Computer Animation and Simulation

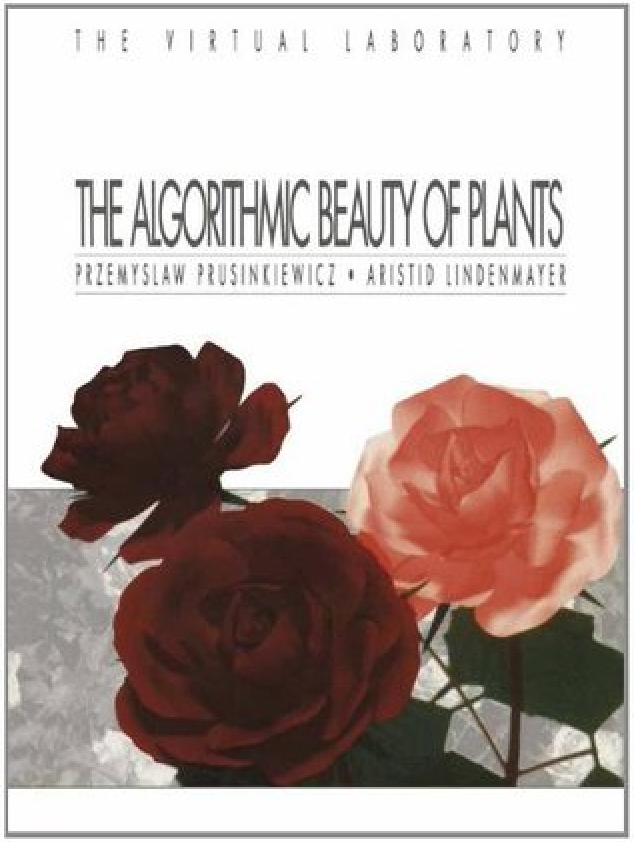
Plants

Context

- Natural Phenomena
  - Plants
  - Gaseous phenomena
    - Fire
    - Smoke
    - Clouds
  - Water
  - …

Plants

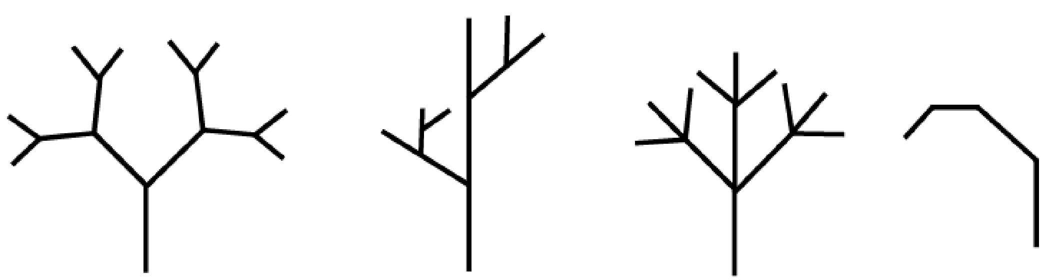
- Particle systems
- Fractals
- 3D Modelling
- L-systems
  - Lindenmayer Systems
  - *"The Algorithmic Beauty of Plants"* (Prusinkiewicz + Lindenmayer)



Topology

- growth from a single source point
- branching structure over time
  - individual structural elements elongate
  - self-similarity under scale (cf. fractals)

Basic branching schemes



Structures resulting from repeated application of a single branching scheme

Structural Components

Simplifications for graphics modelling vs botany

- roots
  - not visual, so not important
- stems and branches
  - above ground, grow upward and bear leaves
- buds
  - embryonic state of stems, leaves and flowers
  - terminal vs lateral bud
  - vegetative, flower or dormant buds
- leaves
  - alternate, opposite, whorled pattern
- flowers

Growth of a Cell Influenced by…

- lineage
  - growth controlled by age
  - older cells always larger than younger cells
- cellular descent
  - growth by passing of nutrients and hormones from adjacent cells
  - ends of plants growing more than interior sections
- tropisms
  - external influences changing the direction of growth
  - phototropism (bending toward light), geotropism (responding to gravity)
- physical obstacles
  - affect shape and growth

Modelling

L-systems

- mathematical model (< Astrid Lindenmayer)
  - set of production rules of the form $\alpha_i \longrightarrow \beta_i$
    - α_i predecessor, single symbol
    - β_i successor, sequence of symbols
- parallel rewriting system
  - sequence of symbols given as initial string (i.e. axiom)
  - apply production rules to string, in parallel
    - rewrite each occurrence of α_i as β_i
    - identity rule for symbols without production rule
  - result of productions is a new string
  - repeat iteratively until no production rules can be applied

Parallel Rewriting System

- assume following production rules
  - S → ABA
  - A → XX
  - B → TT

- generated string sequence
  1. S (= axiom)
  2. ABA
  3. XXTTXX

- interpret strings to generate images

Geometric Interpretation

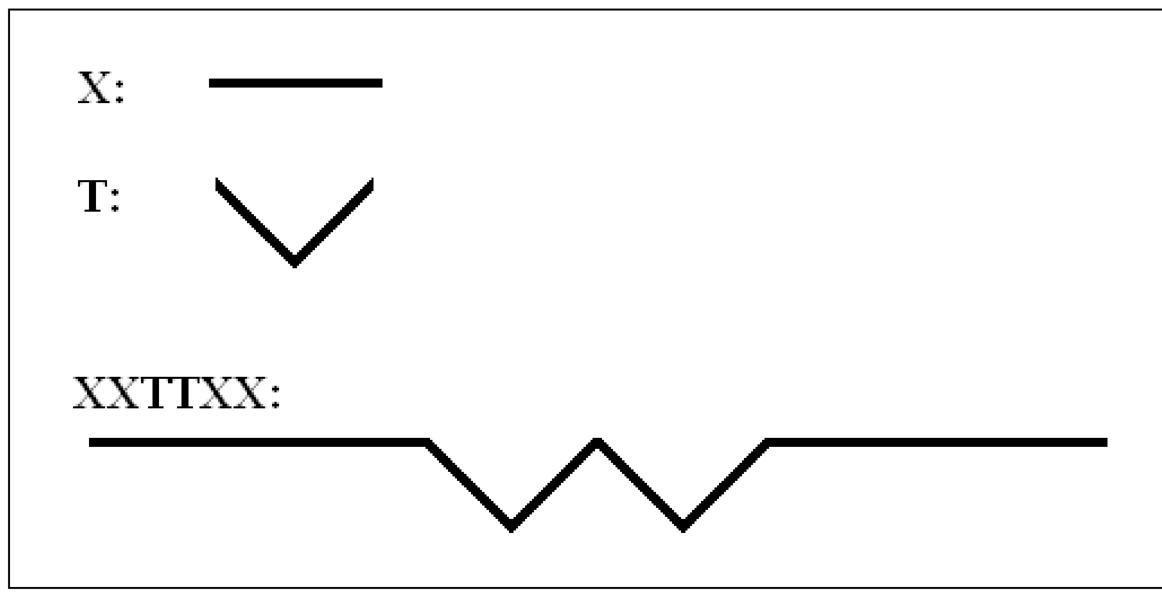
Geometric replacement

- symbol --> geometric element

- Example

  S --> ABA
  A --> XX
  B --> TT

  1. S
  2. ABA
  3. XXTTXX



Geometric Interpretation

Turtle graphics

- symbols are interpreted as drawing commands

The turtle obeys to the following commands:

F draw a line of length d, the state changes to ($x+d\cos\alpha$, $y+d\sin\alpha$, α)

f move forward a step of length d without drawing

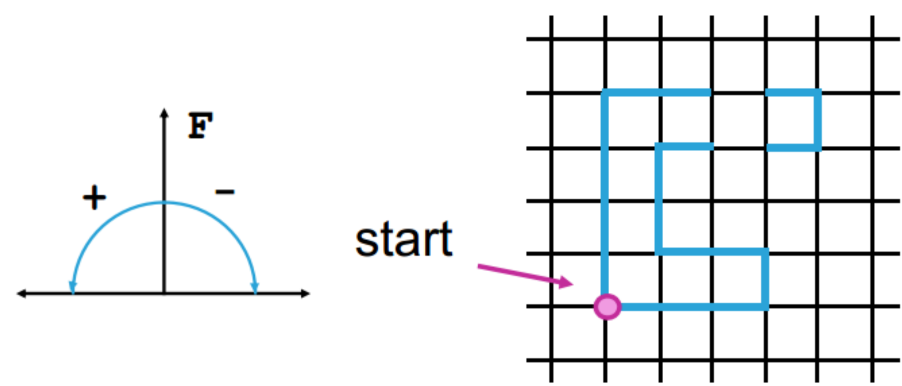
+ turn left by angle δ, the state changes to ($x,y,\alpha+\delta$)

− turn right by angle δ, the state changes to ($x,y,\alpha-\delta$)

Starting conditions for the turtle:
Initial state, d and δ

Example: `FFFF-FFfF-F-FfF+FF+FF-F-FFF`

$d=1$, $\delta = 90°$



Geometric Interpretation

Turtle graphics

S –> ABA
A –> FF
B –> TT
T –> −F++F−

Production rules

S ⟵ axiom
ABA
FFTTFF
FF−F++F−−F++F−FF

Sequence of strings produced from the axiom

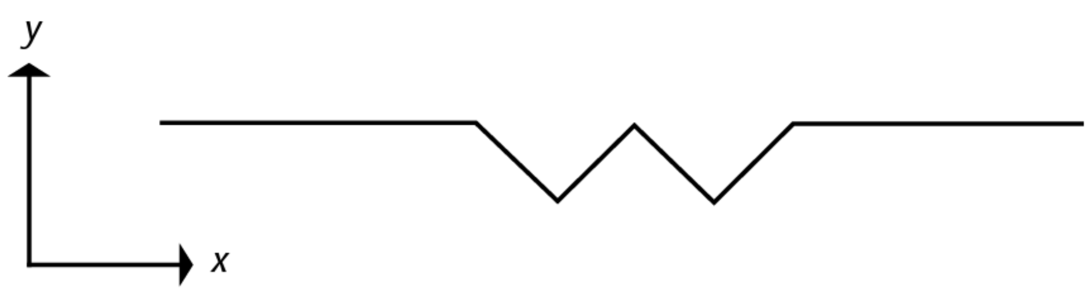
$d =$ |———|

$\delta = 45°$

reference direction: ⟶

initial state: (10, 10, 0)

Initial conditions



Geometric Interpretation

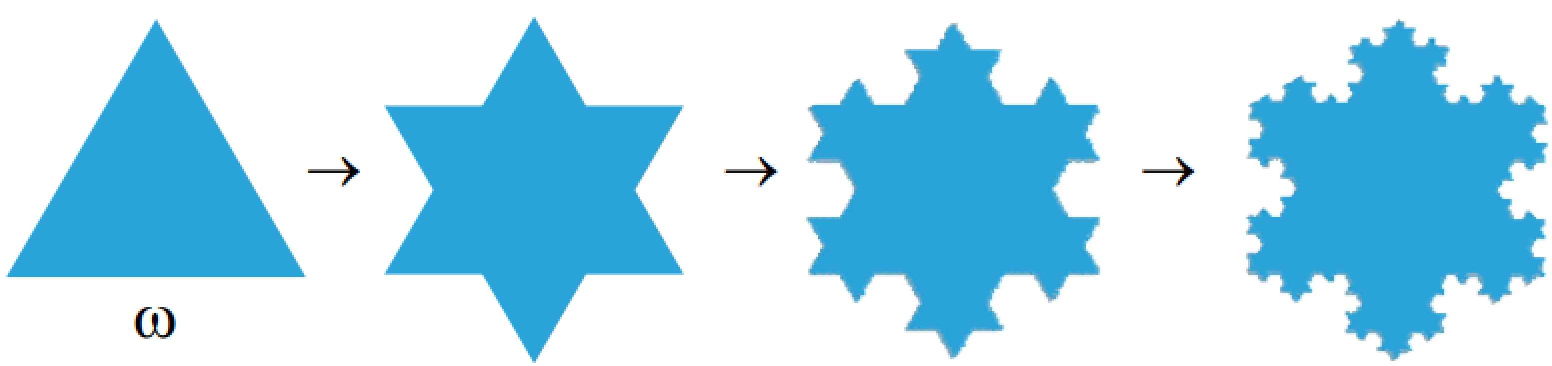
Turtle graphics

- using the turtle commands as alphabet
- construction of Koch's island

$\delta = 60°$, d depends on derivation length

$\omega = \mathtt{F{-}{-}F{-}{-}F}$ `//Initiator`

$\mathtt{F} \rightarrow \mathtt{F{+}F{-}{-}F{+}F}$ `//Generator`



D0L-systems

- simplest class of L-system
  - see previous examples
- deterministic
  - predecessor α_i appears only once on the left-hand side of a production rule
- context free
  - no context-sensitive production rules

S –> ABA	S	⟵ axiom
A –> XX	ABA	
B –> TT	XXTTXX	
Production rules	String sequence	

Bracketed L-systems

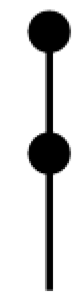
- L-systems up till now only linear
- brackets [and] used to mark the beginning and end of additional offshoots from the main lineage
- stack of turtle graphics is used, brackets push and pop states onto the stack
  - [= push state
  -] = pop state

Bracketed L-systems

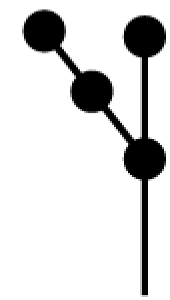
$S \longrightarrow FAF$
$A \longrightarrow [+FBF]$
$A \longrightarrow F$
$B \longrightarrow [-FBF]$
$B \longrightarrow F$

(non-deterministic in this case: so, random choice of production rule)

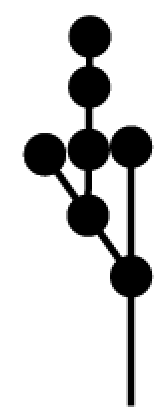
FAF



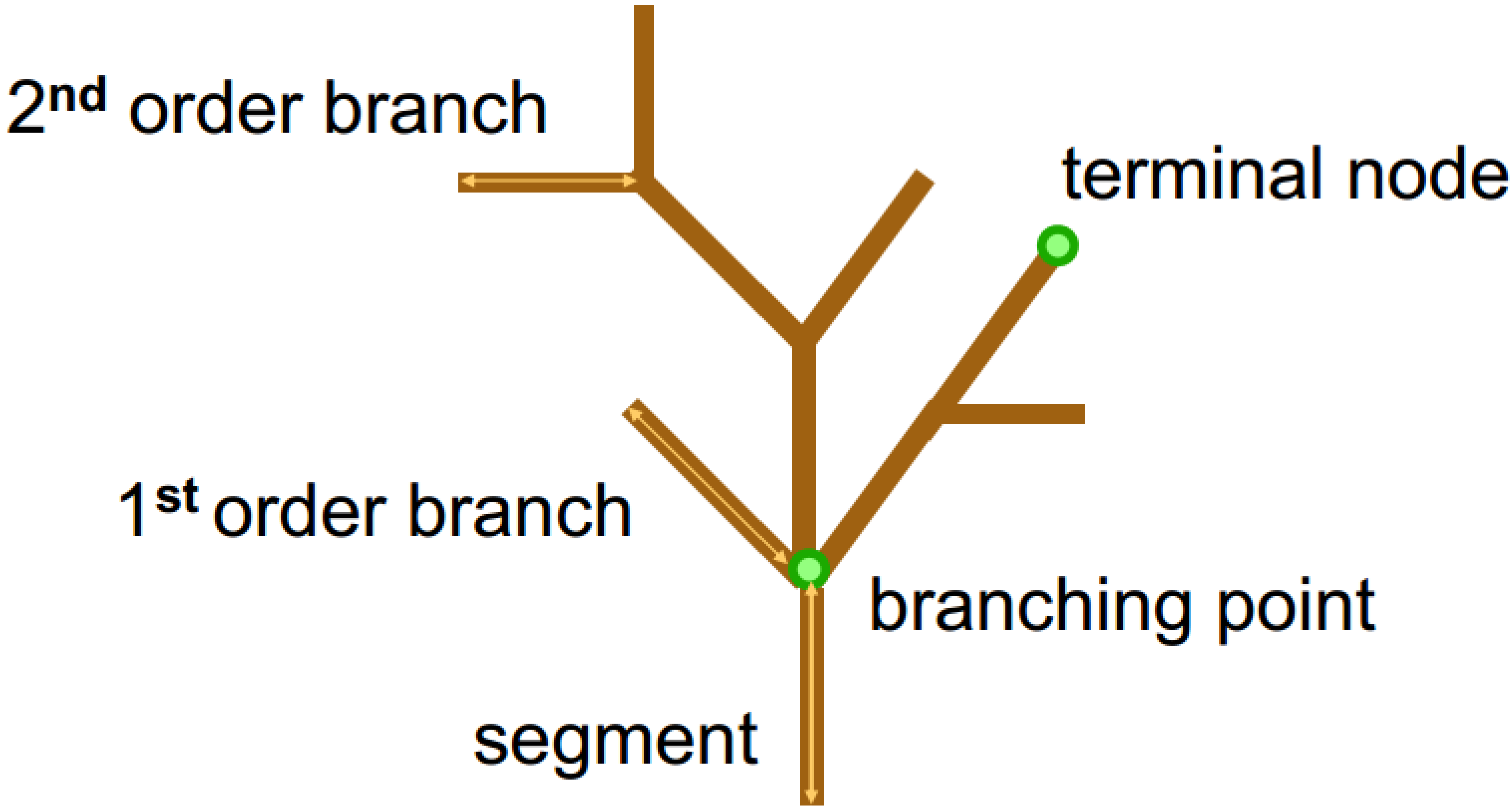
F[+FBF]F



F[+F[−FFF]F]F

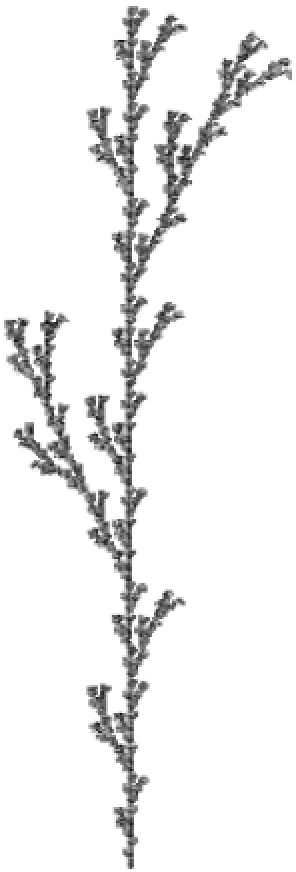


Bracketed L-systems



F[+F][-F[-F]F]F[+F[+F][-F]][-F]

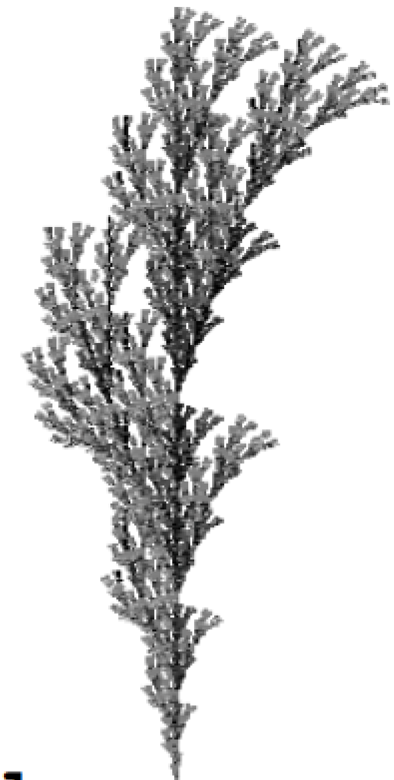
Bracketed L-systems



n=5, δ=25.7°

ω:**F**

F→F[+F]F[-F]F



n=5, δ=20°

ω:**F**

F→F[+F]F[-F][F]

Bracketed L-systems

Node replacement

n=7, δ=20°

ω:**X**

X → F[+X]F[-X]+X

F → FF

n=5, δ=22.5°

ω:**X**

X → F-[[X]+X]+F[+FX]-X

F → FF

Stochastic L-systems

- assign probabilities to nondeterministic L-systems
  - probabilities of production rules with same predecessor sum up to 1
  - id: pred $\longrightarrow$ succ : probability
- example

$S_{1.0}$ --> FAF

$A_{0.8}$ --> [+FBF] // $A_{0.8}$ [+FBF] : 0.8

$A_{0.2}$ --> F

$B_{0.4}$ --> [-FBF]

$B_{0.6}$ --> F

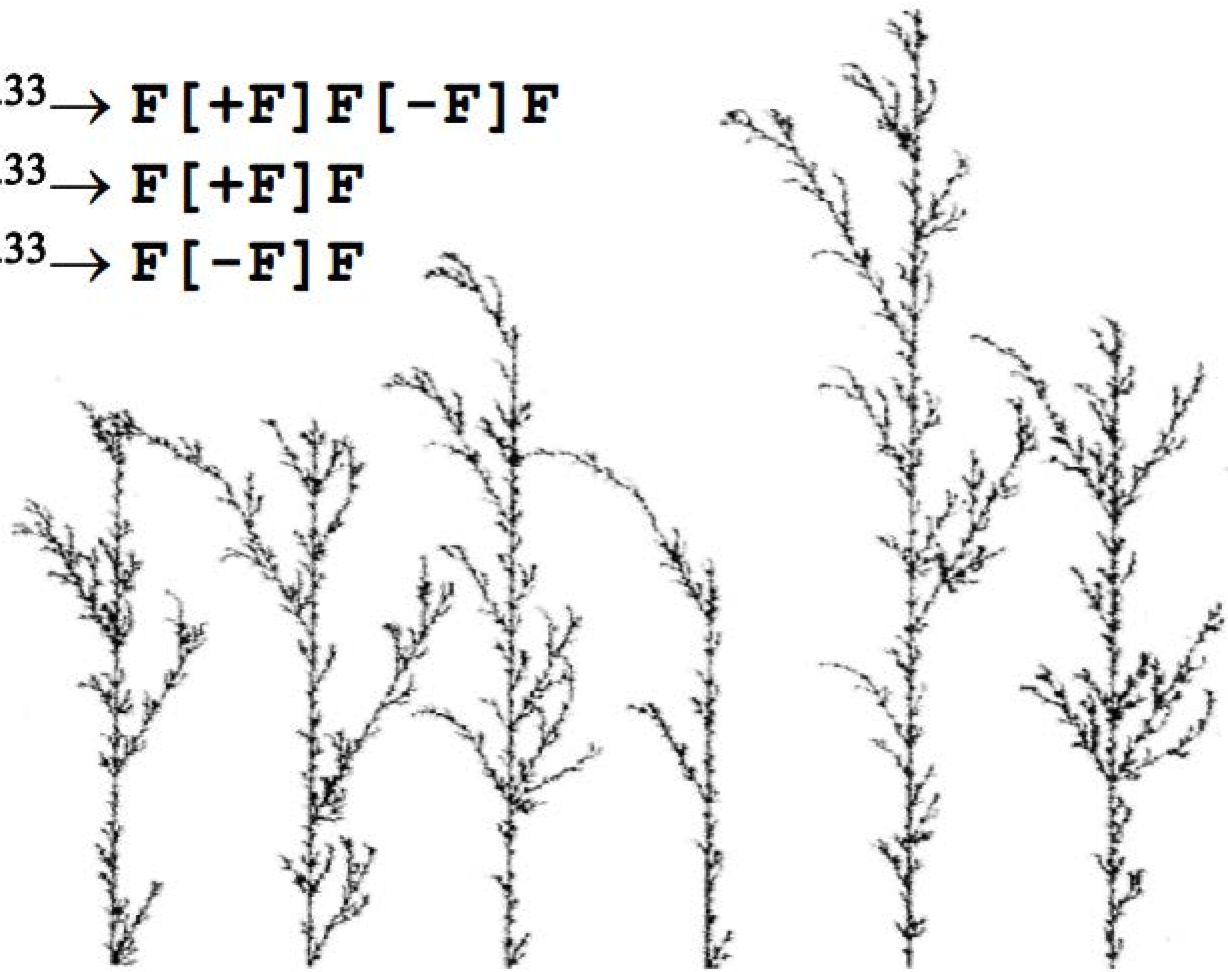
Stochastic L-systems

ω: F

p_1: $F \xrightarrow{0.33} F[+F]F[-F]F$

p_2: $F \xrightarrow{0.33} F[+F]F$

p_3: $F \xrightarrow{0.33} F[-F]F$



Context Sensitive L-systems

- specify a context, in which the predecessor must appear in order for the production rule to be applicable

id: left-side_context < pred > right-side_context ⟶ succ : prob

- *n* left-side and *m* right-side context symbols
  - (n, m) L-systems

Context Sensitive L-systems

- production rules

  S --> FAT

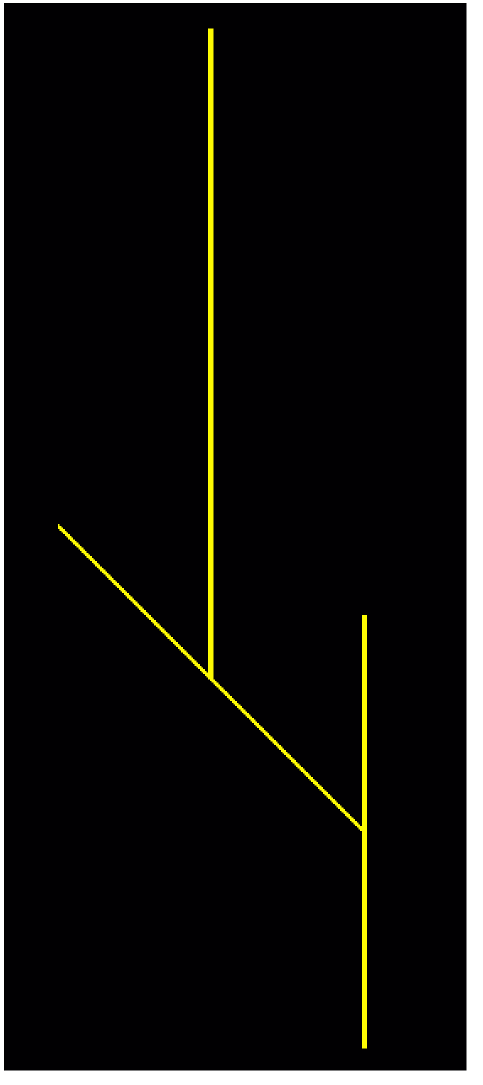
  A > T --> [+FBF]

  A > F --> F

  B --> [-FAF]

  T --> F

- string sequence
  1. S
  2. FAT
  3. F[+FBF]F
  4. F[+F[-FAF]F]F
  5. F[+F[-FFF]F]F



Context Sensitive L-systems

- used to simulate the propagation of signals like hormones and nutrients

ω: baaaaaaa

p_1: b<a $\rightarrow$ b

p_2: b $\rightarrow$ a

baaaaaaa
abaaaaaa
aabaaaaa
aaabaaaa
aaaabaaa
aaaaabaa
aaaaaaba

Animation

Types of Animation

- flexible movement of static structure
  - e.g., plant being subjected to wind
  - see chapter *"physically-based animation"*
- changes in topology during growth
  - modeled by L-system as the application of a production that encapsulates a branching of the form A --> F[+F]B
- elongation of existing structures
  - modeled by productions of the form F --> FF
  - uniform growth
  - no criteria to stop
  - ==> solution: introduce parameters into L-systems

Parametric L-systems

- symbols can have one or more parameters
  - parameters can be set and modified by productions
  - conditional terms can be associated with productions
    - production is valid $\Leftrightarrow$ condition is "true"

- example

S	-->	A(0)
A(t)	-->	A(t+0.01)
A(t) : t>=1.0	-->	F

- context-sensitive example
  - passing nutrients along stem
  - A(t0) < A(t1) > A(t2): t2>t1 & t1>t0 --> A(t1+0.01)

Parametric L-systems

ω: `B(2)A(4,4)`

```
p1: A(x,y): y<=3 → A(x*2,x+y)
p2: A(x,y): y>3  → B(x)A(x/y,0)
p3: B(x)  : x<1  → C
p4: B(x)  : x>=1 → B(x-1)
```

Result:

```
B(2)A(4,4)
B(1)B(4)A(1,0)
B(0)B(3)A(2,1)
C   B(2)A(4,3)
C   B(1)A(8,7)
C   B(0)B(8)A(1.142,0)
```

Timed L-systems

- 2 new concepts
  - global time variable, accessible to all productions
  - local age value τ_i associated with each letter μ_i
- a timed L-system production rule
  - $(\mu_0,\beta_0) \dashrightarrow ((\mu_1,\alpha_1), (\mu_2,\alpha_2), \ldots, (\mu_n,\alpha_n))$
    - β_0 = terminal age of μ_0
    - α_i = initial age of μ_i
  - applied when symbol's terminal age is reached
- geometric interpretation of each symbol is potentially based on local age of symbol

Timed L-systems

- Axiom (A,0)
  (A,3) → (S,0)[+(B,0)](S,0)
  (B,2) → (S,0)

- Sequence global time

Sequence	global time
(A,0)	0
(A,1)	1
(A,2)	2
(A,3)	3
(S,0)[+(B,0)](S,0)	4
(S,1)[+(B,1)](S,1)	5
(S,2)[+(B,2)](S,2)	6
(S,3)[+(S,0)](S,3)	7

A = plant seed
S = internode stem segment
B = bud turning into stem of a branch (length ~ age)

Environment-sensitive L-systems

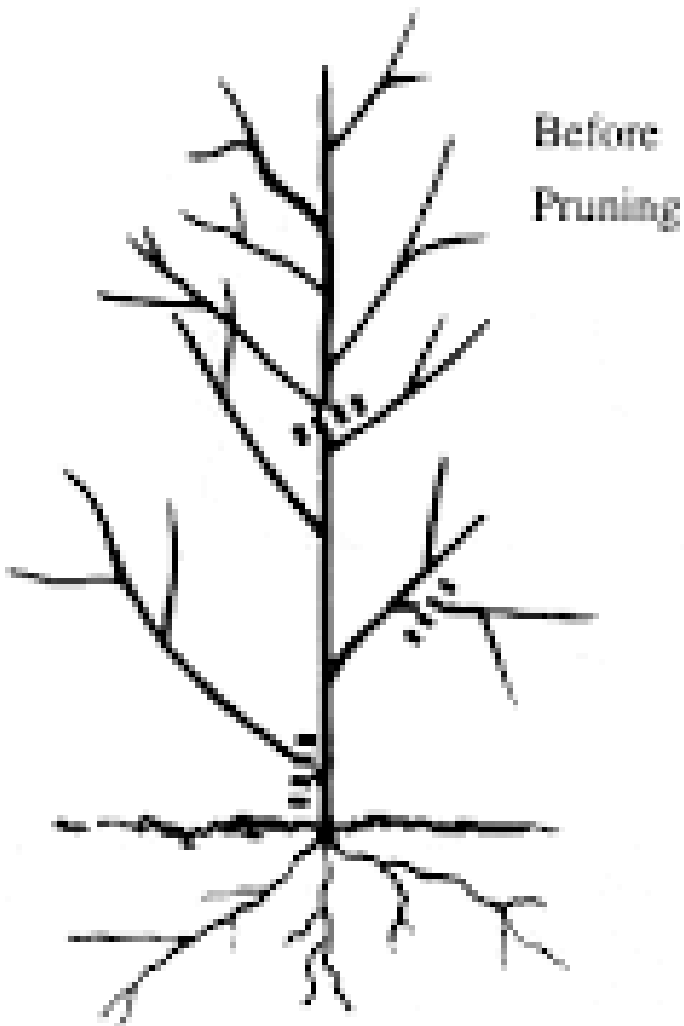
- interaction with objects, other plants, parts of the plant itself, light, gravity, wind…
  - competition for space between individual plants
  - competition for light between branches of a tree
  - competition between roots for water in the soil
- open L-systems
  - introduction of communication symbols which can exchange parameter values with the environment
- pruning
  - “%”: remove all symbols that are still present between the current []-pair
  - example: T(p):p==0 -->%

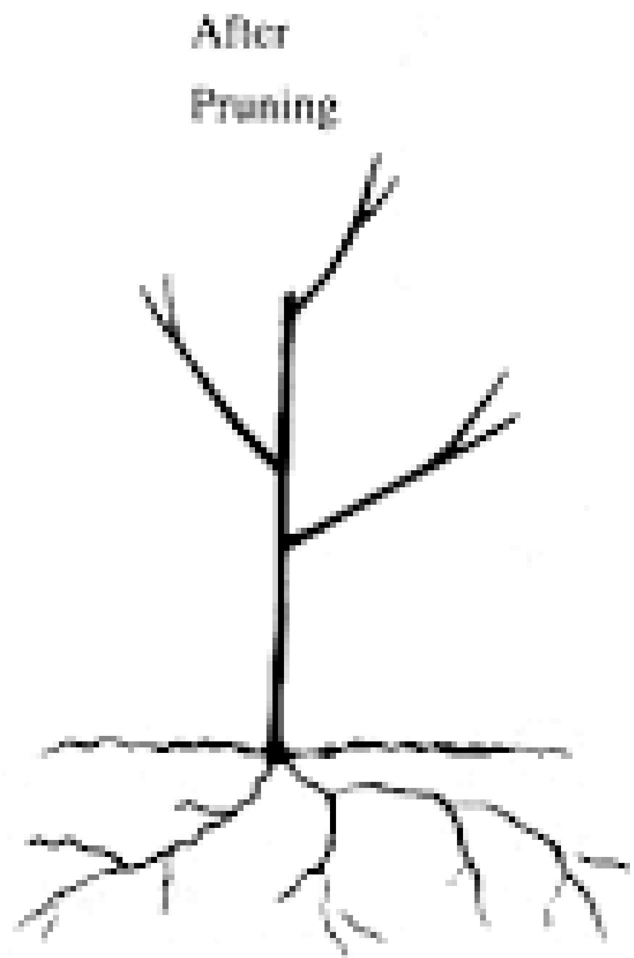
F[+F[+FF]FT(?)F[-F]F]F[-FF]

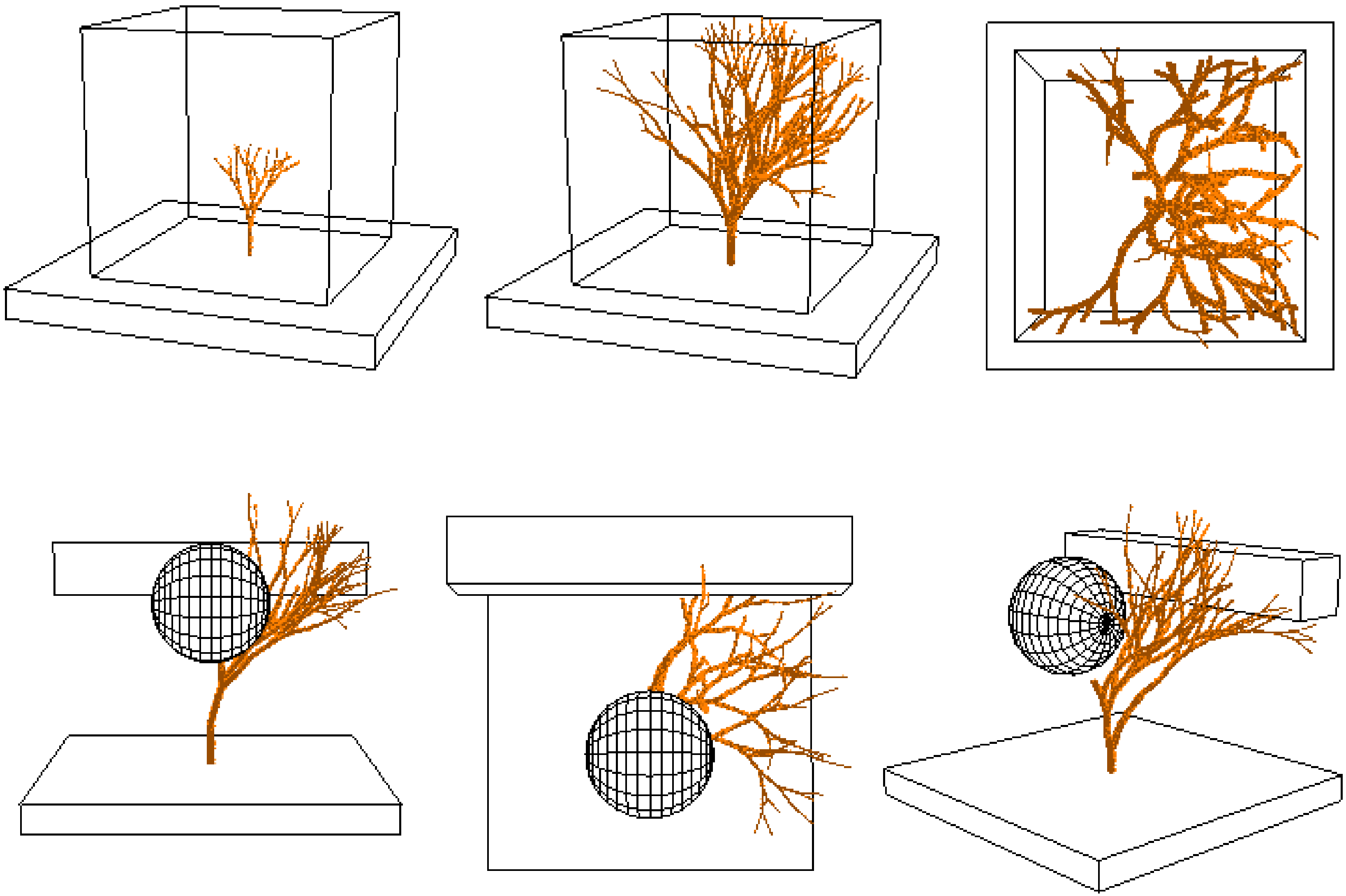
F[+F[+FF]F%F[-F]F]F[-FF]

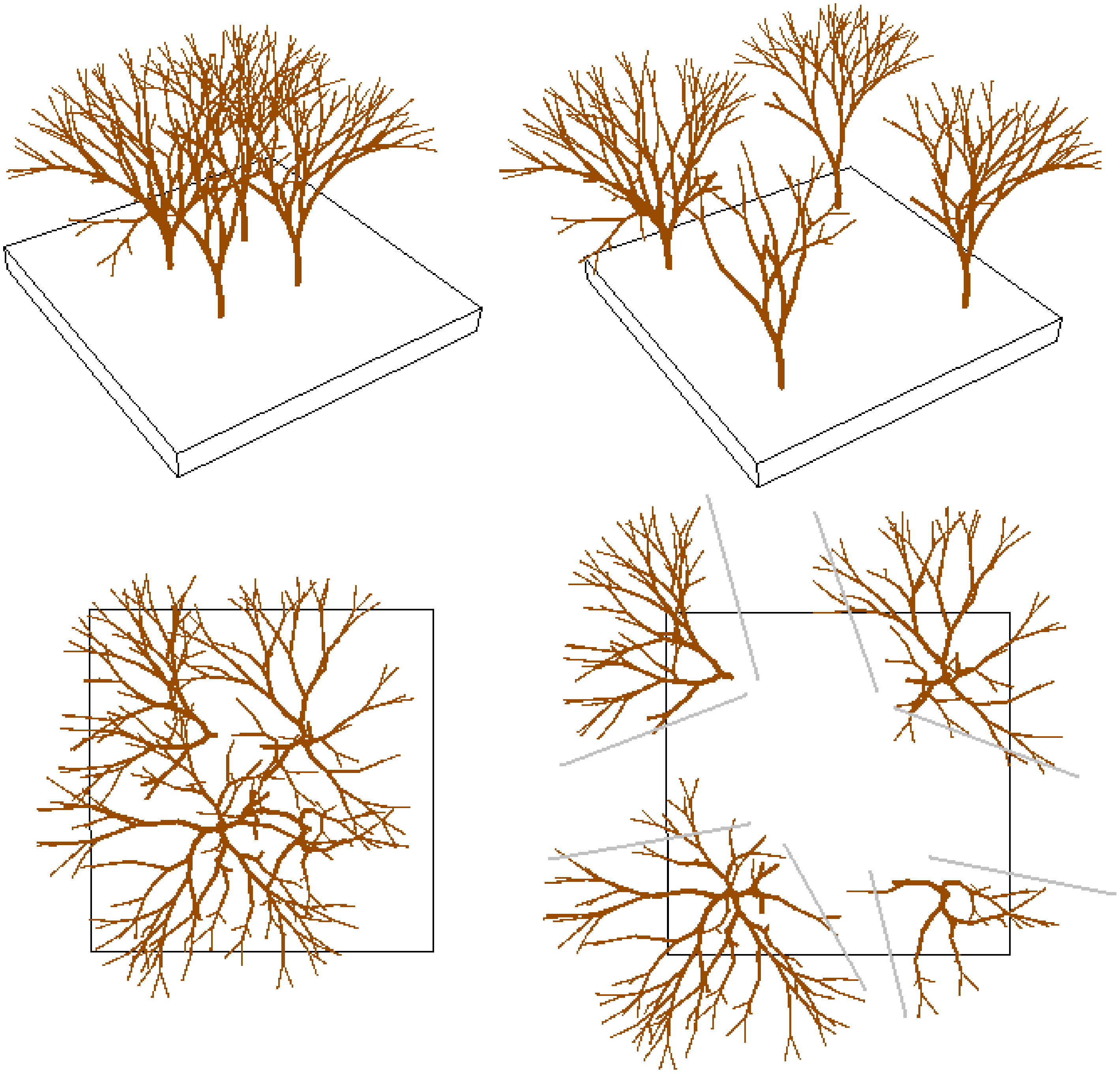
F[+F[+FF]F]F[-FF]

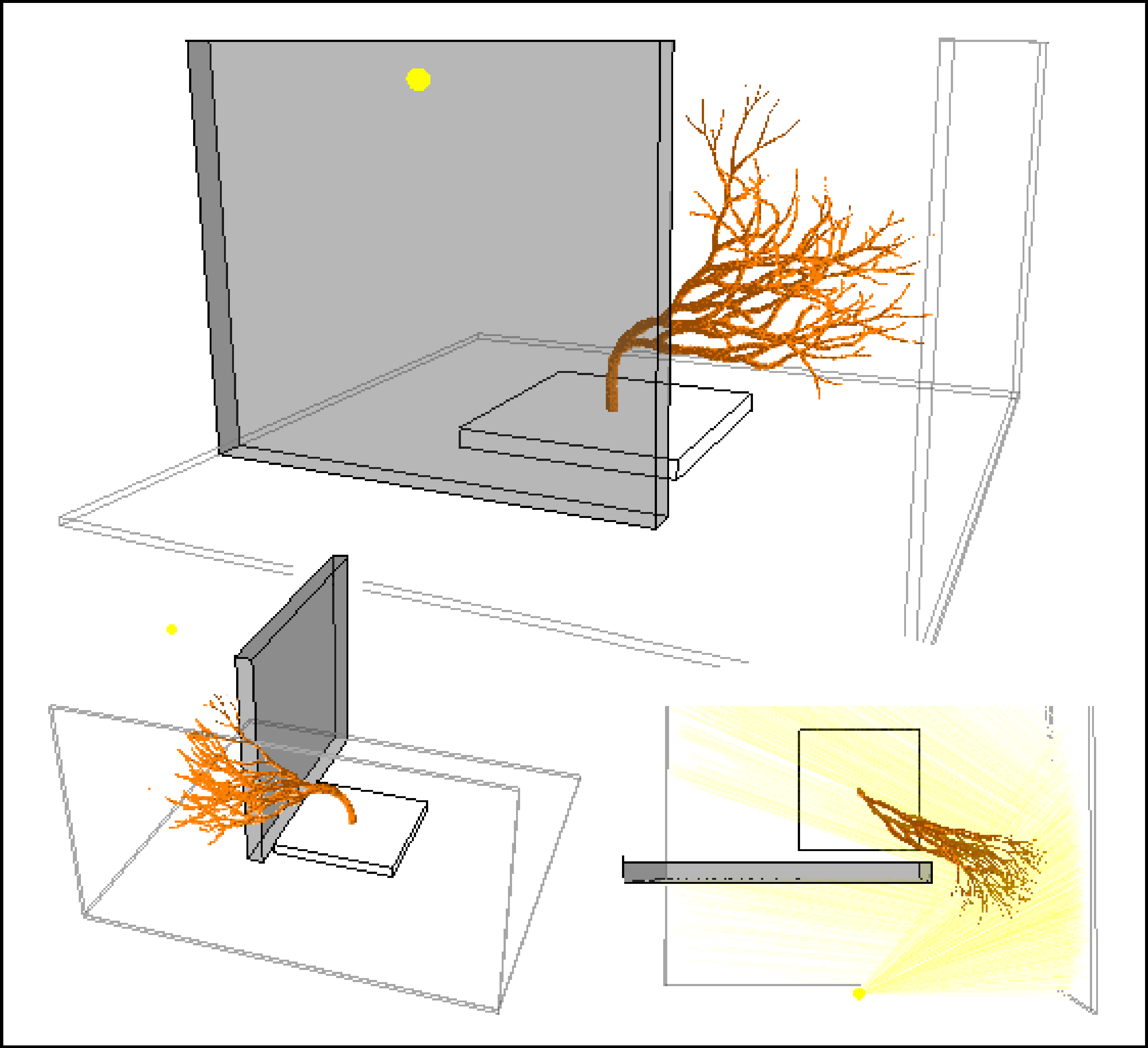
Pruning











Growth under a table

References

- http://algorithmicbotany.org
- http://xfrog.com/