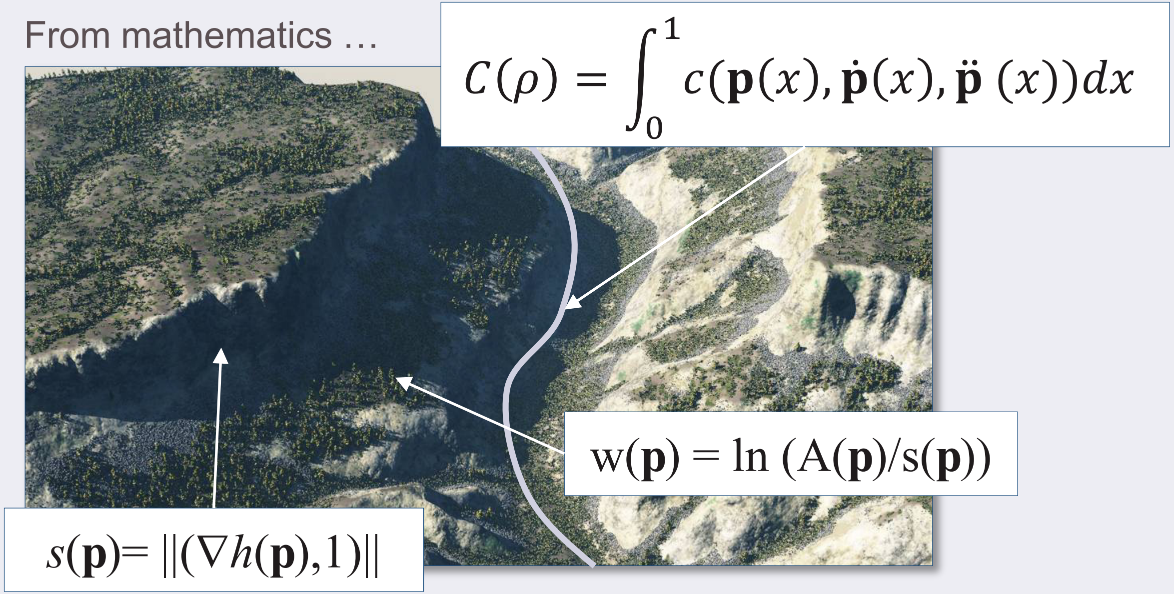
Digital World Modeling

From mathematics …



$$C(\rho) = \int_0^1 c(\mathbf{p}(x), \dot{\mathbf{p}}(x), \ddot{\mathbf{p}}\,(x))dx$$

$$w(\mathbf{p}) = \ln\,(A(\mathbf{p})/s(\mathbf{p}))$$

$$s(\mathbf{p}) = \|(\nabla h(\mathbf{p}),1)\|$$

… to the screen

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Université Lyon 1

Courtesy of
Benoit Martinez
UBISOFT

Digital World Modeling

Data Structures

Procedural Modeling

Erosion Simulation

Procedural Road Generation

Vegetation and Ecosystems

Growth models

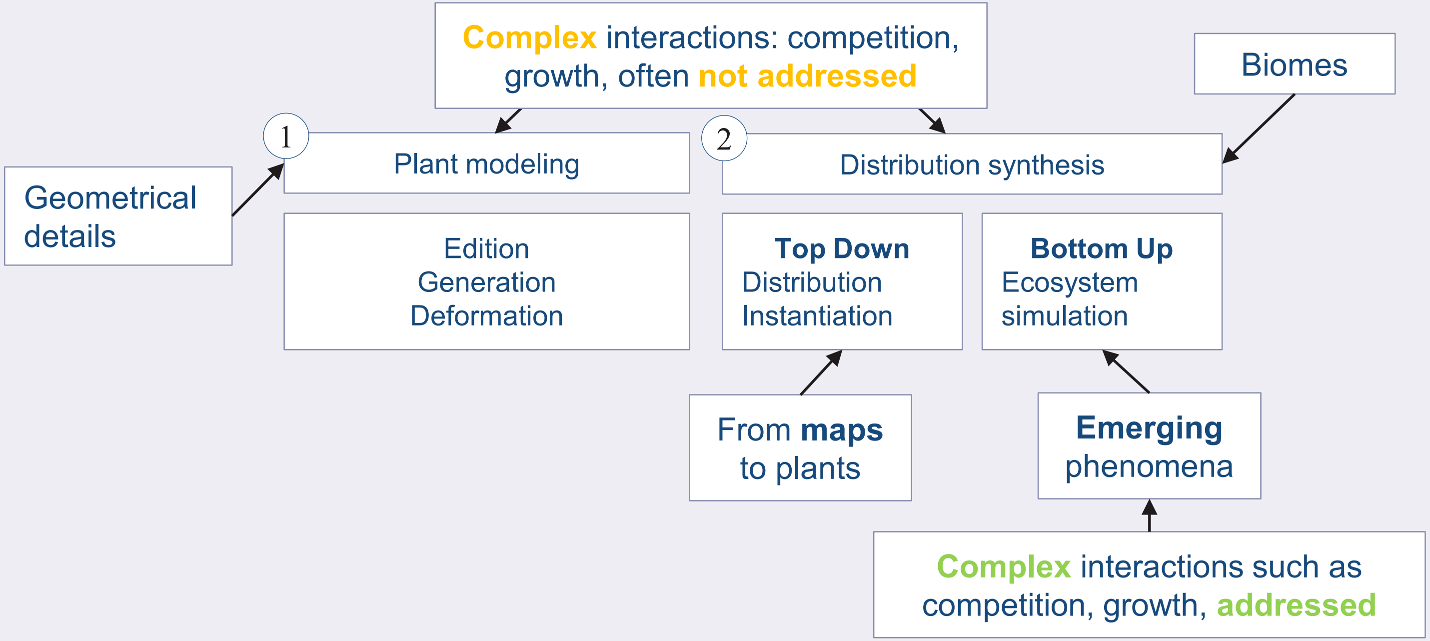
Aging and weathering

Overview

Overview
Modeling
Ecosystems
Procedural
Hybrid

Fields

Vegetation modeling: shape and geometry
Ecosystem simulation: distribution according to biotic and abiotic parameters [Kapp2020]



Complex interactions: competition, growth, often **not addressed**

Biomes

① Plant modeling

② Distribution synthesis

Geometrical details

Edition
Generation
Deformation

Top Down
Distribution
Instantiation

Bottom Up
Ecosystem
simulation

From **maps** to plants

Emerging phenomena

Complex interactions such as competition, growth, **addressed**

K. Kapp, J. Gain, E. Guérin, E. Galin, A. Peytavie. Data-driven Authoring of Large-scale Ecosystems. ACM Transactions on Graphics, 2020

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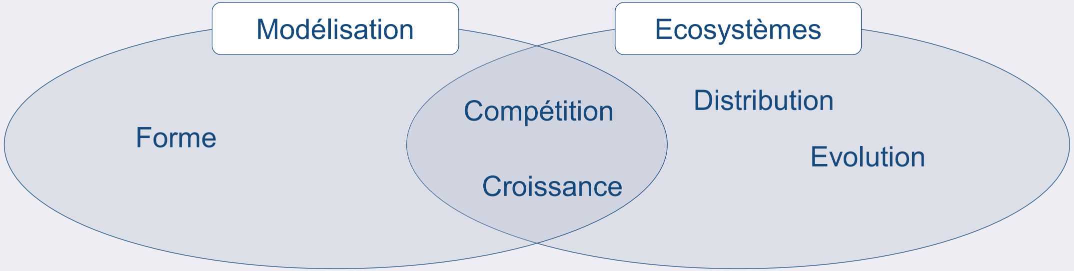
Overview

Thématiques

Génération de végétaux et simulation d'écosystèmes



Modélisation

Ecosystèmes

Forme

Compétition

Croissance

Distribution

Evolution

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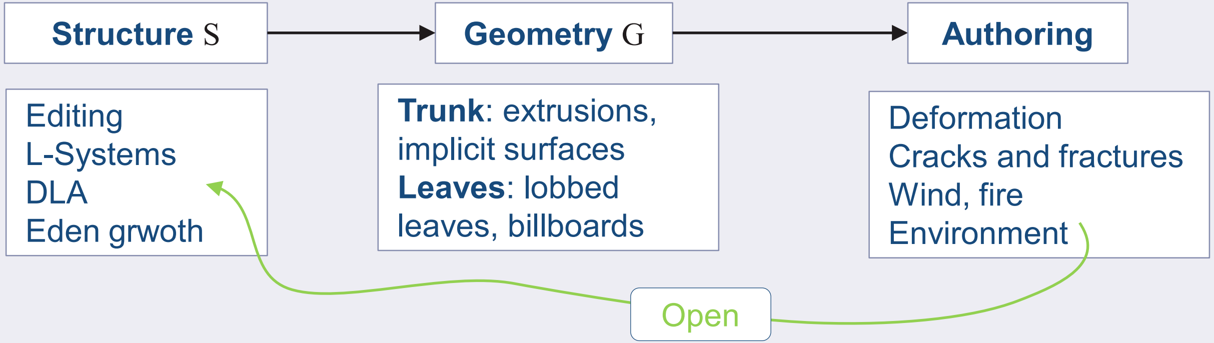
Modeling Trees

Modélisation

- Overview
- **Modeling trees**
- Ecosystems
- Procedural
- Hybrid

Challenges

Modélisation et génération de la structure S [Prusinkiewicz1986]
Géométrie G (et texture) complexes
Evolution au cours du temps
Environnement [Prusinkiewicz2001]



Structure S → **Geometry** G → **Authoring**

Editing
L-Systems
DLA
Eden grwoth

Trunk: extrusions, implicit surfaces
Leaves: lobbed leaves, billboards

Deformation
Cracks and fractures
Wind, fire
Environment

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P. Prusinkiewicz. Graphical applications of L-systems. In Proceedings of Graphics Interface, 1986.
P. Prusinkiewicz, L. Mündermann, R. Karwowski, and B. Lane. 2001. Positional Information in the Modeling of Plants. SIGGRAPH, 2001.

Structure

Overview

Modeling trees

Ecosystems

Procedural

Hybrid

Grammaire formelle

Un L-Système est une grammaire formelle $\{V,S,A,P\}$

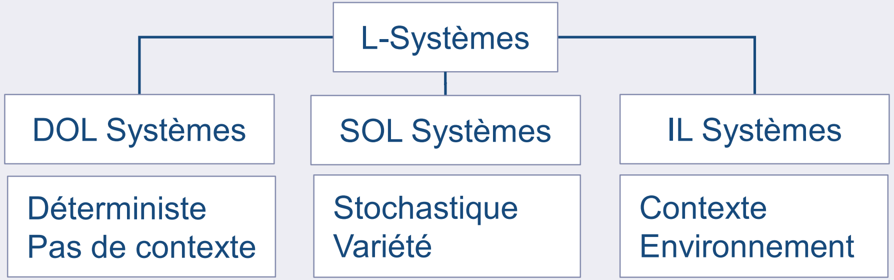
V : ensemble des variables du L-Système.

V^* (et V^+) : ensemble des mots que l'on peut construire avec les symboles de V (au moins un symbole)

S : ensemble de valeur constantes

I : axiome de départ (état initial) choisi parmi V^+

P : règles de reproduction des symboles de V



L-Systèmes

DOL Systèmes

Déterministe
Pas de contexte

SOL Systèmes

Stochastique
Variété

IL Systèmes

Contexte
Environnement

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Edition interactive

Création à faible nombre de polygones

Maillages (tronc, branches) et imposteurs (feuillage)
Différents niveaux de détail

Low poly $\approx 400\text{–}2000$ triangles

SpeedTree https://speedtree.com/

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Arbres déformables

Fondamentaux

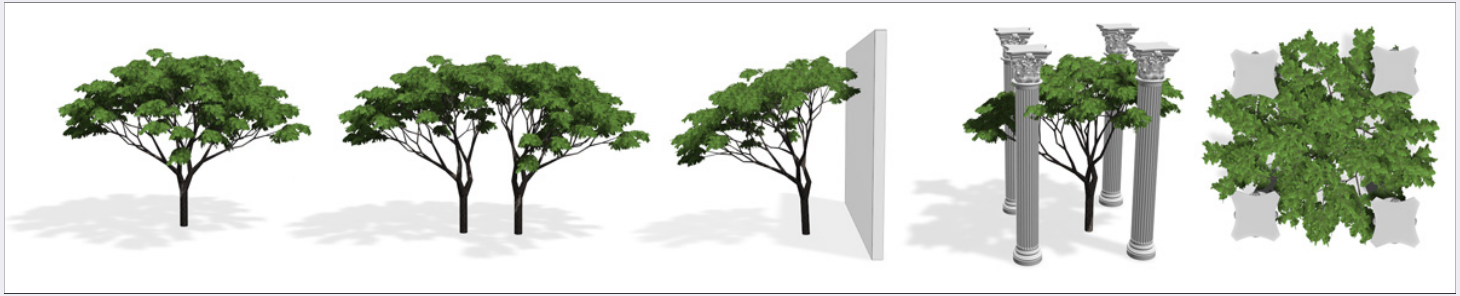
Adapter la forme de l’arbre aux contraintes de l’environnement
Eviter tout processus de génération procédurale ou de simulation

Perte de cohérence de forme

Coût en temps de calcul

Méthode

Définition d’une structure simplifiée S (squelette) de l’arbre G
Déformation ou élagage en $\tilde{\mathrm{S}}$ selon l’environnement et transfert pour $\widetilde{\mathrm{G}}$



S. Pirk et al., O. Stava, J. Kratt, M. Abdul-Massih, B. Neubert, R. Mech, B. Benes, O. Deussen, Plastic Trees: Interactive Self-Adapting Botanical Tree Models, ACM Transactions on Graphics, 2012

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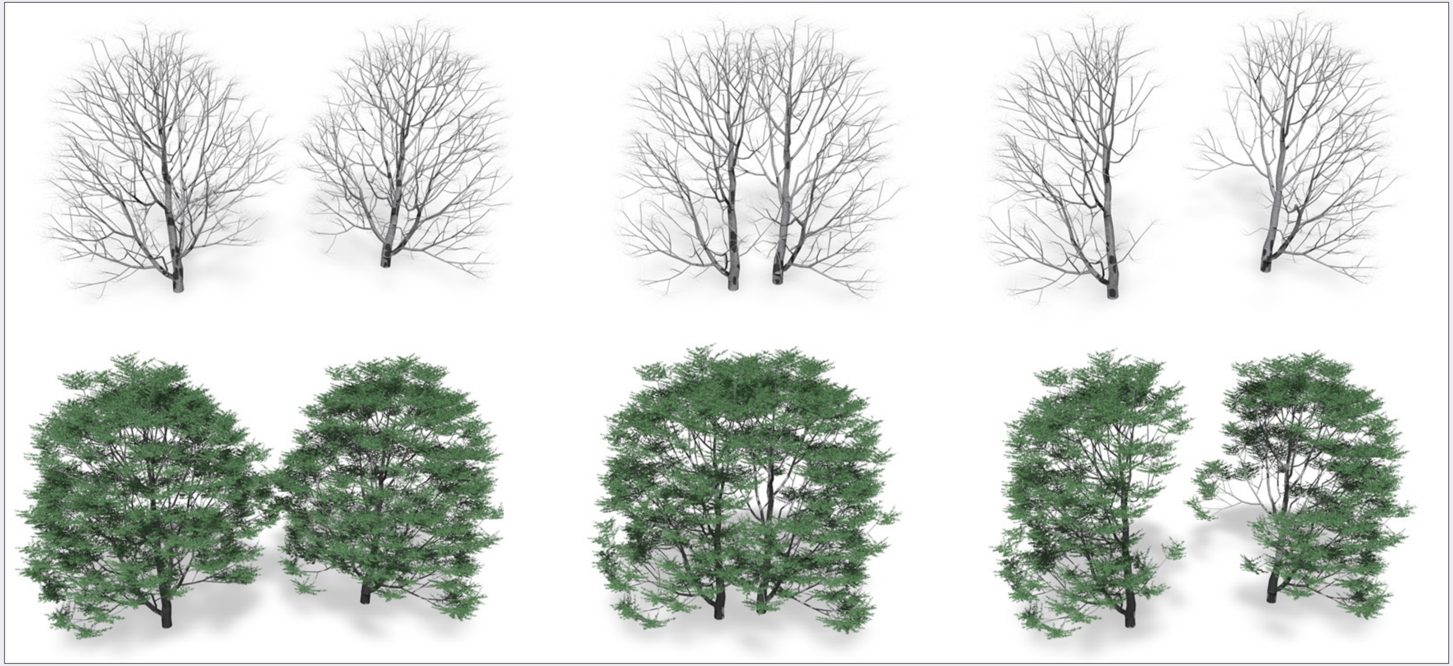
Arbres déformables

Applications

Collisions ou compétition entre arbres, élagage

Video



S. Pirk et al., O. Stava, J. Kratt, M. Abdul-Massih, B. Neubert, R. Mech, B. Benes, O. Deussen, Plastic Trees: Interactive Self-Adapting Botanical Tree Models, ACM Transactions on Graphics, 2012

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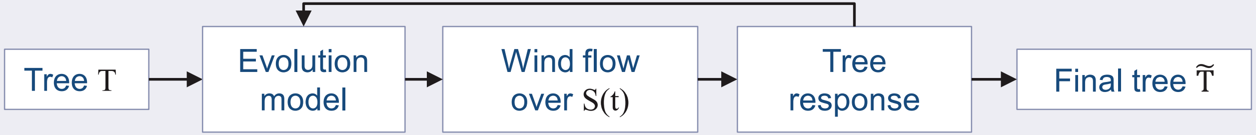
Déformation au vent

Simulation

Wind simulation (SPH) taking into account tree geometry
Warp tree skeleton S and transfer to T into $\tilde{T}$

Video


Tree T → Evolution model → Wind flow over $S(t)$ → Tree response → Final tree $\tilde{T}$

S. Pirk, T. Niese, T. Härich, B. Benes, O. Deussen, Windy Trees: Computing Stress Response for Developmental Tree Models, ACM Transactions on Graphics, 2014

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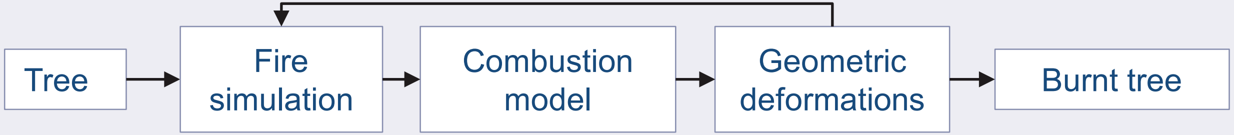
Combustion

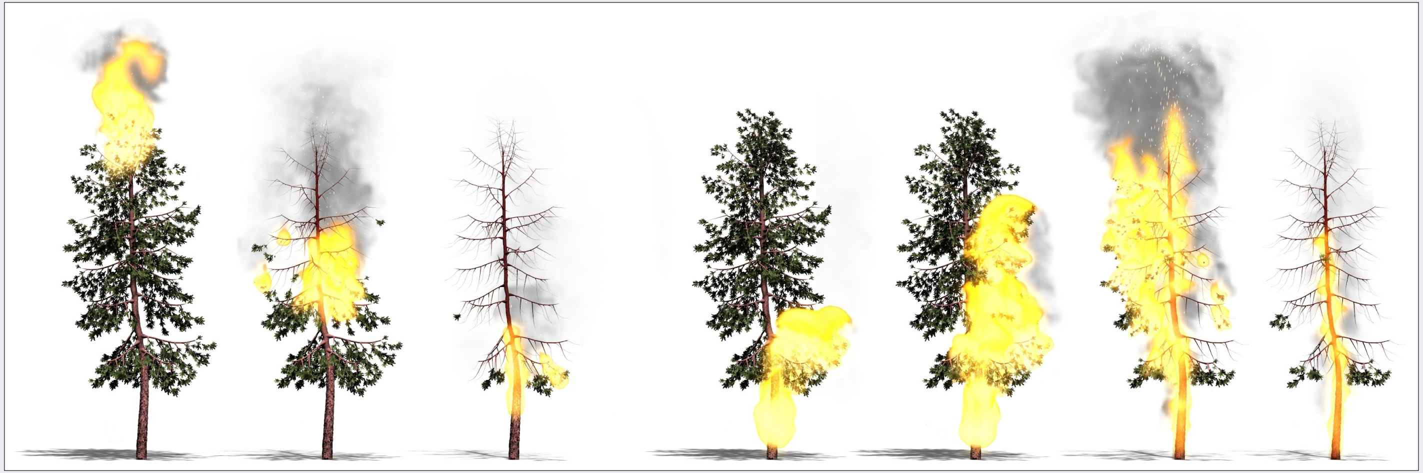
Simulation

Propagation of temperature according to material properties

Video



Tree → Fire simulation → Combustion model → Geometric deformations → Burnt tree



S. Pirk, M. Jarząbek, T. Hädrich, D. L. Michels, W. Palubicki, Interactive Wood Combustion for Botanical Tree Models, ACM Transactions on Graphics, 2017

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Procedural Generation

Procedural approaches to distribution synthesis

Overview

Modeling trees

Ecosystems

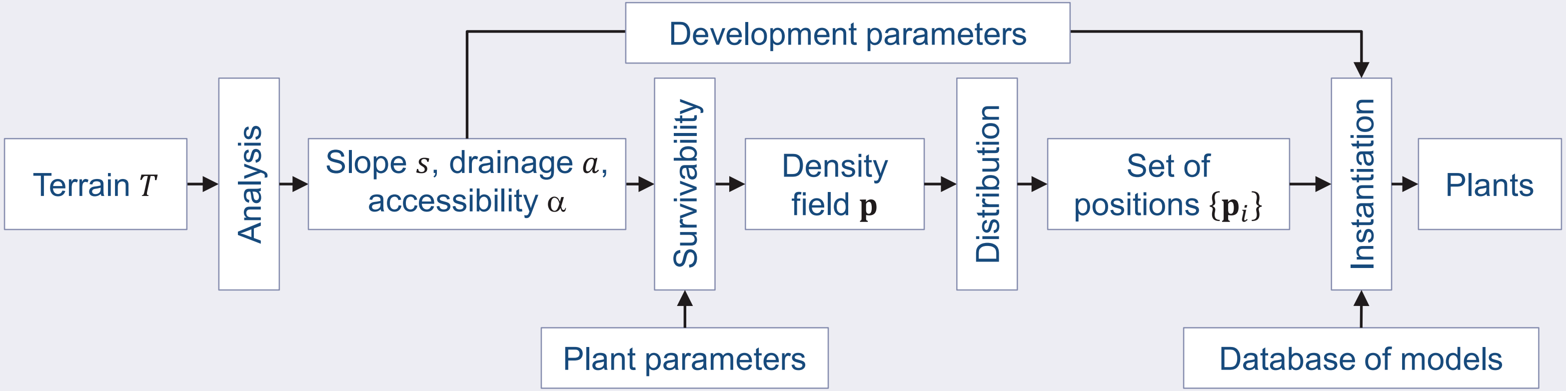
Procedural

Hybrid

Distribution synthesis

Top down approach featuring **control**

Generate plant positions $\{\mathbf{p}_i\}$ according to an underlying distribution $\mathbf{p}: \mathbf{R}^2 \rightarrow [0,1]$



Development parameters

Terrain T

Analysis

Slope s, drainage a, accessibility α

Survivability

Density field $\mathbf{p}$

Distribution

Set of positions $\{\mathbf{p}_i\}$

Instantiation

Plants

Plant parameters

Database of models

O. Deussen, P. Hanrahan, B. Lintermann, R. Měch, M. Pharr, and P. Prusinkiewicz. Realistic Modeling and Rendering of Plant Ecosystems. *SIGGRAPH*, 1998.

M. Alsweis and O. Deussen. Modeling and Visualization of symmetric and asymmetric plant competition. *Eurographics Workshop on Natural Phenomena*, 2005.

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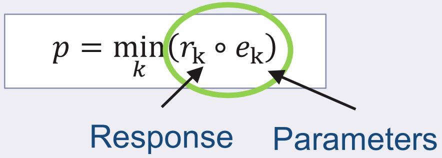
Distribution maps

Statistical presence of plant

Probability function $p\colon \mathbf{R}^2 \rightarrow [0,1]$ for every species



$$p = \min_k (r_k \circ e_k)$$

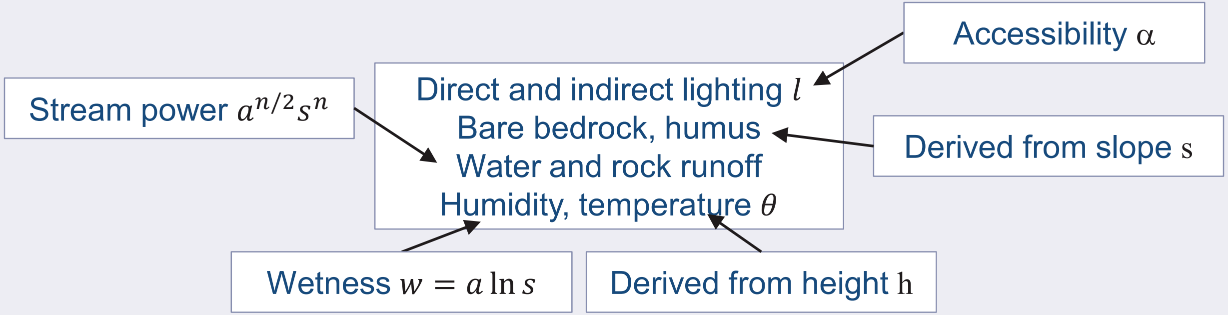
Response

Parameters

Abiotic parameters

Computationally intensive simulation

Approximation of environment parameters e from elevation h



Accessibility α

Stream power $a^{n/2}s^n$

Direct and indirect lighting l
Bare bedrock, humus
Water and rock runoff
Humidity, temperature θ

Derived from slope s

Wetness $w = a \ln s$

Derived from height h

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Instantiation

Overview
Modeling trees
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Categories

- Half toning [Deussen1998]
- Dart throwing and Poisson disc sampling [Lane2002, Andújar2014]
- Dominant-species placement using greedy cluster merging [Li2018]
- Field-of-neighborhood plant distributions placed on Wang tiles [Alsweis2006]
- Inter and intra-species distribution histograms [Emilien2015, Gain2017]

M. Alsweis and O. Deussen. Wang-tiles for the simulation and visualization of plant competition. *Computer Graphics International*, 2006.
C. Andújar, A. Chica, M. Vico, S. Moya, and P. Brunet. Inexpensive Reconstruction and Rendering of Realistic Roadside Landscapes. *Computer Graphics Forum* **33**(6), 2014.
J. Gain, H. Long, G. Cordonnier, and M.-P. Cani. Eco Brush: Interactive Control of Visually Consistent Large-Scale Ecosystems. *Computer Graphics Forum 36*, **2**(3), 2017.

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Poisson Disc Sampling

Dart throwing

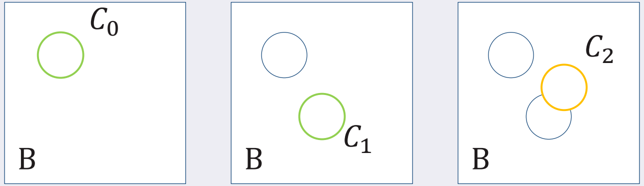
Rejection-based iterative algorithm

Iteratively throw discs C_i in a region $B \subset \mathbf{R}^2$ such that they do not overlap

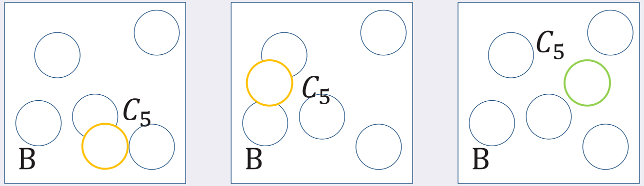
```
Initialize the starting set $C = \emptyset$
    Throw a candidate $C_i(\mathbf{c}, r)$
    Add $C_i$ to $C$ if $C_i \cap C = \emptyset$
    Iterate until $B$ is full
```

$O(n)$: test C_i with **all** discs in C

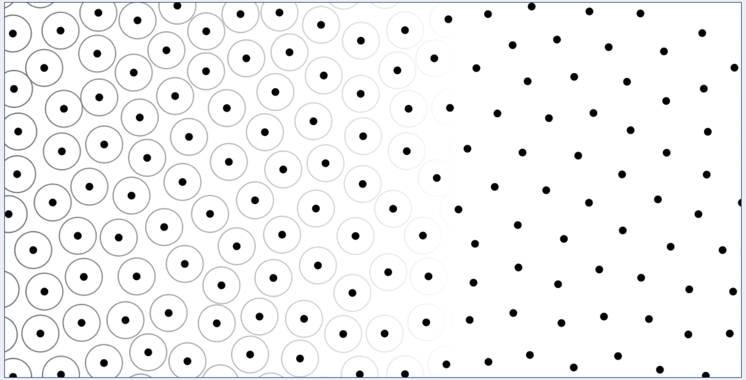
Detection ?



Efficient first steps



Intensive last steps : $P(C_i \cap C = \emptyset) \approx 0$



A. Lagae, P. Dutré. An Alternative for Wang Tiles: Colored Edges versus Colored Corners. *ACM Transactions on Graphics*. (245), 2006.

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Variable Radii Poisson-Disk Sampling
Scott A. Mitchell⇤ Alexander Rand†
Mohamed S. Ebeida‡ Chandrajit Bajaj§

R. Bridson. Fast Poisson disk sampling in arbitrary dimensions, Proceedings of Siggraph Sketches, 2007.

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Ebeida, Patney, Mitchell, Davidson, Knupp, Owens. Efficient Maximal Poisson-Disk Sampling, SIGGRAPH 2011.

Ebeida, Mitchell, Patney, Davidson, Owens. A Simple Algorithm for Maximal Poison-Disk Sampling in High Dimensions. Eurographics 2012

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Rendu réaliste du caillou et brins d’herbe aux montagnes… Outils et technique de création et manipulation de terrain

Courtesy of
Benoit Martinez
UBISOFT

Ecosystem Simulation

Ecosystem simulation

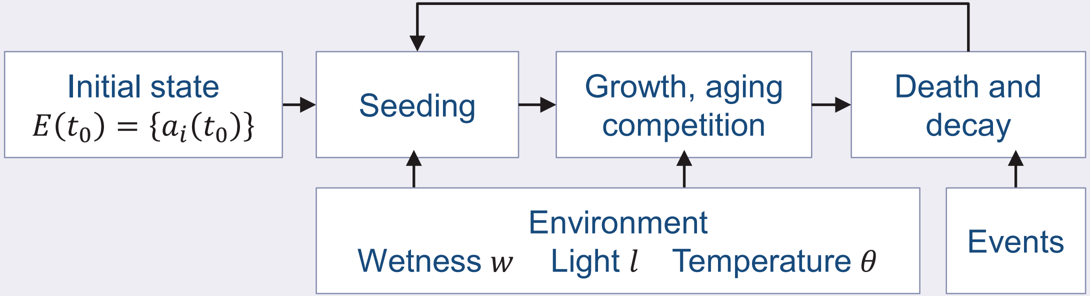
Simulation

Bottom up approach featuring **emerging phenomena** (clustering, competition)

Presence often approximated by discs

Biotic rules for simulating seeding, growth, aging, death, competition

Influence of the environment: abiotic parameters (lighting, temperature θ, wetness w)



Initial state
$E(t_0) = \{a_i(t_0)\}$

Seeding

Growth, aging
competition

Death and
decay

Environment
Wetness w Light l Temperature θ

Events

O. Deussen, P. Hanrahan, B. Lintermann, R. Měch, M. Pharr, and P. Prusinkiewicz. Realistic Modeling and Rendering of Plant Ecosystems. SIGGRAPH, 1998.

M. Alsweis and O. Deussen. Modeling and Visualization of symmetric and asymmetric plant competition. In Eurographics Workshop on Natural Phenomena, 2005.

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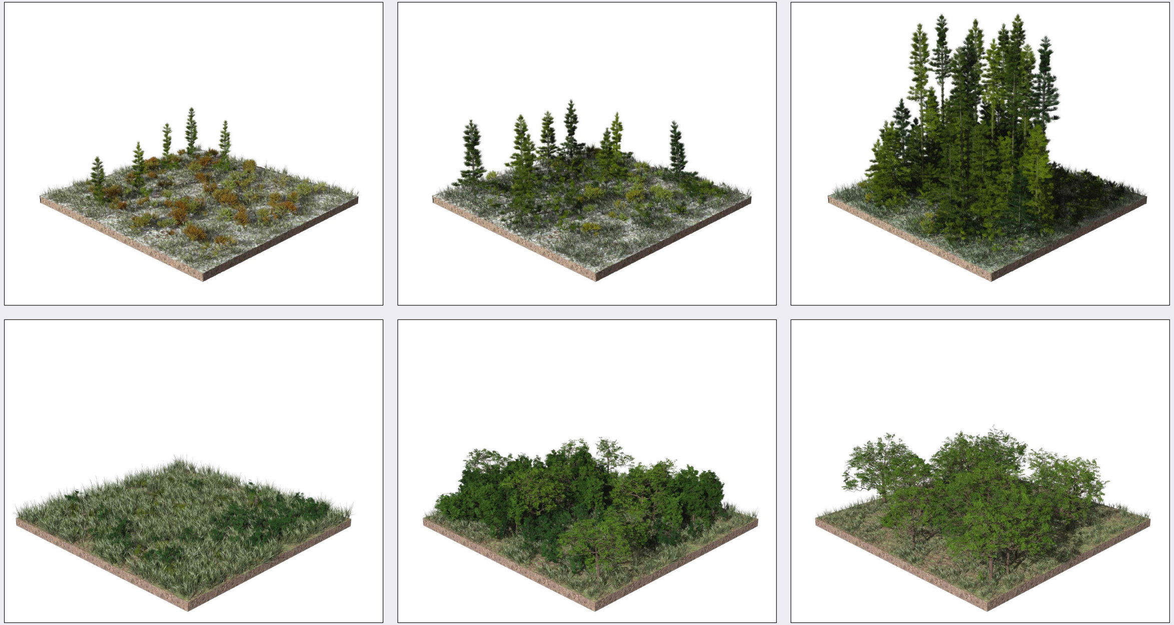
Combined instantiation and simulation

Hybrid approach

- Considers the phenotype of plants by instantiating and orienting **branch templates**
- Sunlight-adapted structural plant models during simulation [Makowski2019]
- Most accurate at a plant level, **computationally intensive**

Video



M. Makowski, T. Hädrich, J. Scheffczyk, D. Michels, S. Pirk, and W. Pałubicki. Synthetic Silviculture: Multi-Scale Modeling of Plant Ecosystems. ACM Transactions on Graphics **38**(4), 2019.

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Cluster Growth: Diffusion Limited Aggregation

Fundamentals

Diffusion **L**imited **A**ggregation as a growth process
Define an particle as a starting cluster $\mathrm{C}_0 = \{\mathbf{p}_0\}$
Launch a new particle $\mathbf{p}_k$ far away, move randomly (diffusion)
If $\mathbf{p}_k$ touches $\mathrm{C}_{\mathrm{k}-1}$, aggregate $\mathrm{C}_{\mathrm{k}} = \mathrm{C}_{\mathrm{k}-1} \cup \{\mathbf{p}_k\}$

Could start with a set of seeds

Brownian motion

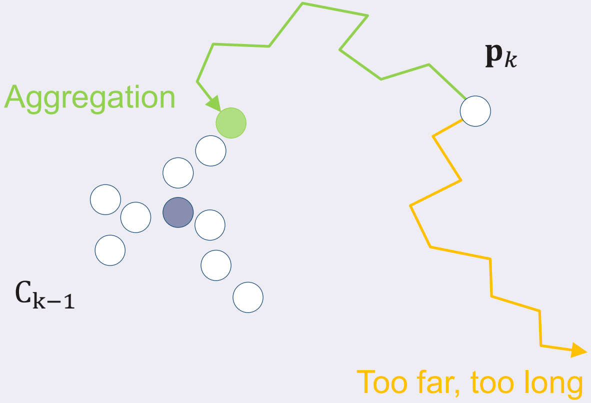
Could use statistics for aggregation

Improvements

Conditional aggregation : if $\mathbf{p}_k$ touches $\mathrm{C}_{\mathrm{k}-1}$,
and conditions on $\mathrm{C}_{\mathrm{k}-1}$ and $f\big(B(\mathbf{p}_k, r)\big)$ are met

Function defining conditions

Neighborhood



Condition: few particles in the neighborhood

$$\#\big(\mathrm{C} \cap B(\mathbf{p}_k, r)\big) < \mathrm{N}$$

T. Witten, L. Sanders. Diffusion-limited aggregation, a kinetic critical phenomenon. Physical Review Letters 47 (1981)

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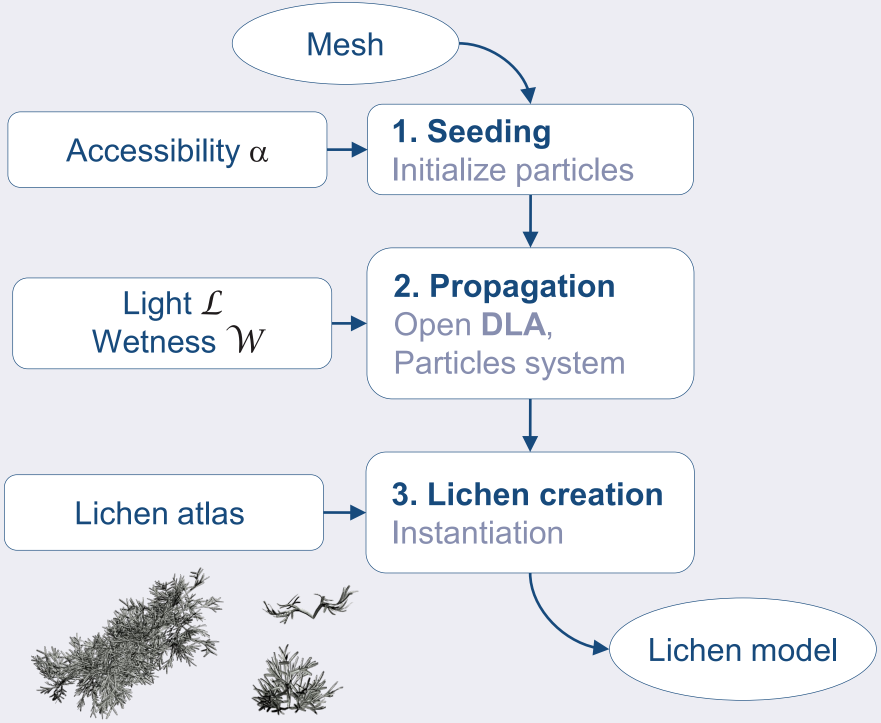
Méthode

Lichens

Croissance selon un algorithme de type **D**iffusion **L**imited **A**ggregation
Instanciation de modèles maillés texturés



Mesh

Accessibility α

1. Seeding
Initialize particles

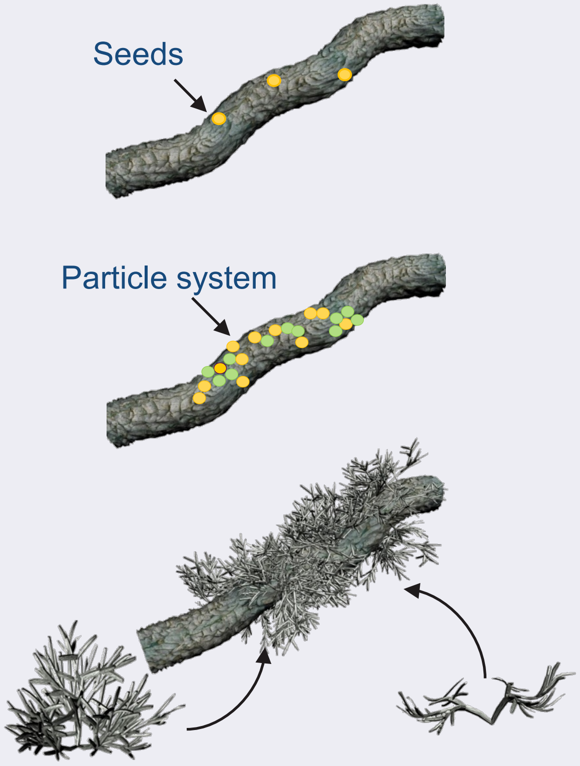
Light $\mathcal{L}$
Wetness $\mathcal{W}$

2. Propagation
Open **DLA**,
Particles system

Lichen atlas

3. Lichen creation
Instantiation

Lichen model



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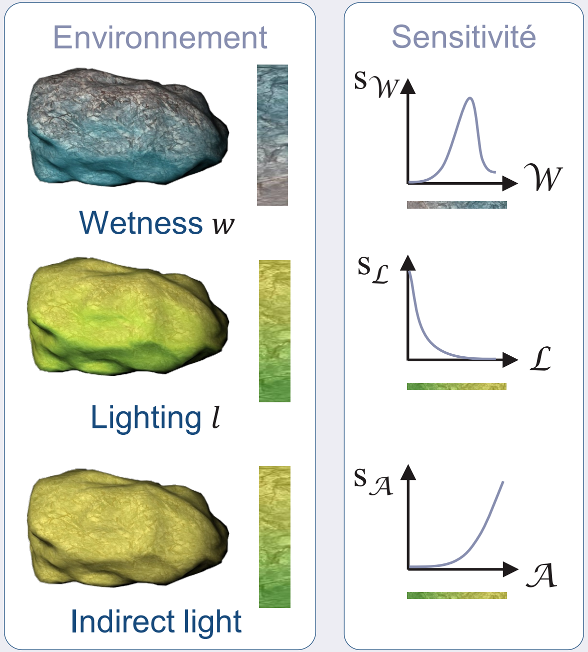
Colonisation

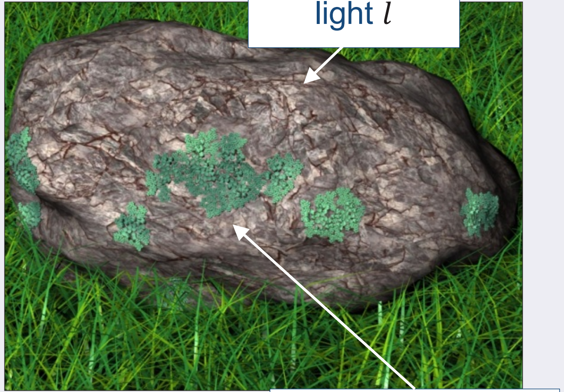
Overview
Modeling trees
Ecosystems
Procedural
Hybrid

Lichens

Agrégation fonction des caractéristiques de l’environnement

$$p\big(B(\mathbf{p}_k, r)\big) = \min(s_W \circ W, s_L \circ L, s_A \circ A)$$





Too much light l

Good wetness w and indirect light

B. Desbenoit, E. Galin and S. Akkouche, Simulating and Modeling Lichen Growth, *Computer Graphics Forum*, **23**(3), 2004

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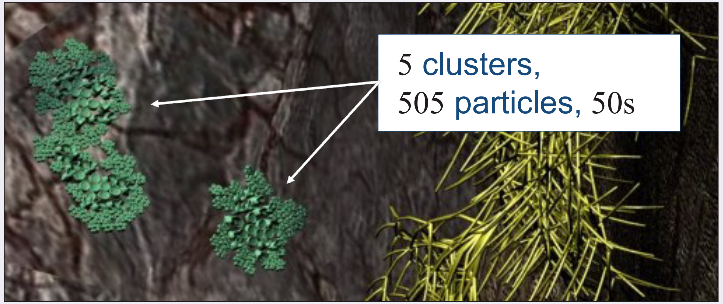
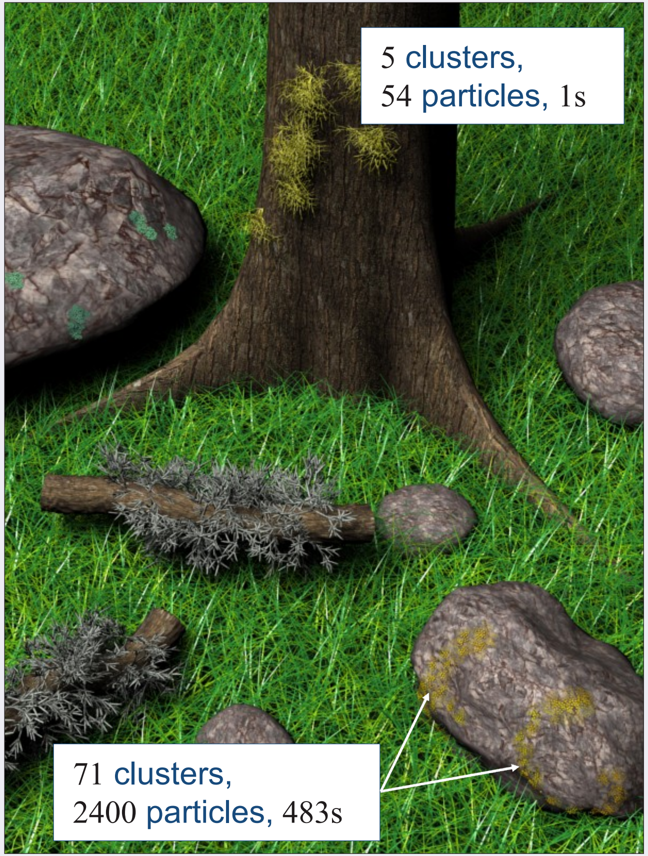
Lichens



5 clusters,
505 particles, 50s



5 clusters,
54 particles, 1s

71 clusters,
2400 particles, 483s

24 clusters, 522 particles, 26s

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Hybrid Approaches

Données et fonctions

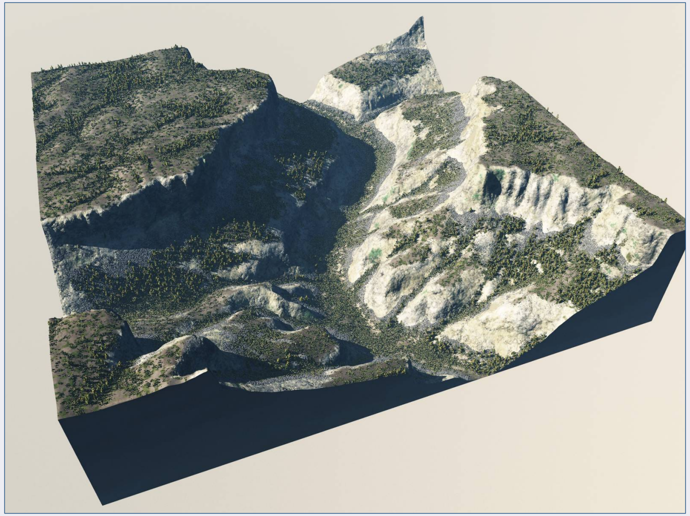
Système

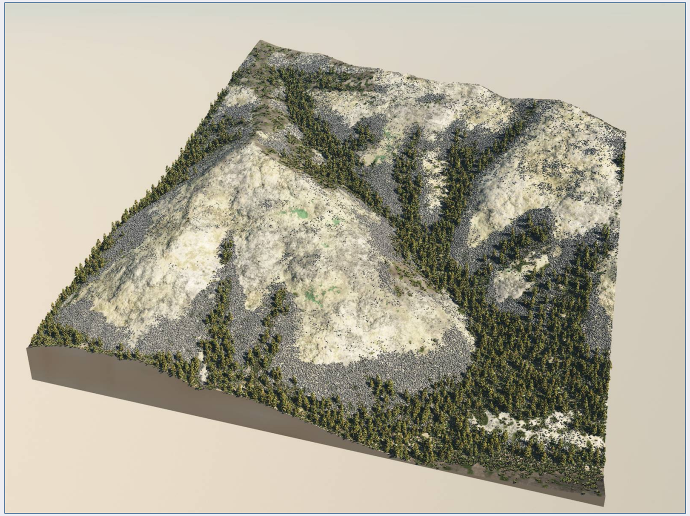
Données

Représentation de terrains **multi matériaux** par couches de matière
Couches représentant la **densité de végétation** pour des variétés d'espèces

Simulation

Modèle à base d'évènements **stochastiques**
Interaction entre des phénomènes naturels différents : éolien, hydraulique, thermique …
Contrôle direct et indirect





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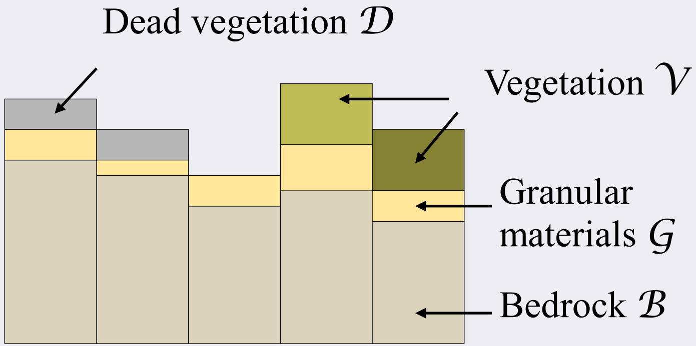
Modèle

Structure

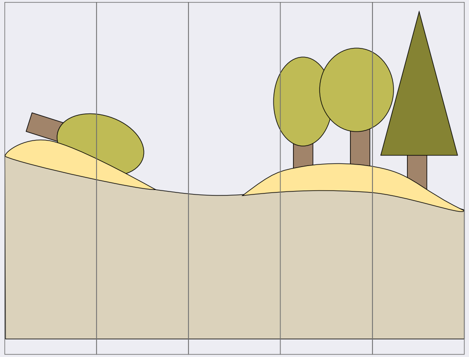
Grille régulière multi matériaux
Echelle **spatiale** : cellules de $10\times10\ \mathrm{m}^2$;et terrains de $10\times10\ \mathrm{km}^2$
Echelle **temporelle** : période de $100\text{–}1000\ \mathrm{y}$ par pas de $1\ \mathrm{y}$

Matériaux

Terrain : matériaux granulaires $G(\boldsymbol{x},t)$ et roche $B(\boldsymbol{x},t)$
Végétation : une densité $V(\boldsymbol{x},t)$ par type et plantes mortes $D(\boldsymbol{x},t)$
Eau : liquide $W(\boldsymbol{x},t)$



Discrete layered representation



Instantiated ground and models from layer data

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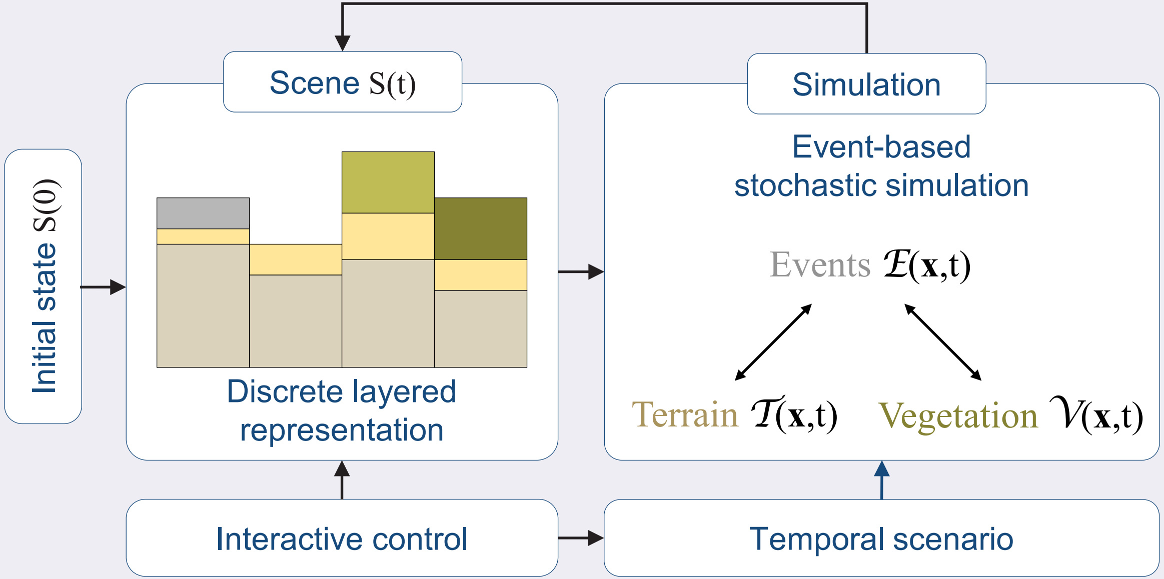
Architecture

Simulation

Evènements pouvant **déclencher** d'autres évènement en **cascade**
Contrôle par **interaction** directe, ou par **scénario temporel**



Scene $S(t)$

Simulation

Initial state $S(0)$

Discrete layered representation

Event-based stochastic simulation

Events $\mathcal{E}(\mathbf{x},t)$

Terrain $\mathcal{T}(\mathbf{x},t)$

Vegetation $\mathcal{V}(\mathbf{x},t)$

Interactive control

Temporal scenario

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Effets complexes

Végétation

Croissance de végétation résistante sur les régions d'accrétion

Grand Canyon (USA)

Compétition entre les éboulements et le développement de la végétation

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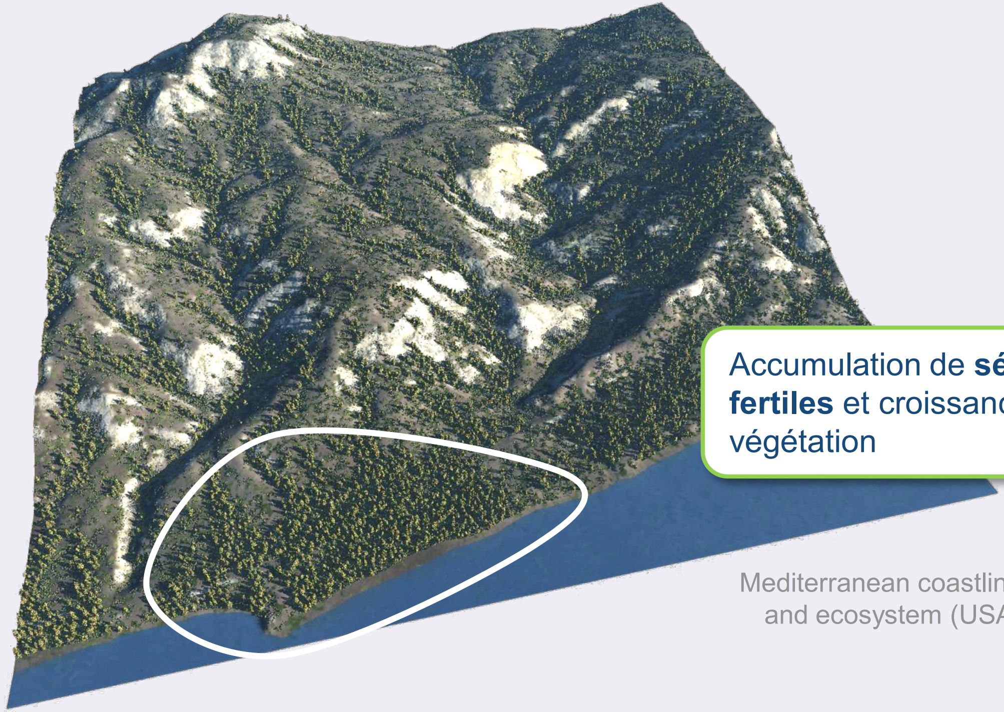
Effets complexes

Erosion

Conquête de terrain sur la mer suite à l'érosion des montagnes
Développement de la végétation sur les sédiments accumulés



Accumulation de **sédiments fertiles** et croissance de la végétation

Mediterranean coastline and ecosystem (USA)

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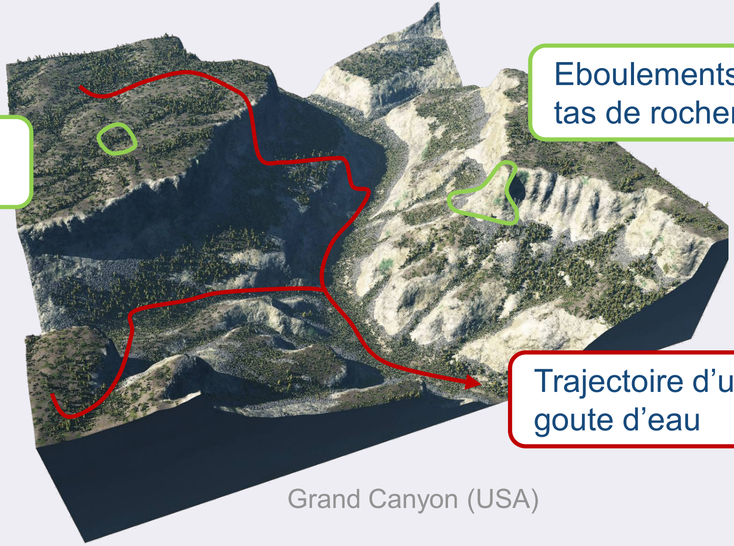
Performance

Temps

Terrain de 1×1 km^2, discrétisation 128×128, édition interactive 0,1s
Coût en $O(n^4)$ où n représente la discrétisation, 10s pour 1024×1024

Processus locaux (érosion thermique, impact de foudre, glissements de terrains, écosystème) **efficaces** :
$O(k^2n^2)$ où $k \ll n$

Erosion hydraulique avec un transport de sédiments sur des longues distances **couteux** :
$O(k^2n^2)$ avec $k \sim n$ donc $O(n^4)$



Compétition inter espèces

Eboulements et tas de rochers

Trajectoire d'une goute d'eau

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Supplementary Material

Botanique

Définitions

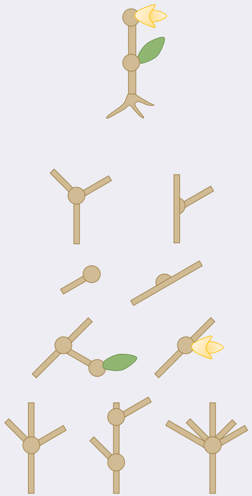
Plante herbacée ou ligneuse
Tige, racine, branche, bourgeon, feuille, fleur

Structures

Dichotomique ou monopodiale
Bourgeon de type terminal ou latéral
Bourgeon végétatif ou à fleur
Structure alternée, en opposition, spiralée

Influences sur la croissance

Tropismes : phototropisme (recherche de la lumière), géotropisme (déformation selon la gravité).
Obstacles et recherche d’espace



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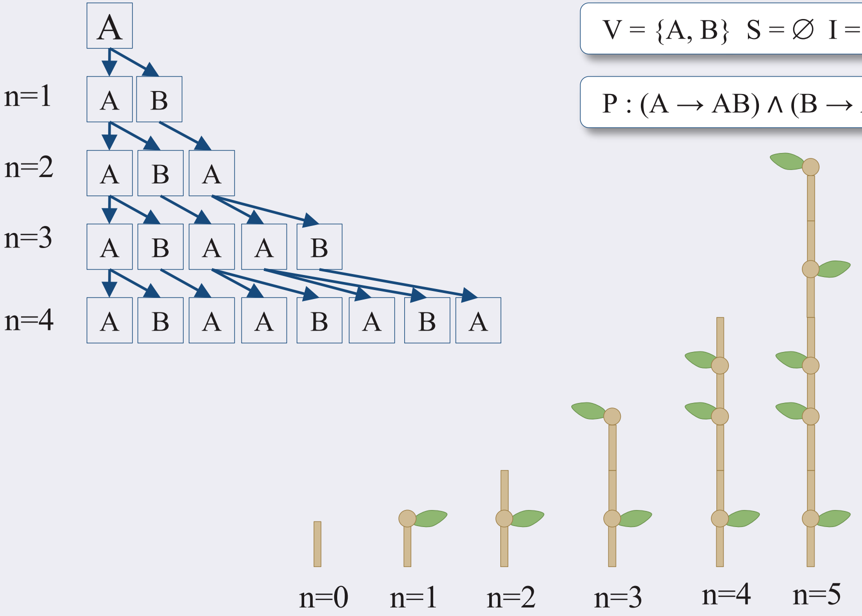
L-Systèmes

Système déterministe

Determinist O-context System : une seule évolution de l'axiome à la $n^{\text{ième}}$ génération

Une variable ne peut subir qu'un seul type de transformation

Une seule règle par variable



A

n=1 A B

n=2 A B A

n=3 A B A A B

n=4 A B A A B A B A

$V = \{A, B\}\quad S = \varnothing\quad I = A$

$P : (A \rightarrow AB) \land (B \rightarrow A)$

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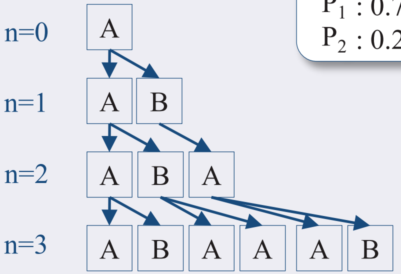
L-Systèmes

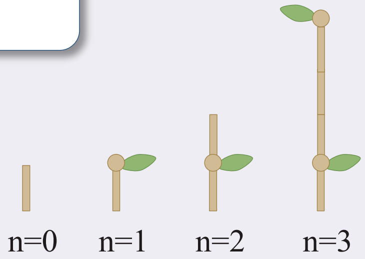
Système stochastique

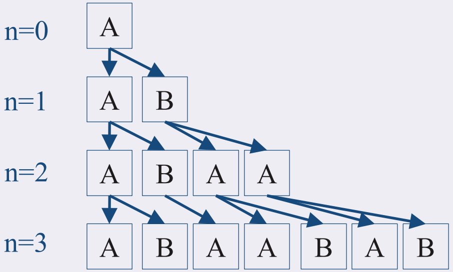
Stochastic O-context System : plusieurs évolutions possibles à chaque génération

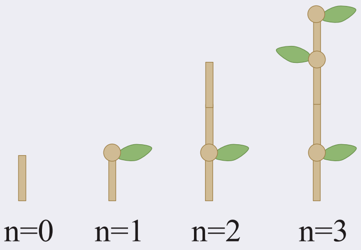
$V = \{A, B\} \quad S = \varnothing \quad I = A$

$P_0 : 1.00 \quad A \rightarrow AB$
$P_1 : 0.75 \quad B \rightarrow A$
$P_2 : 0.25 \quad B \rightarrow AA$









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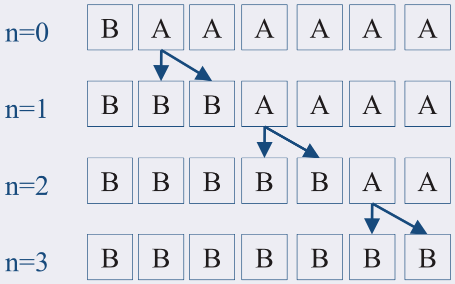
Système dépendant du contexte

OL Systèmes : chaque partie se développe indépendamment

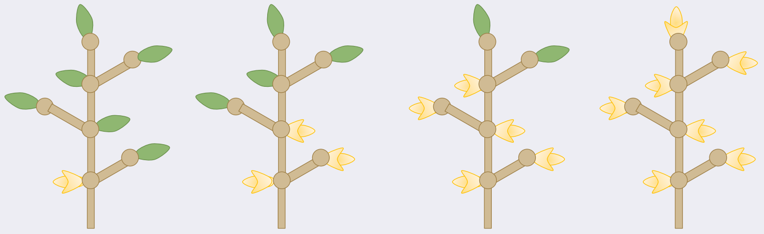
Context **S**ensitive **S**ystem : la règle prend en compte ce qui précède ou succède à une partie

V = {A, B} S = { +, −, [,], < }
I = B[+A]A[−A]A[+A]A

P : B < A → B



n=0	B	A	A	A	A	A	A
n=1	B	B	B	A	A	A	A
n=2	B	B	B	B	B	A	A
n=3	B	B	B	B	B	B	B



n=0 n=1 n=2 n=3

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