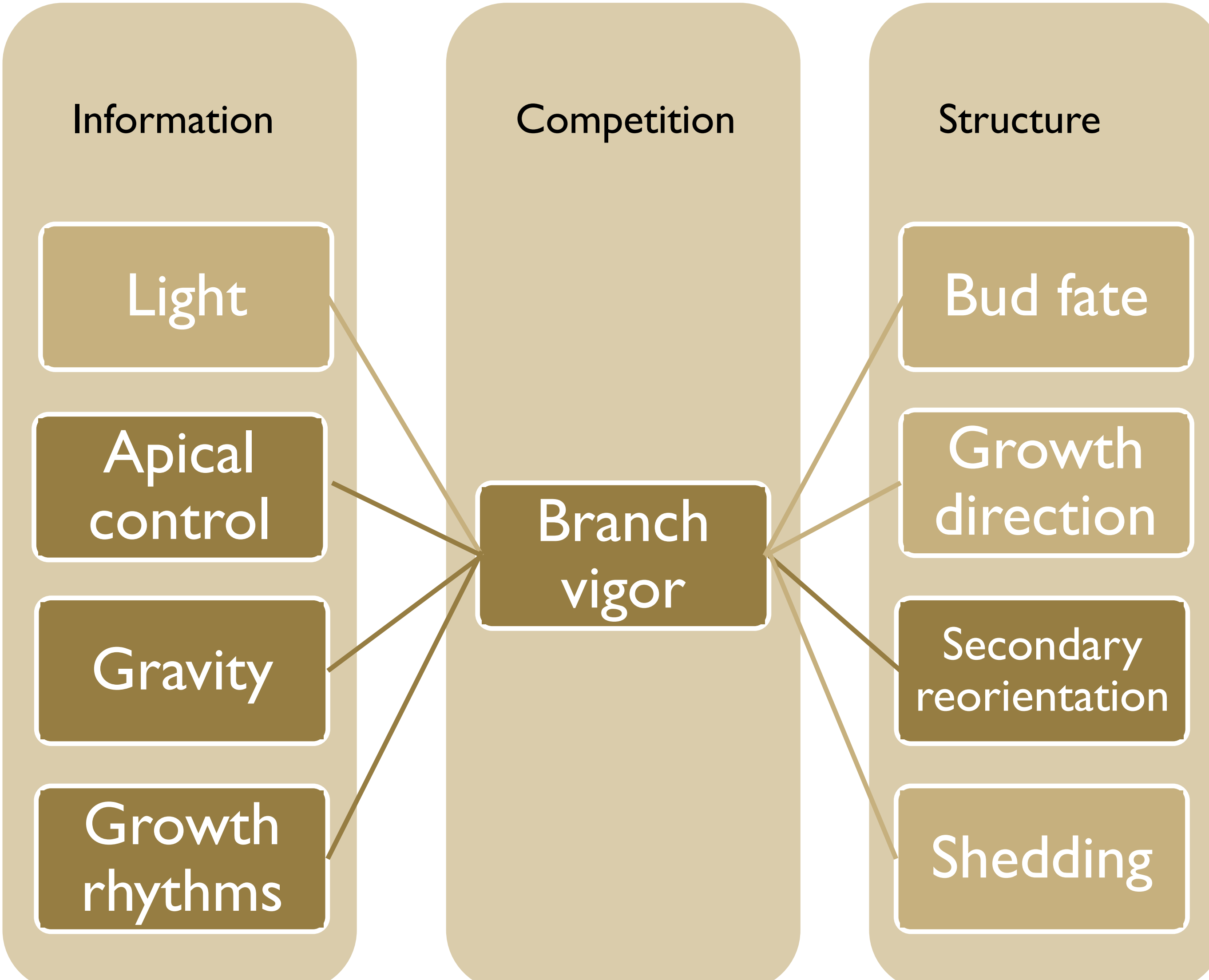





Information
Structure
Bud fate
Light
Growth direction
Shedding

Model controlled by competition for light only




Information
Competition
Structure
Light
Apical control
Gravity
Growth rhythms
Branch vigor
Bud fate
Growth direction
Secondary reorientation
Shedding

Overview: How to compute branch vigor

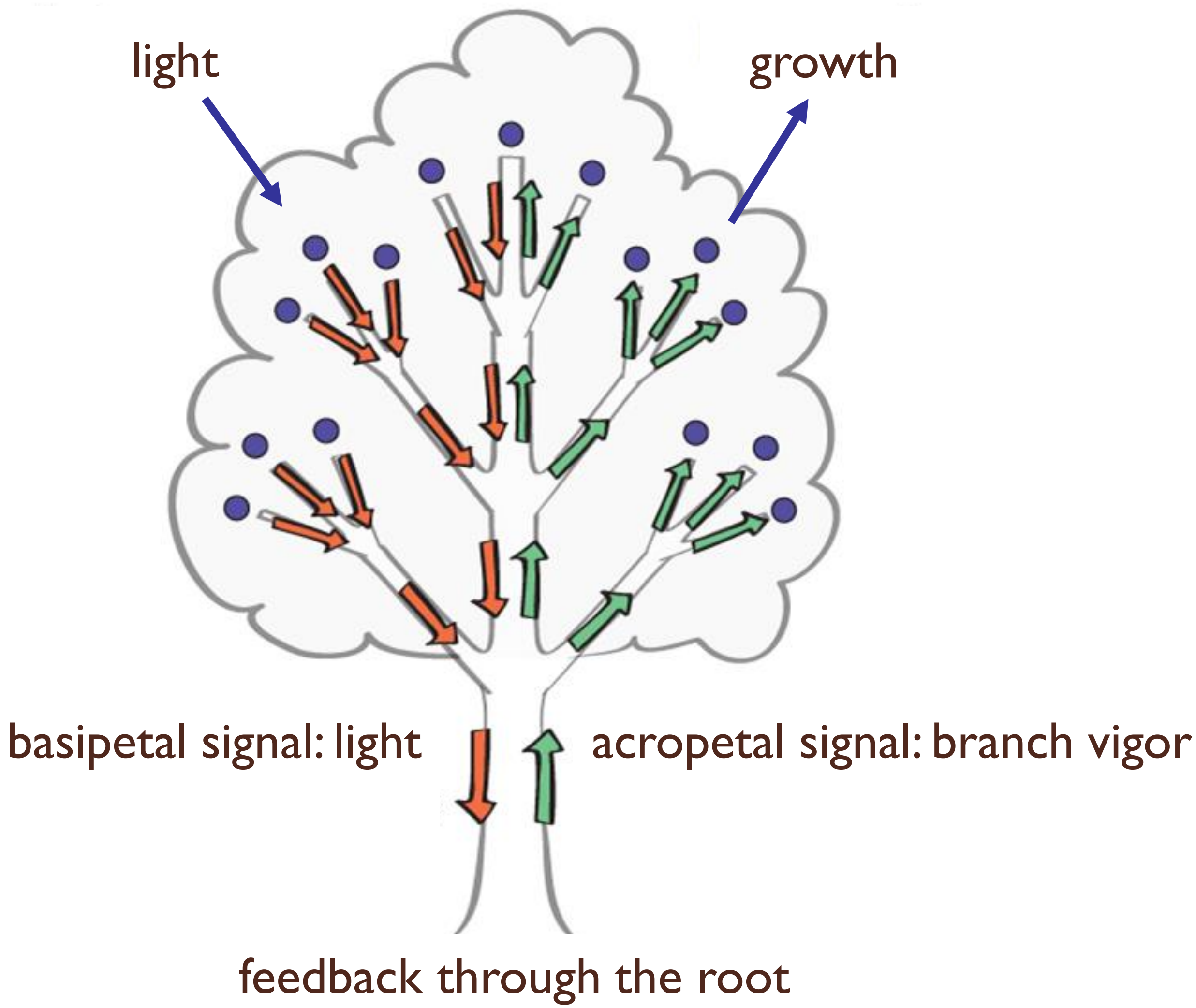
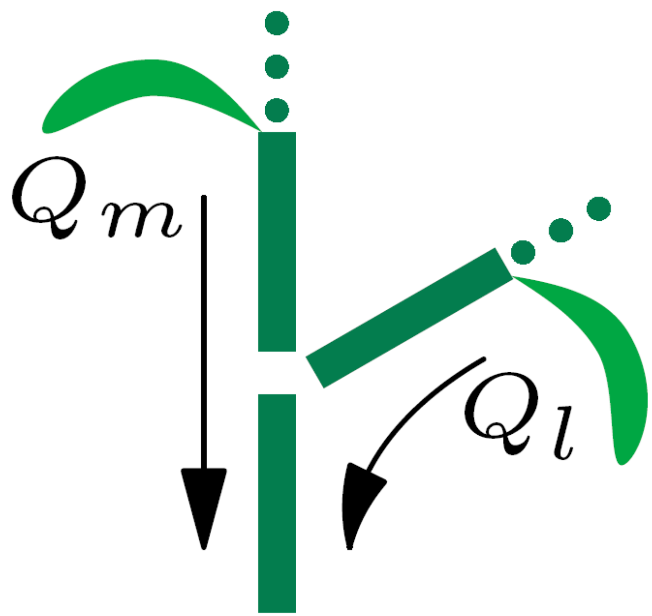


Image courtesy of Kipp Horel

Internal Signals as Flux

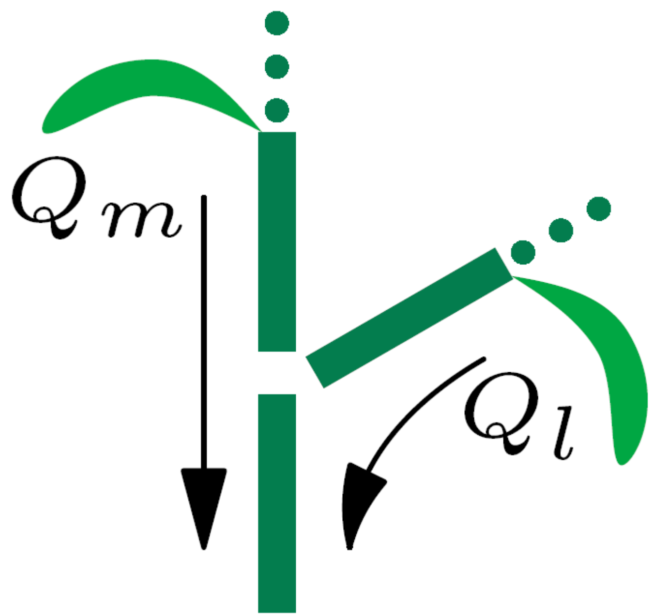
Light flux Q



$$Q = Q_m + Q_l$$

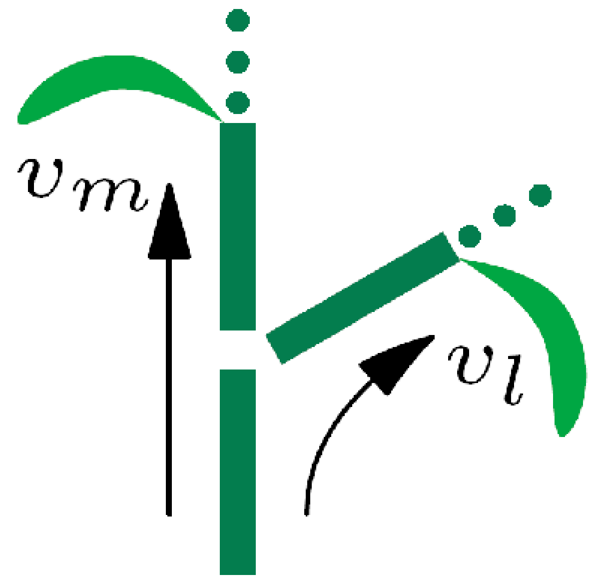
R. Borchert & H. Honda (1984): Control of development in the bifurcating branch system of Tabebuia rosea. *Botanical Gazette* 145 (2), 184-195.

Internal Signals as Flux



$$Q = Q_m + Q_l$$

Light flux Q



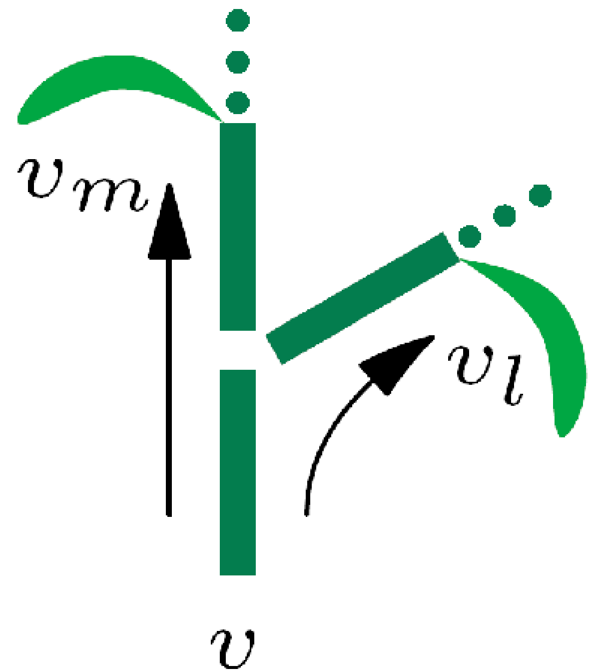
$$v$$

Vigor flux v

Vigor Flux Function

(1) $v_m = \dfrac{\lambda Q_m}{\lambda Q_m + (1-\lambda) Q_l}$

(2) $v_l = 1 - v_m$



Vigor flux v

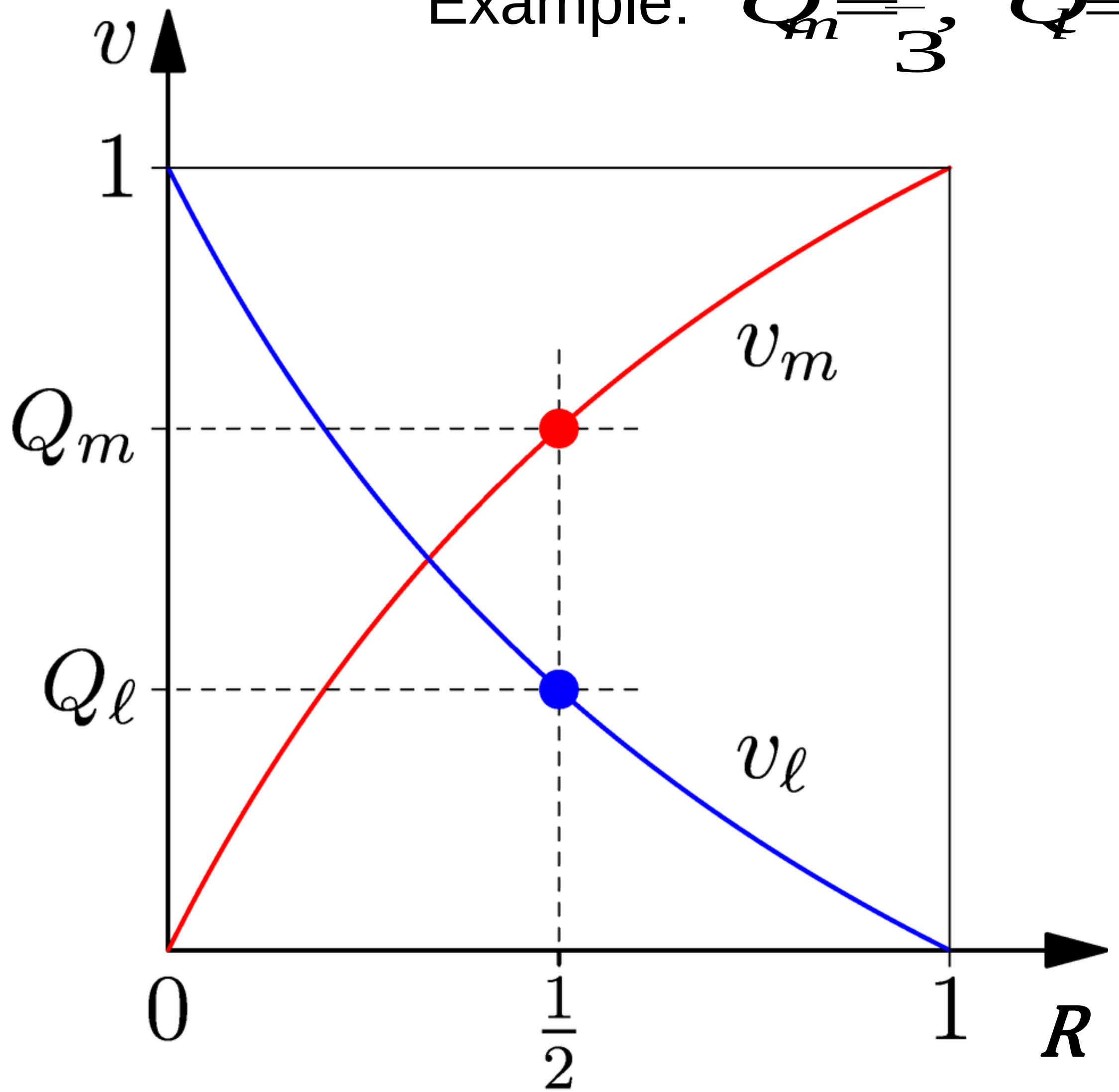
λ – Branch lineage

$$\lambda = \boldsymbol{R}\,[ax^2 + b((y+c)^2)] \quad a, b \in [0,1];\ c \in [-1,1]$$

- Parameter ***R*** conceptualizes the relation between parent branch and child branch.
- A high value for parameter ***R*** favors parent branches, a low value child branches.

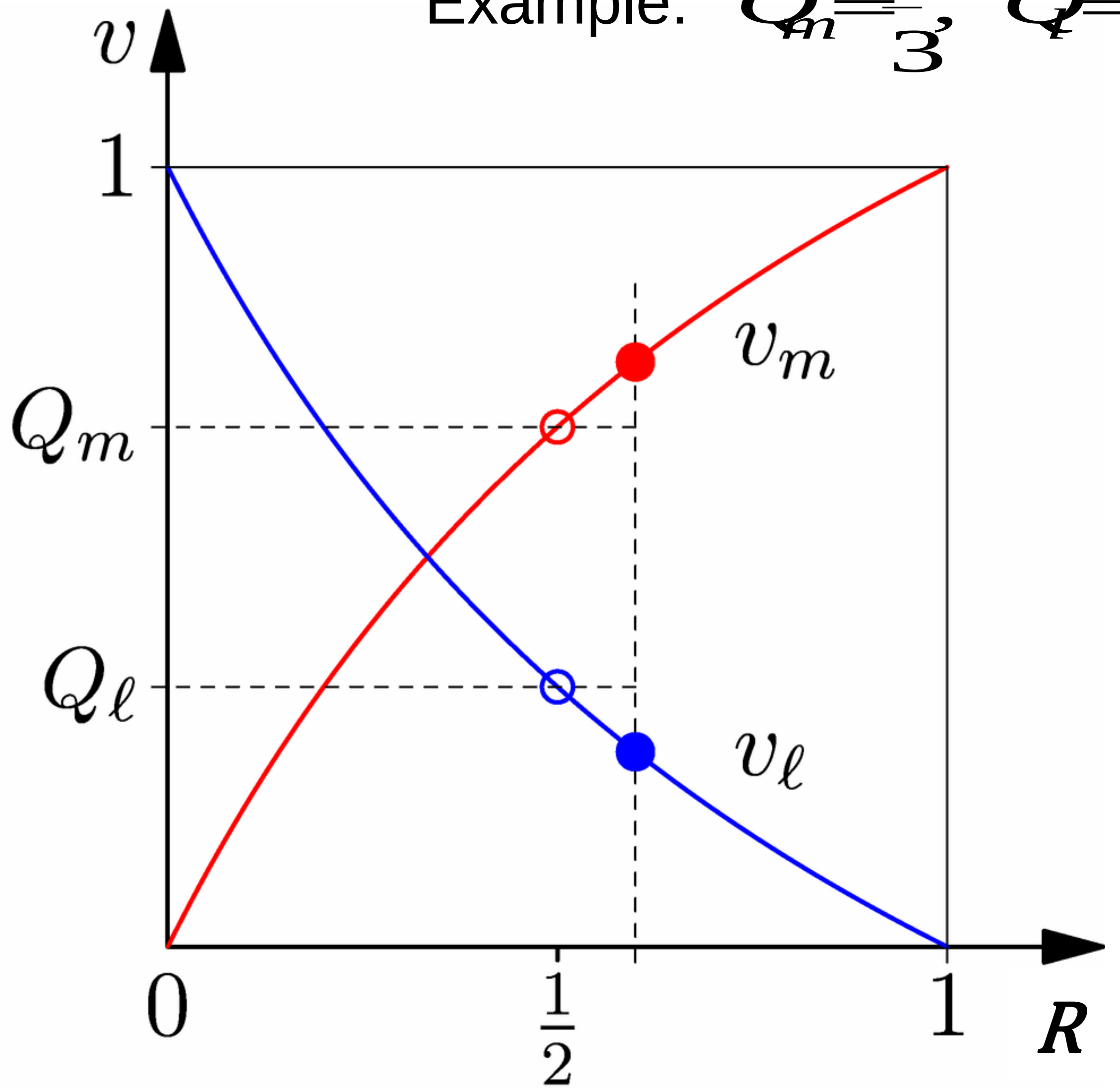
The meaning of R

Example: $Q_m = \frac{2}{3},\ Q_\ell = \frac{1}{3}$



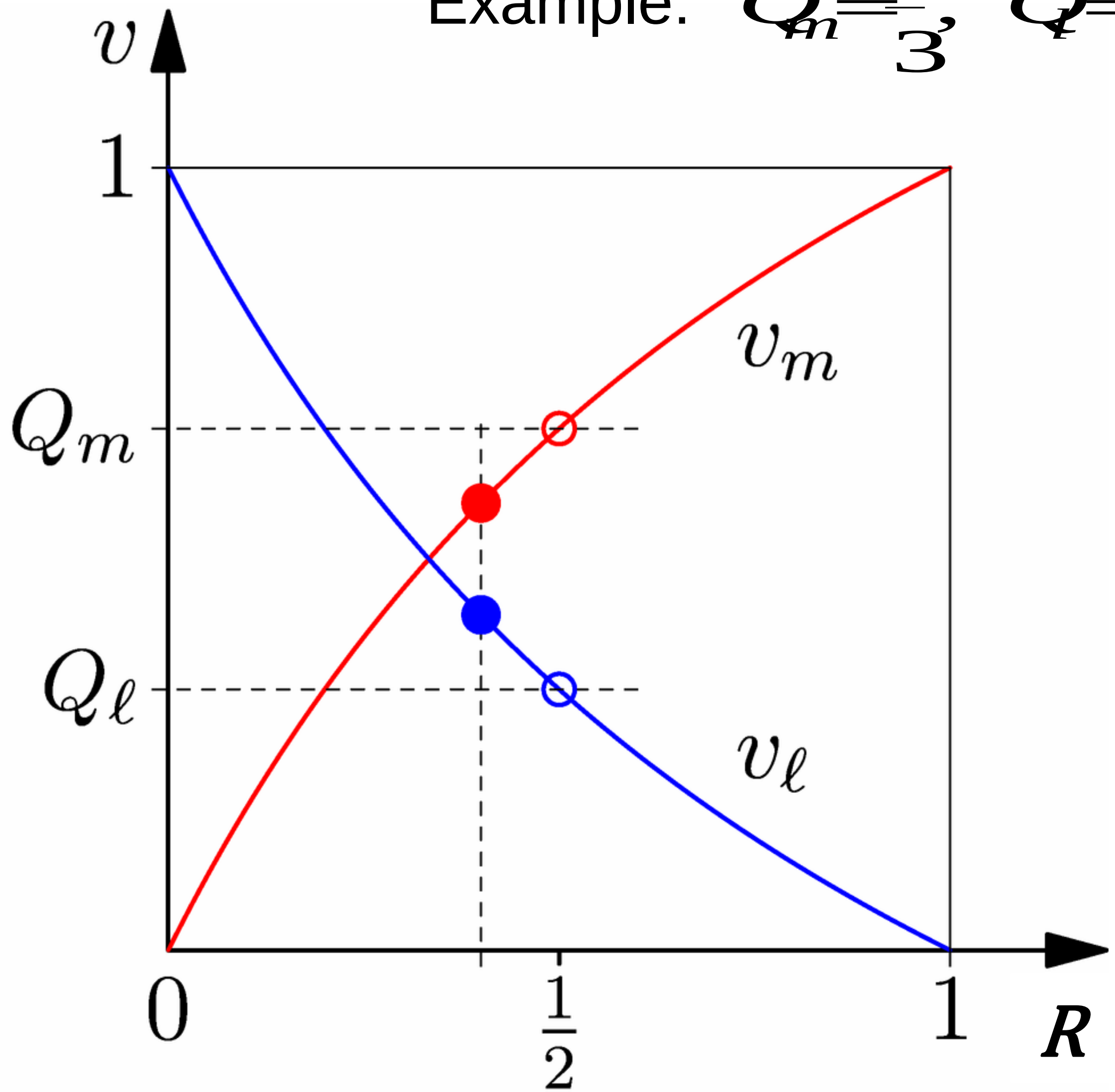
The meaning of R

Example: $Q_m = \frac{2}{3}, \; Q_\ell = \frac{1}{3}$

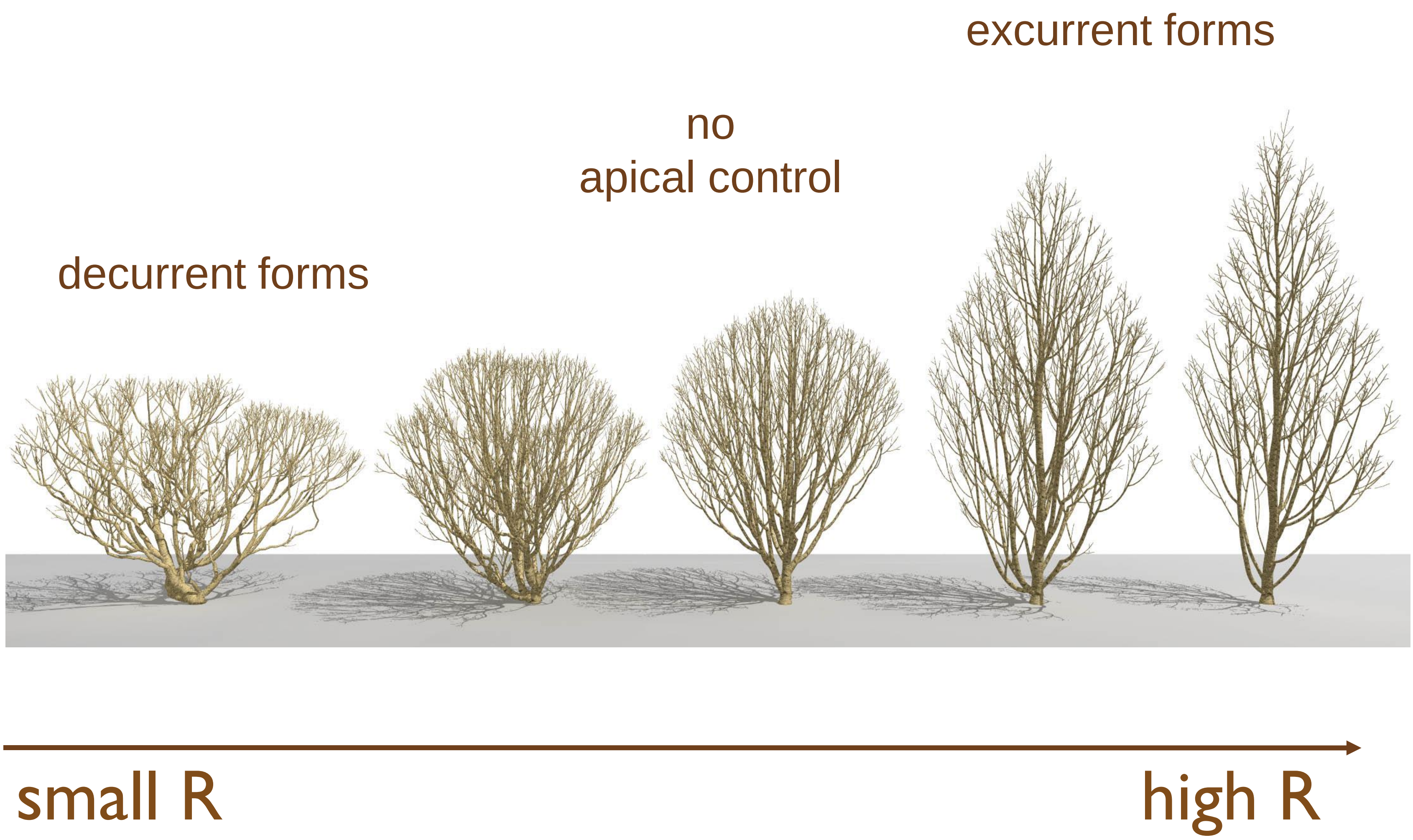


The meaning of R

Example: $Q_m = \frac{2}{3}, \; Q_\ell = \frac{1}{3}$

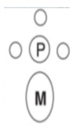


Apical control

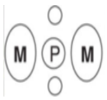


Palubicki, et al. (2009). Self-organizing tree models for image synthesis. *ACM Transactions on Graphics 28*, 58:1-10.

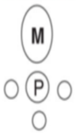
Gravimorphism



Hypotony
(sympodial)



Amphitony

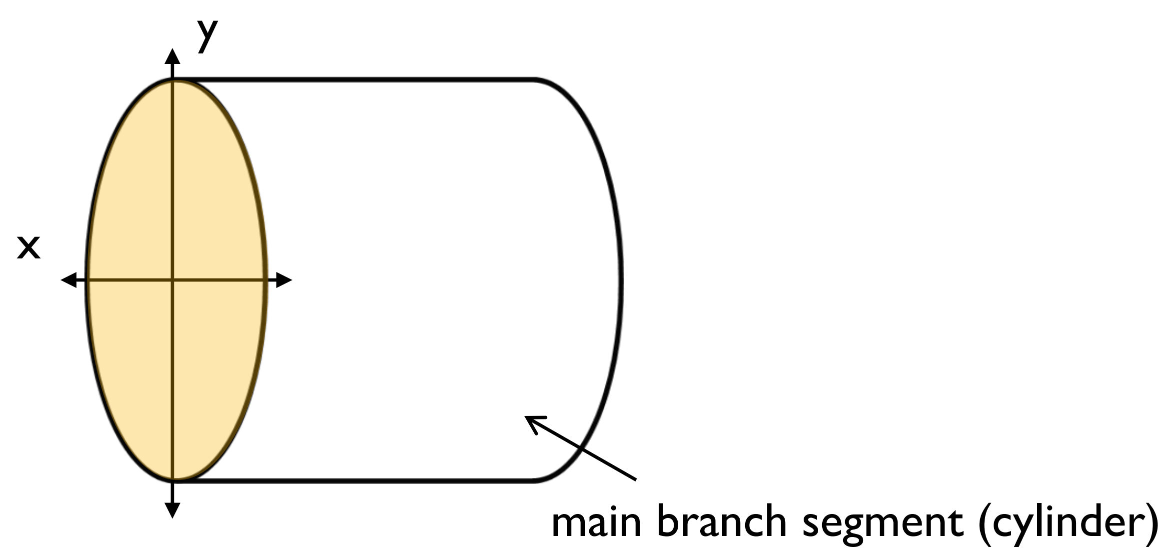


Epitony

λ – Preferential development of lateral axes (Gravimorphism)

$$\lambda = R\,[\mathbf{a}x^2 + \boldsymbol{b}((y + \boldsymbol{c})^2)] \quad a, b \in [0,1];\ c \in [-1,1]$$

- *x* and *y* denote the location of a lateral branch

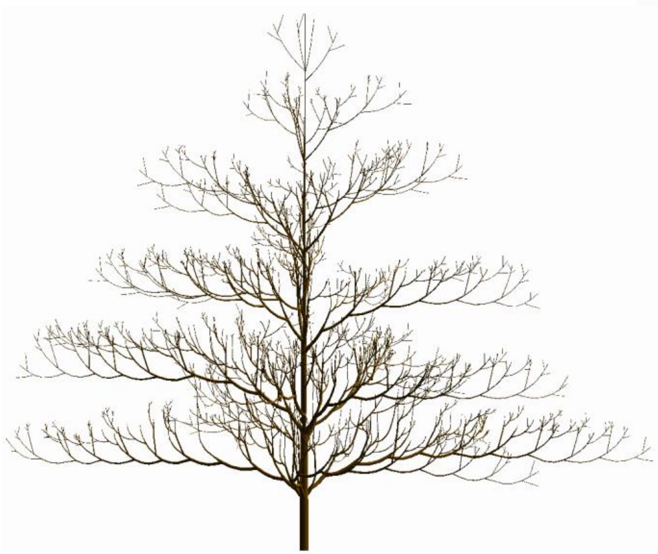


λ – Preferential development of lateral axes (Gravimorphism)

$$\lambda = R\,[\mathbf{a}x^2 + \boldsymbol{b}((y + \boldsymbol{c})^2)] \quad a, b \in [0,1];\ c \in [-1,1]$$

- *x* and *y* denote the location of a lateral branch
- Parameter ***a*** defines preference for buds located at the sides of a branch (**Amphitony**)
- Parameter ***b*** defines preference for buds located at the upper and lower surface of a branch
- Parameter **c** defines a preference for buds located at either upper or lower surface of a branch (**Epitony/Hypotony**)

Gravimorphism - Examples



orthotropism ↑
+
hypotony (high c)

plagiotropism ↔
+
amphitony (high a)

orthotropism ↓
+
epitony (low c)

Bud Fate – Dormant, Flowering and Active

- Buds which satisfy the inequality **flux < flowering threshold** become a flower and are removed from the simulation
- Threshold affects only **active buds**

Active bud

Dormant bud

Before calculating flux

Bud Fate – Dormant, Flowering and Active

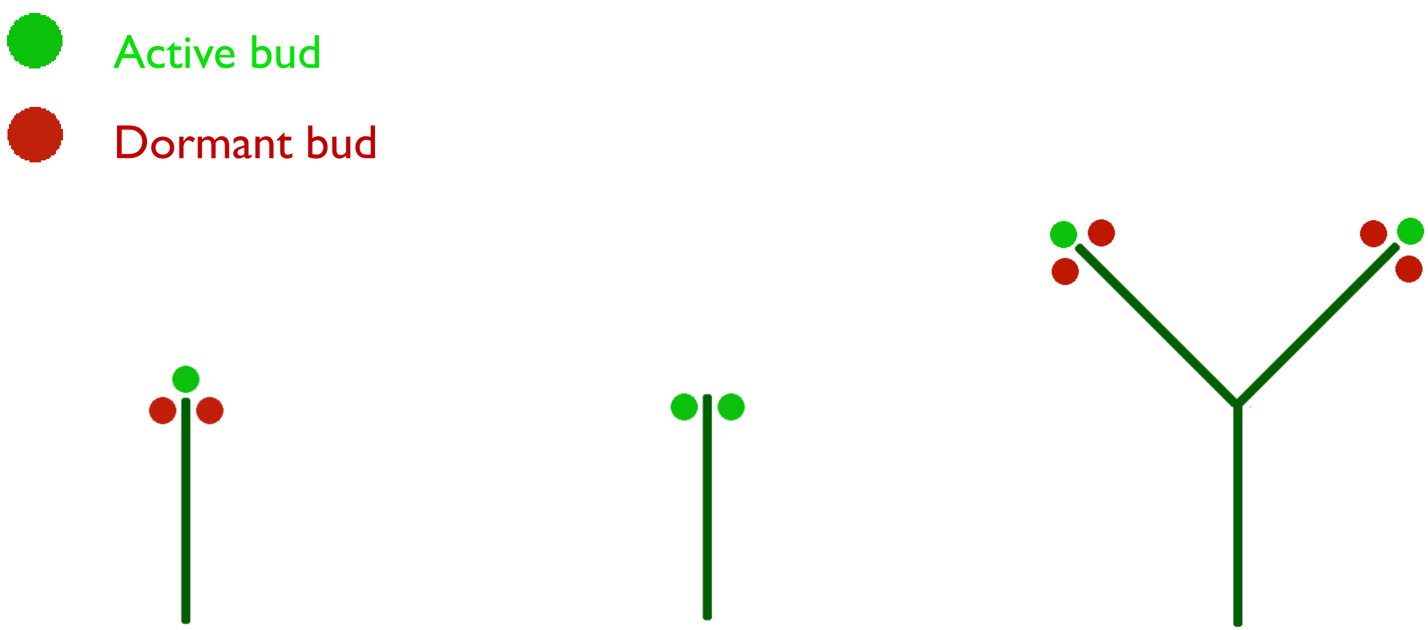
- Buds which satisfy the inequality **flux < flowering threshold** become a flower and are removed from the simulation
- Threshold affects only **active buds**

Before calculating flux

After calculating flux

Bud Fate – Dormant, Flowering and Active

- Buds which satisfy the inequality **flux < flowering threshold** become a flower and are removed from the simulation
- Threshold affects only **active buds**



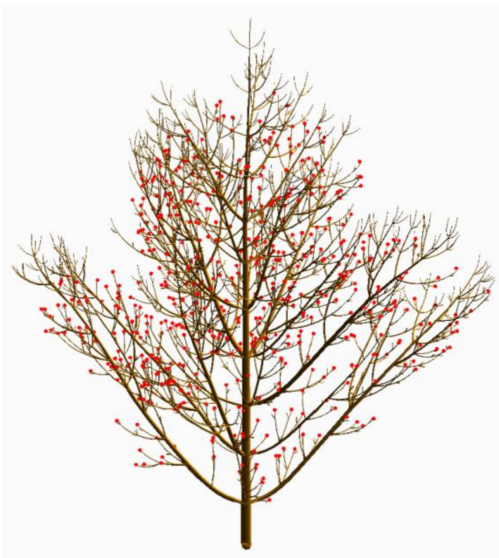
Before calculating flux | After calculating flux | After growth phase

Flowering and Architectural Models

Flowering threshold

(pronounced parent child bias)

Flowering and Architectural Models



Rauh

Scarrone

Leeuwenberg

Flowering threshold

(pronounced parent child bias)

Plagiotropy and Architectural Models

Rauh

Plagiotropy threshold

(pronounced parent child bias)

Plagiotropy and Architectural Models

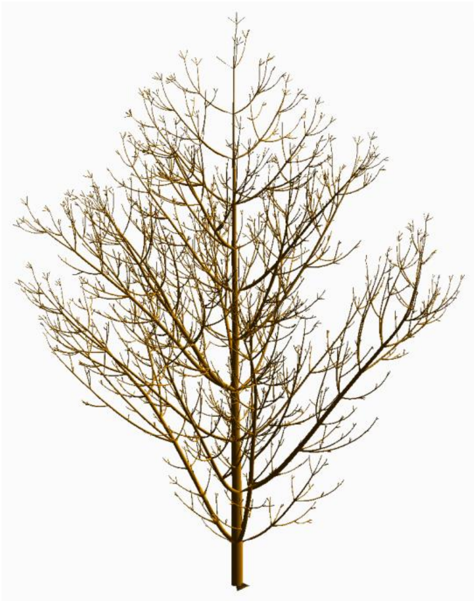
Rauh

Massart

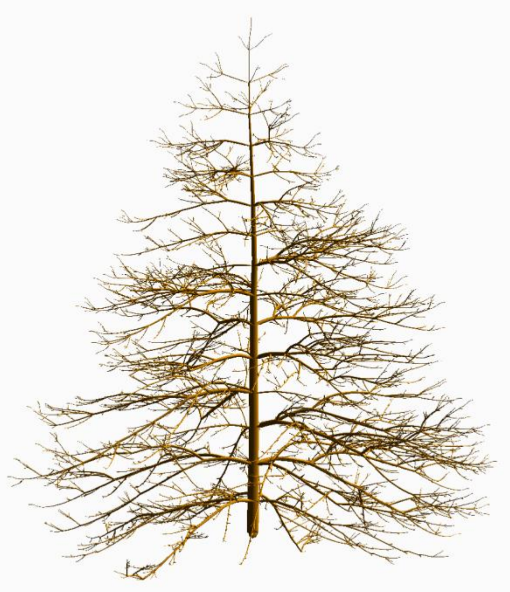
Plagiotropy threshold

(pronounced parent child bias)

Plagiotropy and Architectural Models



Rauh

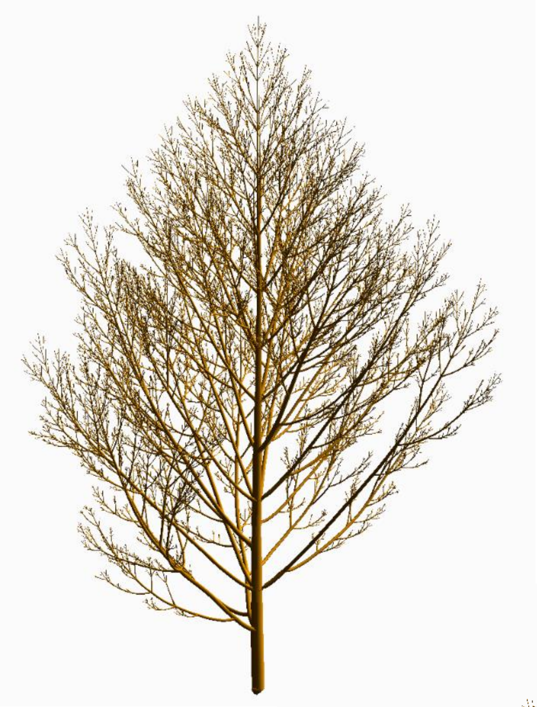


Massart

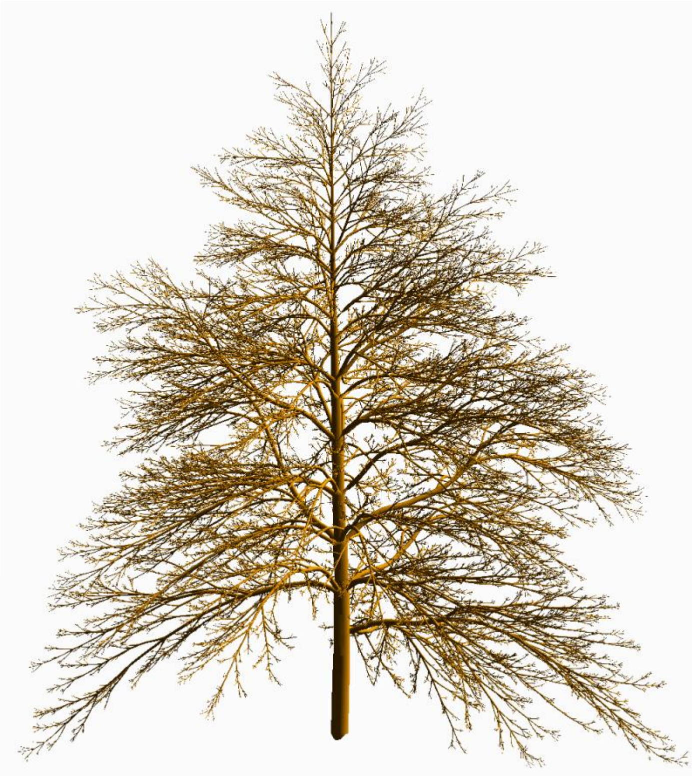
Troll

Plagiotropy threshold

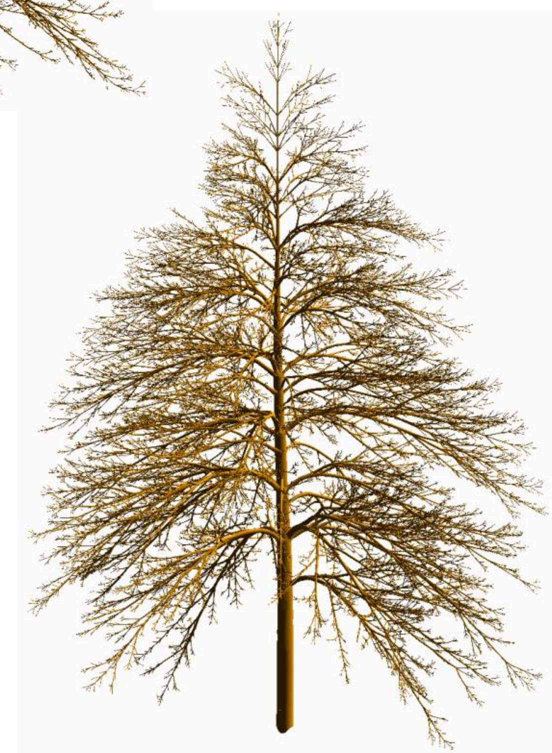
(pronounced parent child bias)



Rauh

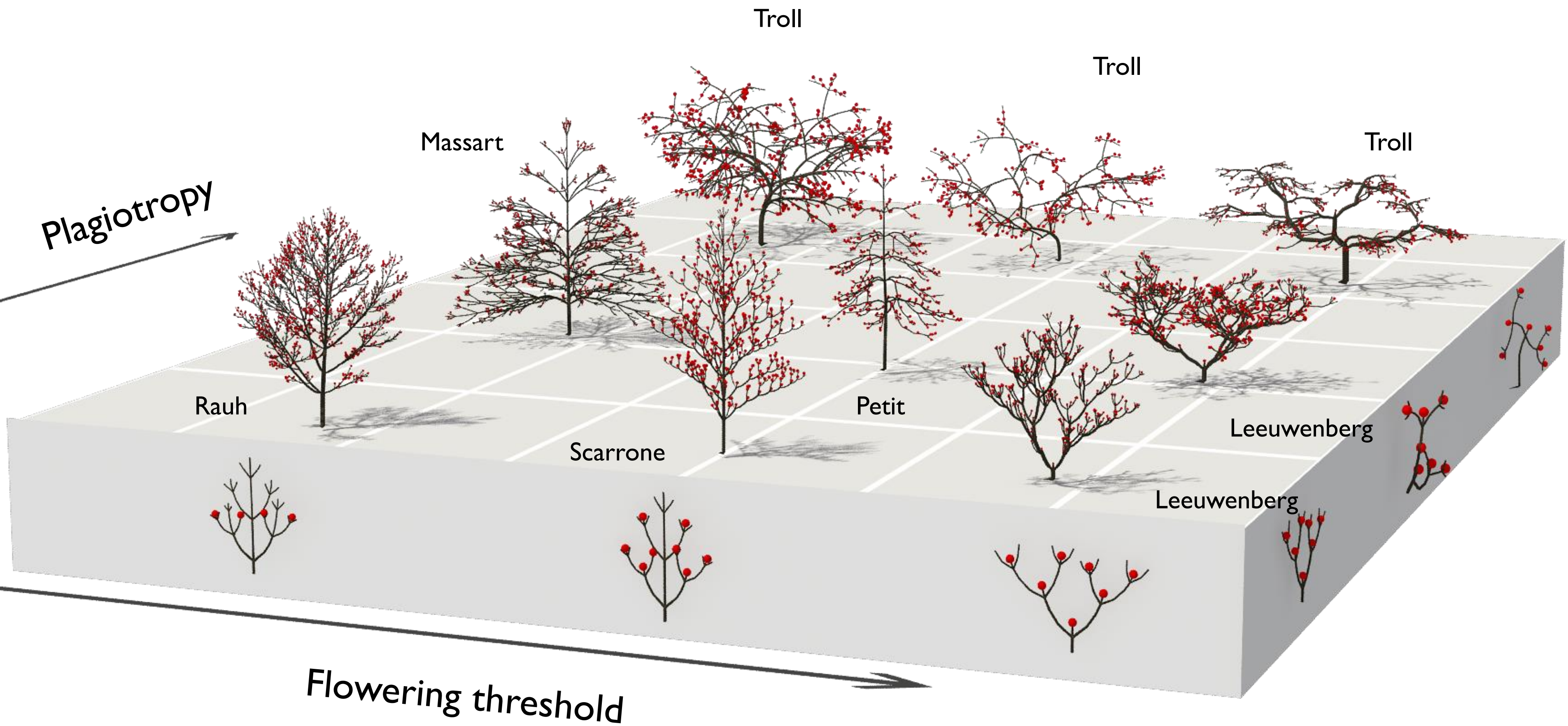


Massart

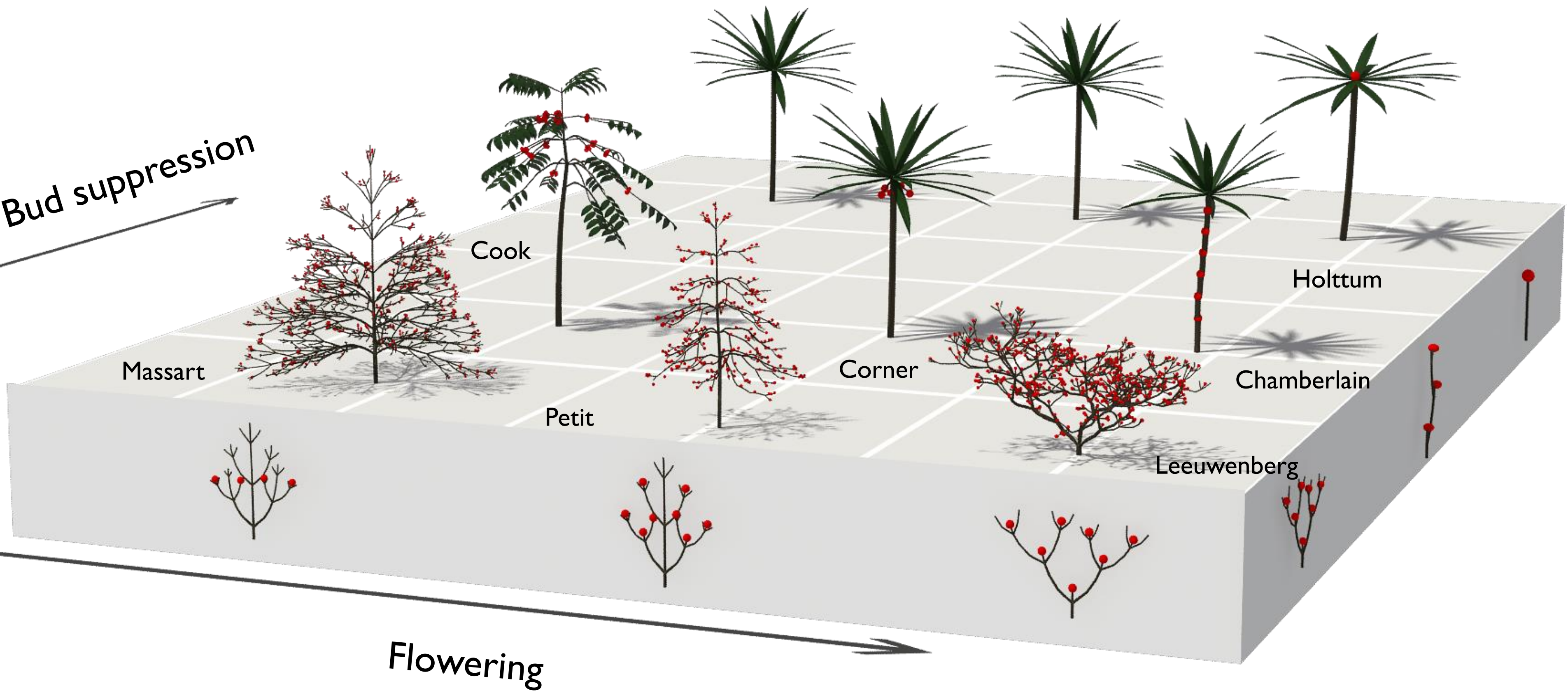


Morphospace containing the Architectural Models

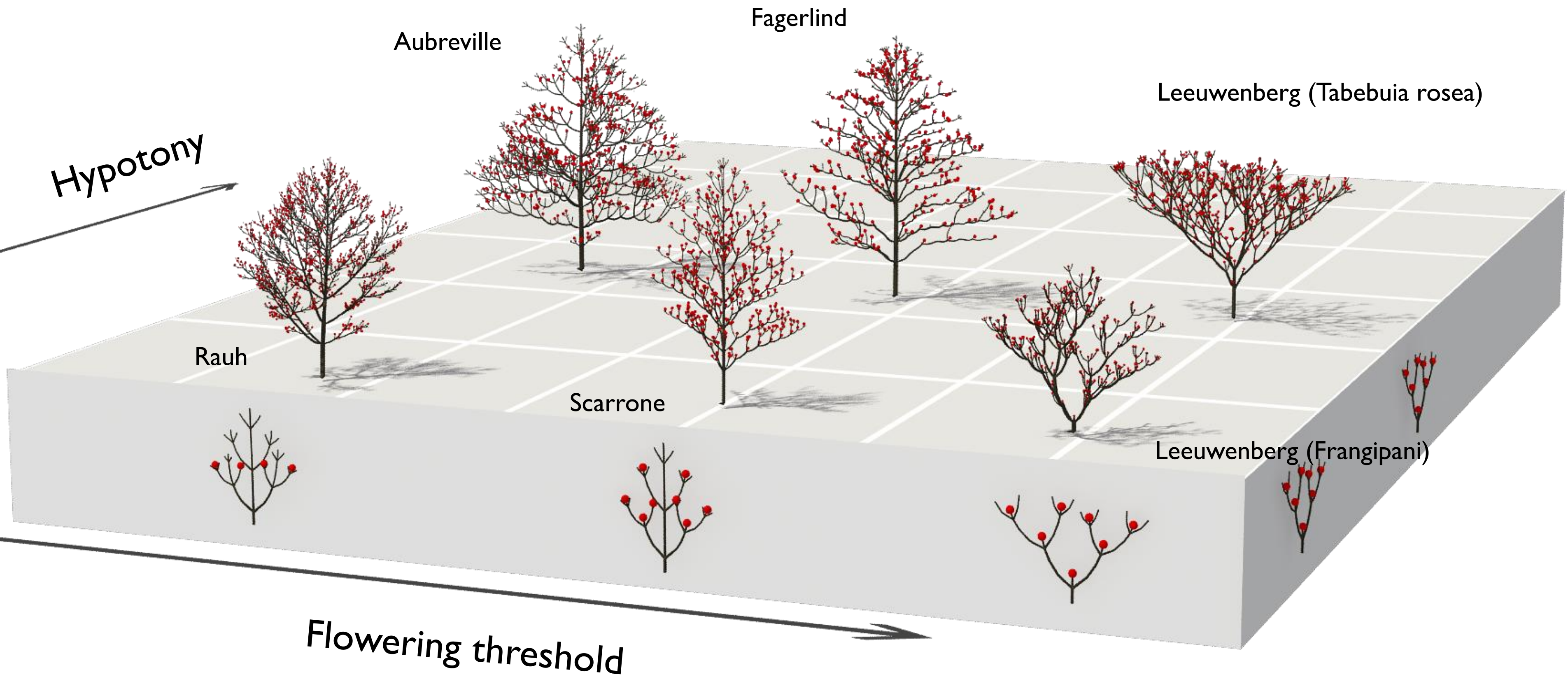
Plagiotropy x Flowering



Bud Suppression x Flowering



Hypotony x Flowering



Comparison to real trees

Tabebuia rosea (Model of Leeuwenberg)

Comparison to real trees

Tabebuia rosea (Model of Leeuwenberg)

Sequoia sempervirens (Model of Massart)

Comparison to real trees

Tabebuia rosea (Model of Leeuwenberg)

Phellodendron chinense (Model of Scarrone)

Sequoia sempervirens (Model of Massart)

Comparison to real trees

Tabebuia rosea (Model of Leeuwenberg)

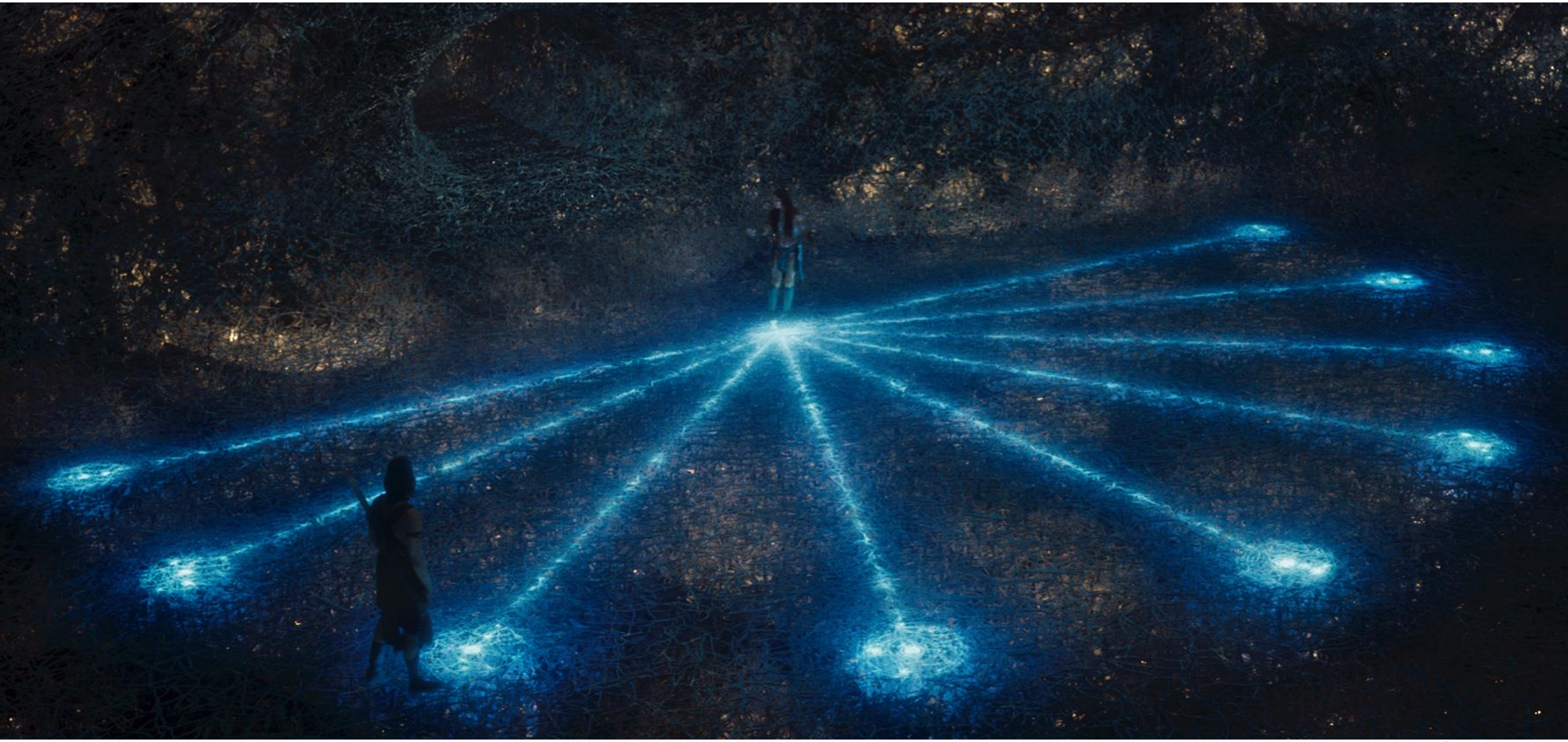
Sequoia sempervirens (Model of Massart)

Phellodendron chinense (Model of Scarrone)

Delonix regia (Model of Troll)

Why model tree growth?

- Computer graphics



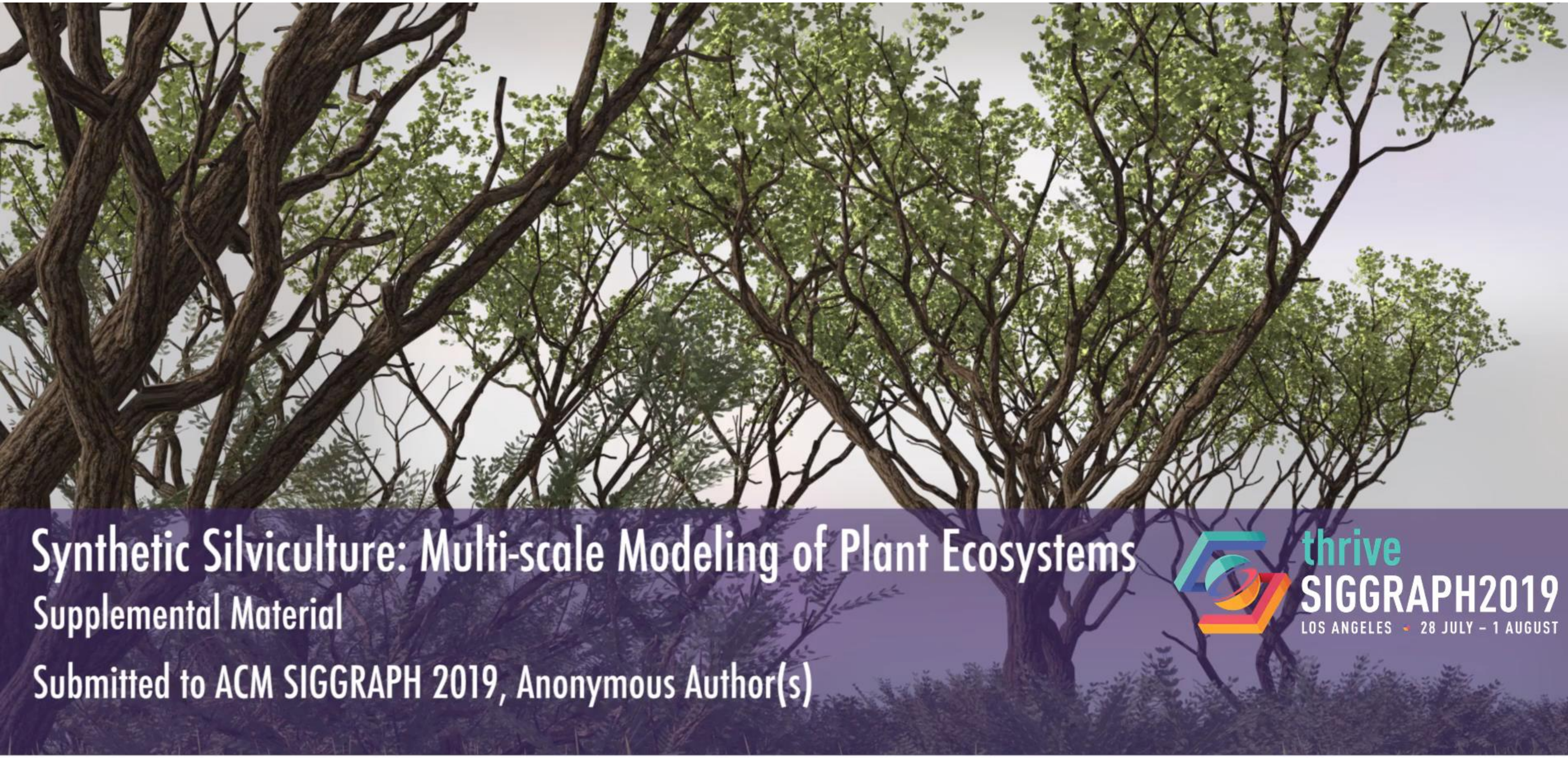
John Carter

Pickler et al. (2012): Thern, the nano technology from John Carter's Mars SIGGRAPH '12 ACM SIGGRAPH 2012 Talks.

Why model tree growth?

- Computer graphics

The Hobbit



Synthetic Silviculture: Multi-scale Modeling of Plant Ecosystems

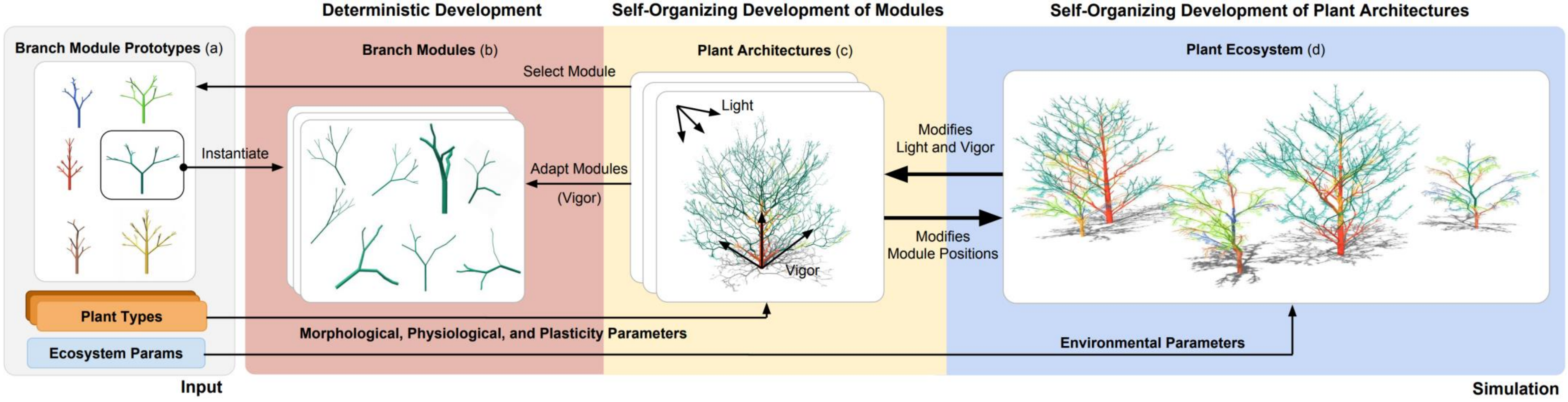
Supplemental Material

Submitted to ACM SIGGRAPH 2019, Anonymous Author(s)

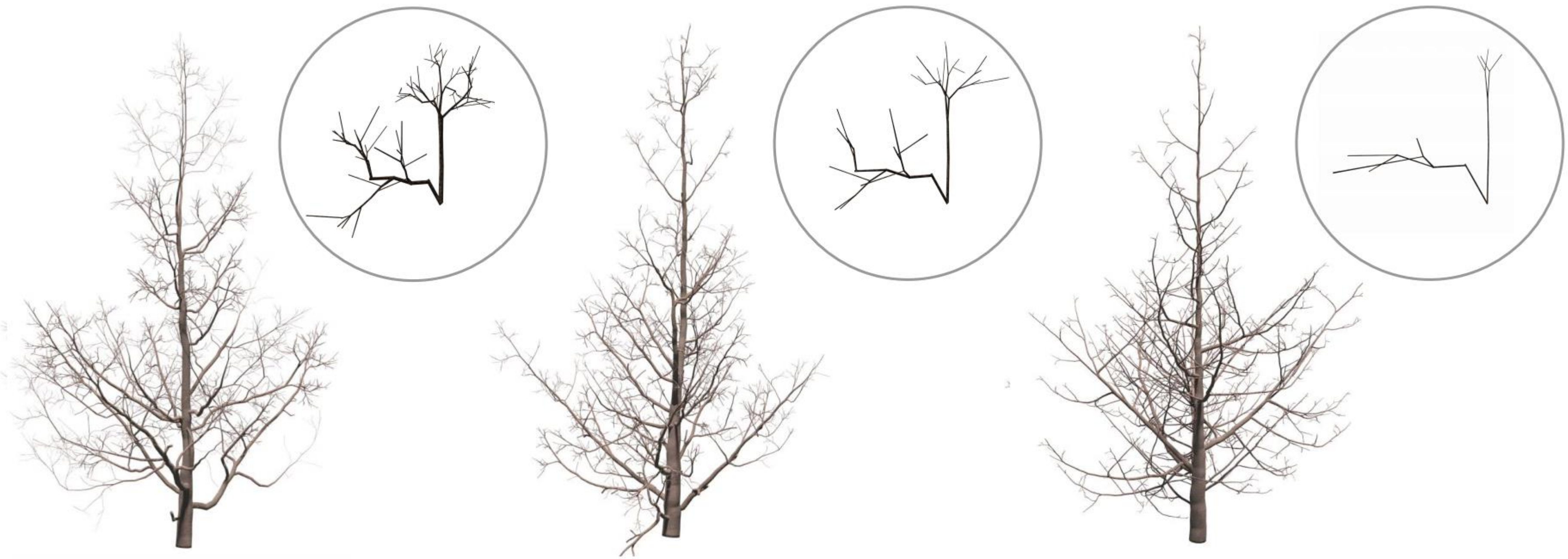
thrive
SIGGRAPH2019
LOS ANGELES · 28 JULY – 1 AUGUST

(Includes Audio Narrations)

Multi-scale Growth



Multi-scale Growth



(a) 99 (b) 294 (c) 1204

Two Student Scholarships Available Soon

- Until end of masters degree
- Machine learning + modeling trees branching structures
- Or your own, novel and interesting idea
- 2K

Shape Synthesis from Sketches via Procedural Models and Convolutional Networks

Haibin Huang, Evangelos Kalogerakis, Ersin Yumer, Radomir Mech

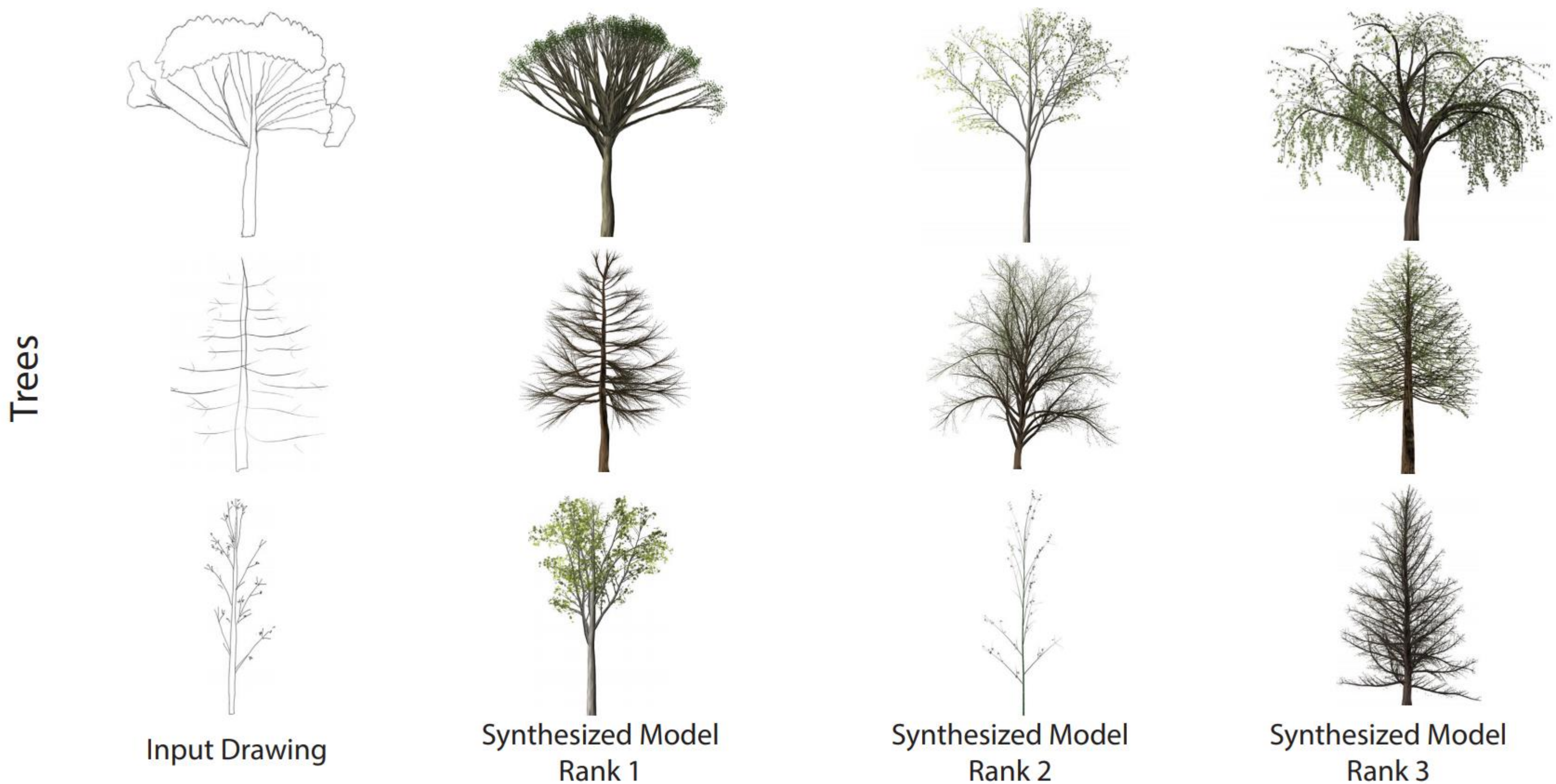


Fig. 6: Input user line drawings along with the top three ranked output shapes generated by our method.

Two Student Scholarships Available Soon

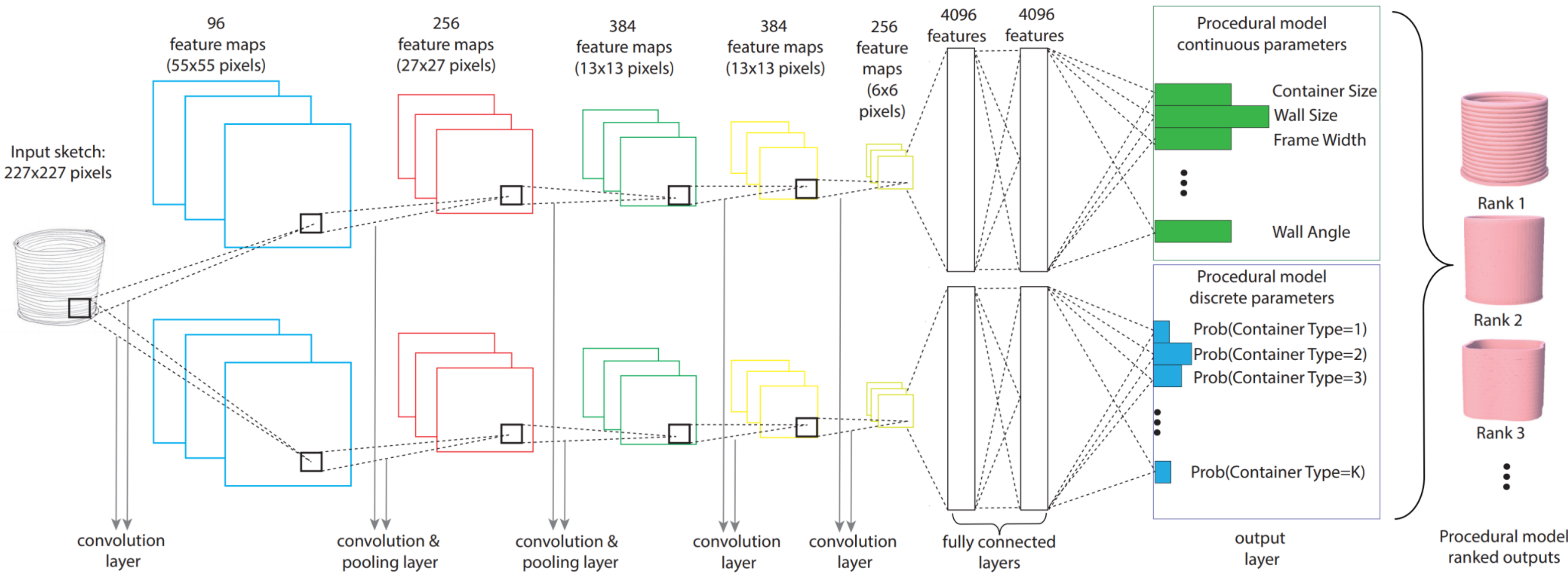


Fig. 2: Convolutional Neural Network (CNN) architecture used in our method. The CNN takes as input a sketch image and produces a set of PM parameters, which in turn yield ranked design outputs.