Terrain Modeling and Generation

Axel Paris

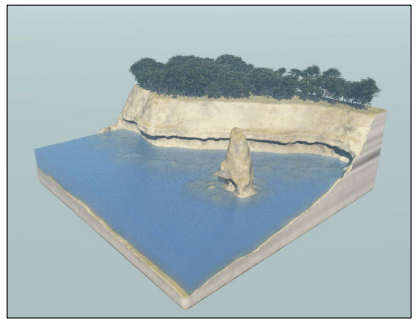
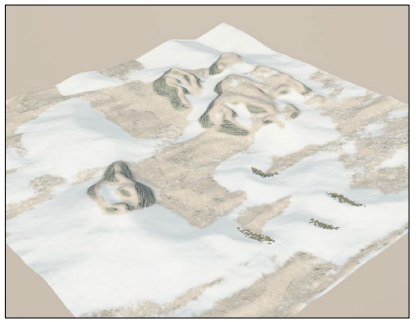
High-Beams Seminar Series

February, 13th 2025

Bio

Completed my PhD in Computer Graphics in 2023
Research Scientist at Adobe
Physics simulation, Implicit Surfaces, Sustainability, Terrain Modeling

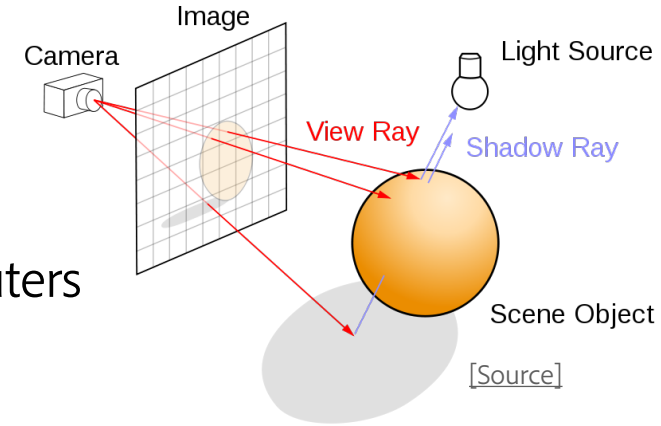
https://aparis69.github.io/
https://github.com/aparis69

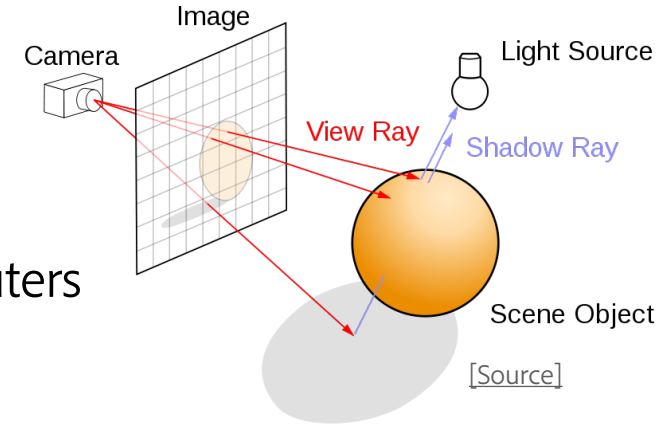
Definitions

Computer Graphics deals with generating images and art with the aid of computers

Core technology in movies, video games, digital art, mobile phones…



Definitions

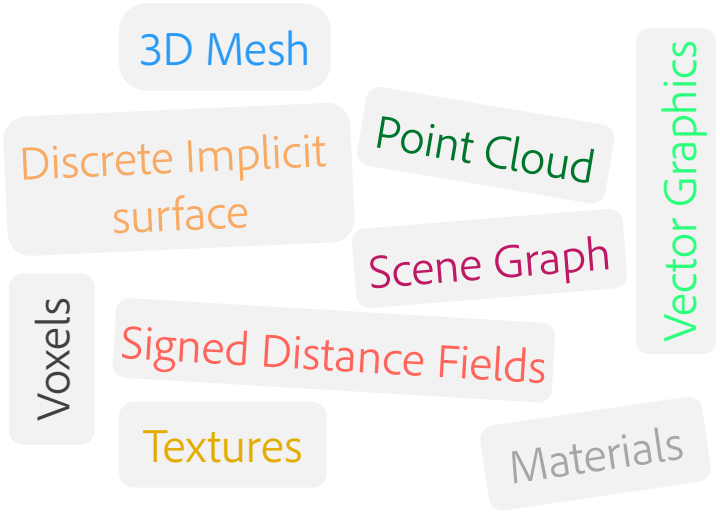


Computer Graphics deals with generating images and art with the aid of computers

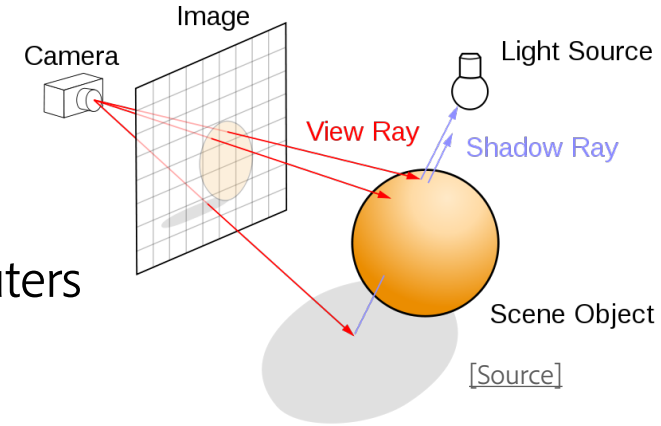
Core technology in movies, video games, digital art, mobile phones…

Modeling is about how to represent various things on a computer

What is the underlying mathematical representation? What is the data structure?



Definitions

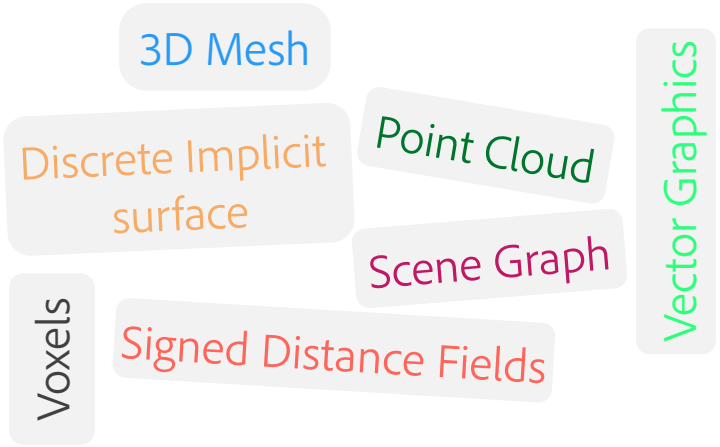


Computer Graphics deals with generating images and art with the aid of computers

Core technology in movies, video games, digital art, mobile phones…

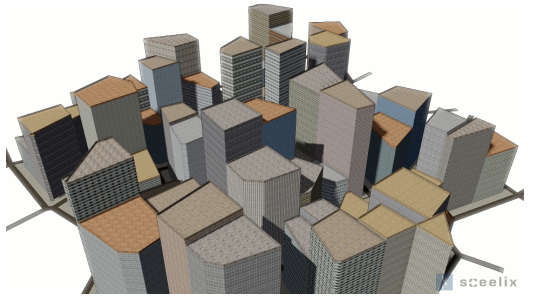
Modeling is about how to represent various things on a computer

What is the underlying mathematical representation? What is the data structure?

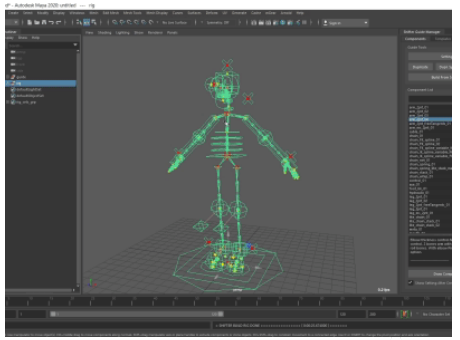


Generation is about how to generate, create, author these things

Encompasses procedural generation, physical simulation, direct manipulation…



[Source]

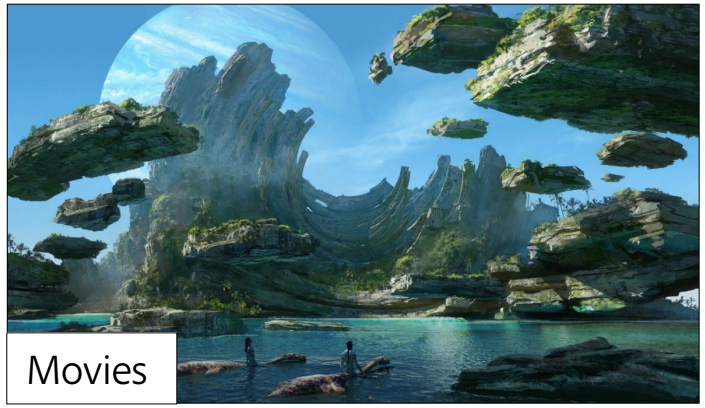


[Source]

Focus on Terrains

Terrains are used as virtual objects in many domains

Video games



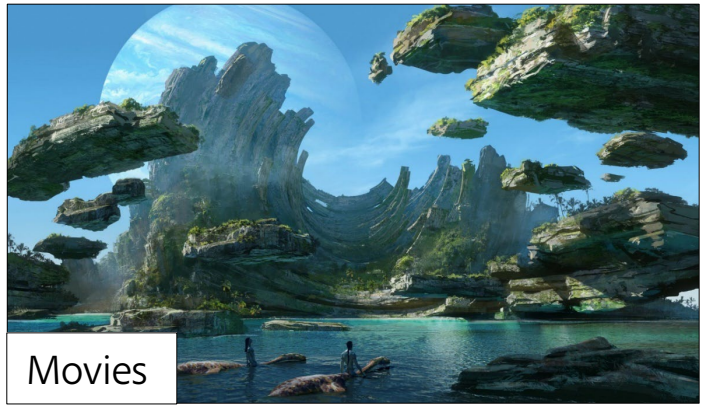
Movies

Geological simulations

Focus on Terrains

Terrains are used as virtual objects in many domains


Video games


Movies


Geological simulations

Key challenges

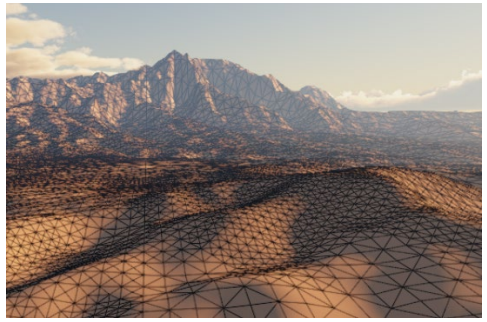
Realism | Extents | Variety | Control


Rainfall
erosion
Stratification
Vegetation
shielding
Sediment transport
Deposition

Outline

I) Planar models (heightfields)

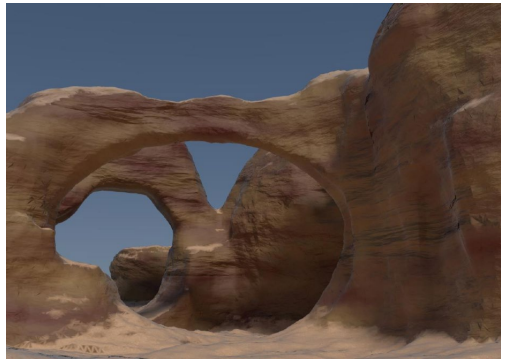
Modeling & Generation
Focus on Multiscale Terrain Erosion
Connection with industry



[Dupuy et al. 2020]

II) Volumetric models

Modeling & Generation
Lack of standard
Focus on Volumetric Implicit Terrains
Connection with industry



[Becher et al. 2017]

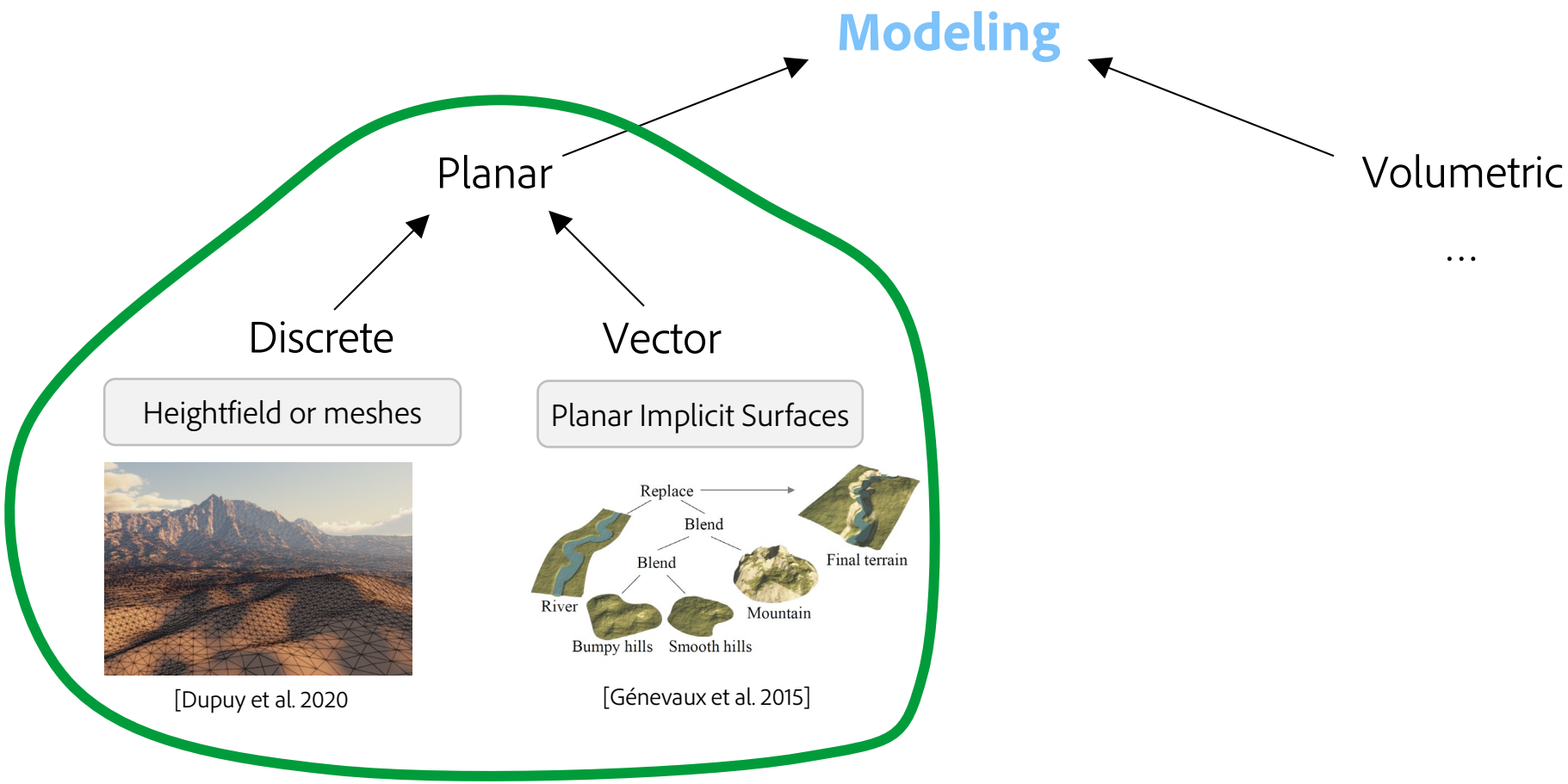
III) What's next?

GenAI everything?
Sustainability & Research

RESEARCH

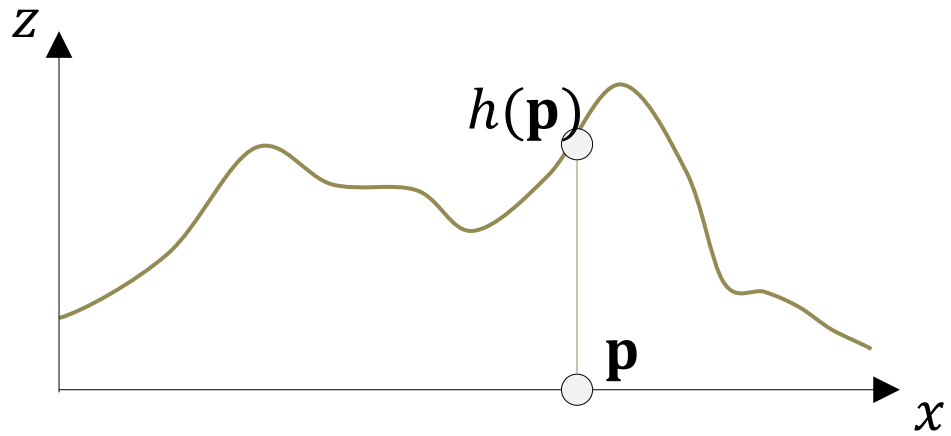
Genie 2: A large-scale foundation world model

Outline


Modeling
Planar
Volumetric
...
Discrete
Vector
Heightfield or meshes
Planar Implicit Surfaces
Replace
Blend
Blend
Final terrain
River
Mountain
Bumpy hills
Smooth hills
[Dupuy et al. 2020
[Génevaux et al. 2015]

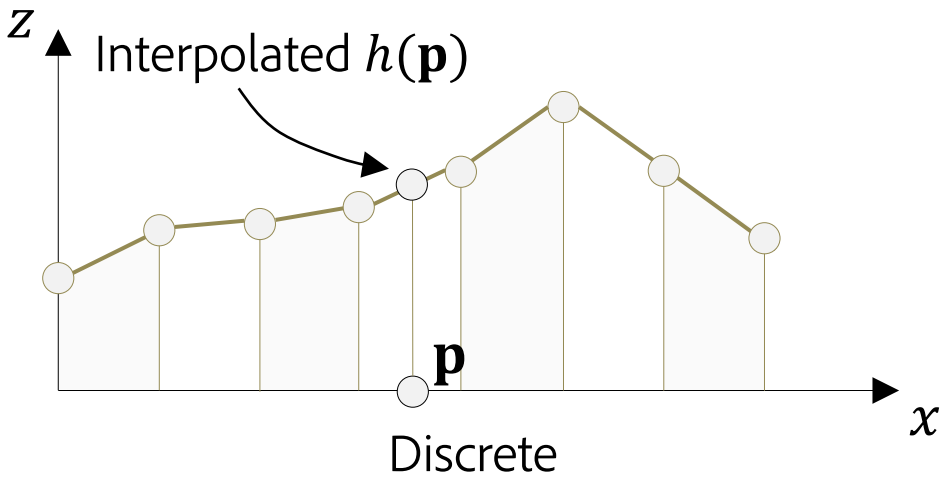
Modeling: planar models

Terrain surface computed from an elevation function $h : \mathbf{R}^2 \rightarrow \mathbf{R}$
Altitude z is defined as $z = h(\mathbf{p}_{xy})$



Procedural (also called Analytic/Function-based)

Compact in memory
Theoritically infinite precision
Incompatible with simulation (or require destructive workflows)



Discrete

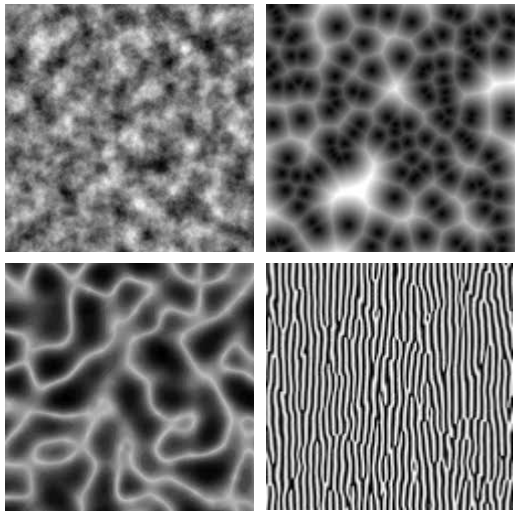
Can come from real data (DEM)
Usable in simulation
Higher memory cost (explicit)

Generation for planar representations

Very much suited for efficient & scalable processing (just as textures are!)

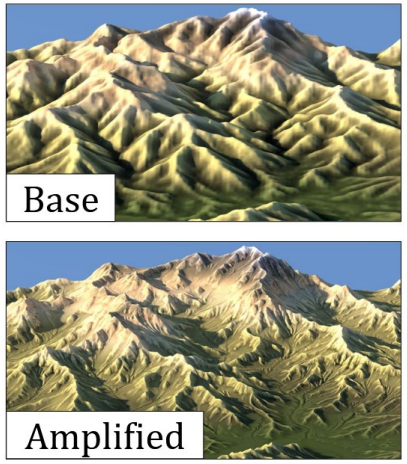
Generation

Procedural generation



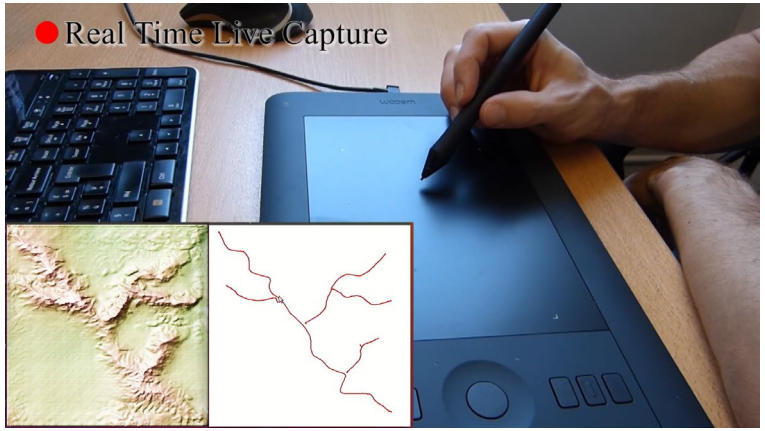
[Perlin et al. 1989]
[Musgrave et al. 1989]
[Worley et al. 1996]
[Tricard et al. 2019]

Physics simulation



[Schott et al. 2024]

By example synthesis



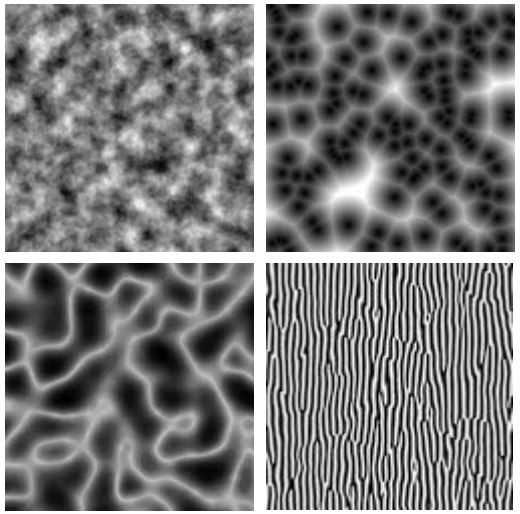
[Guérin et al. 2017]

Generation for planar representations

Very much suited for efficient & scalable processing (just as textures are!)

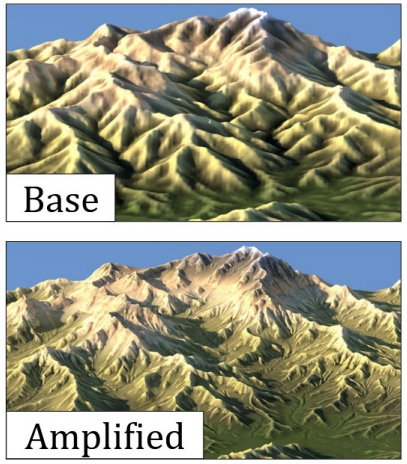
Generation

Procedural generation



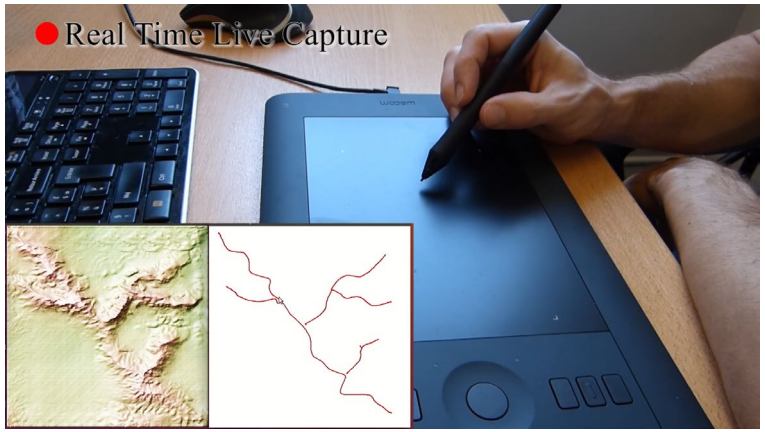
[Perlin et al. 1989]
[Musgrave et al. 1989]
[Worley et al. 1996]
[Tricard et al. 2019]

Physics simulation



[Schott et al. 2024]

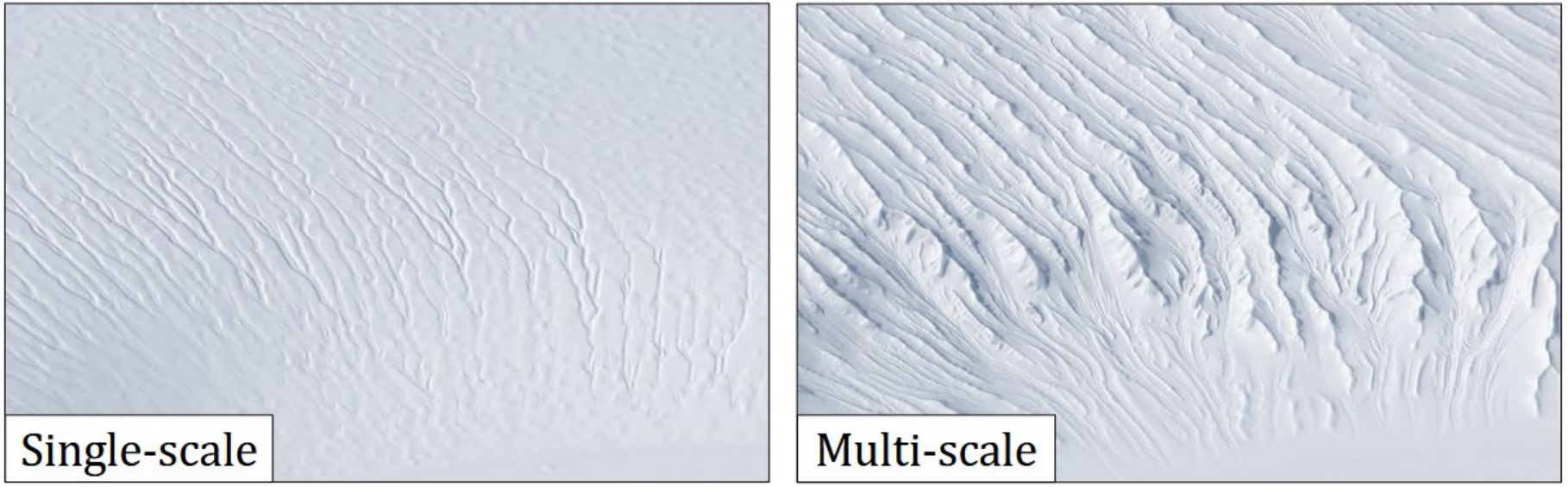
By example synthesis



[Guérin et al. 2017]

Focus: Multiscale Terrain Erosion

Problem: erosion & terrain generation pipeline create features at a **single scale** only

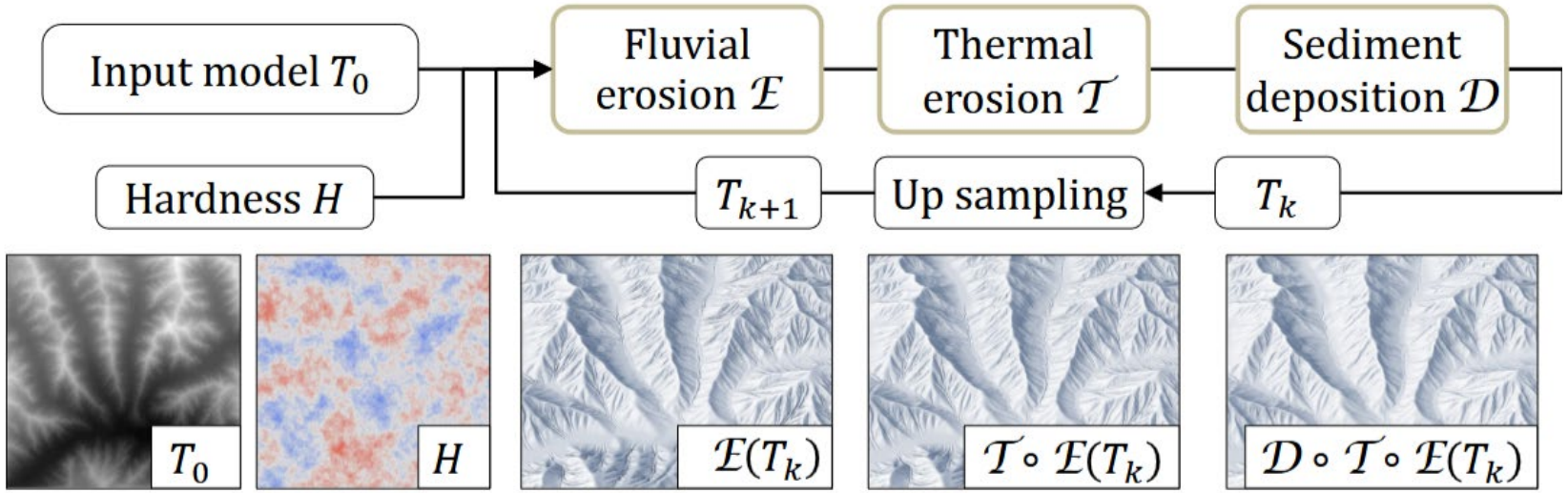


Our approach: new pipeline for creating terrains by interleaving **erosion** & **smart upsampling**

Focus: Multiscale Terrain Erosion

Our approach: new pipeline for creating terrains by interleaving **erosion** & **smart upsampling**

Multiscale terrain amplification, Schott et al. SIGGRAPH 2024



Other contributions

Preservation of peaks & ridges during simulation

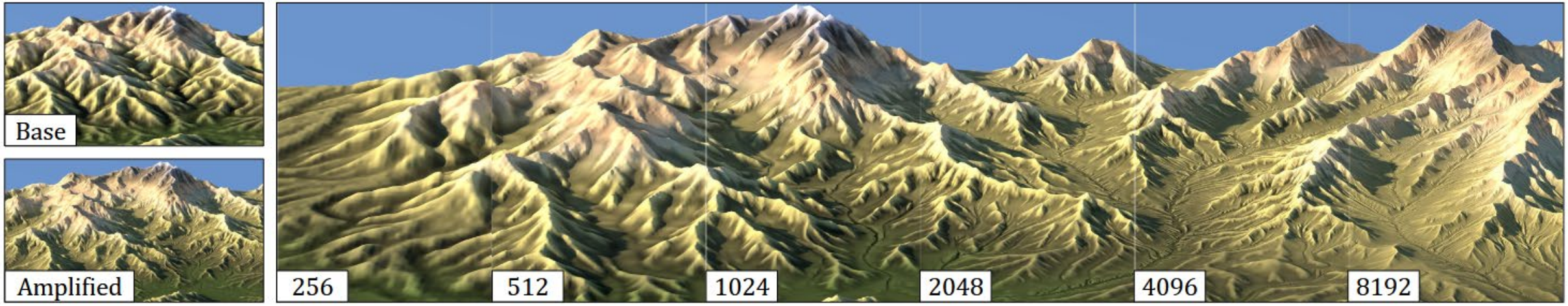
Open source GPU implementation

Hydrological consistency (rivers still exists!)

Focus: Multiscale Terrain Erosion

Our approach: new pipeline for creating terrains by interleaving **erosion** & **smart upsampling**

Multiscale terrain amplification, Schott et al. SIGGRAPH 2024

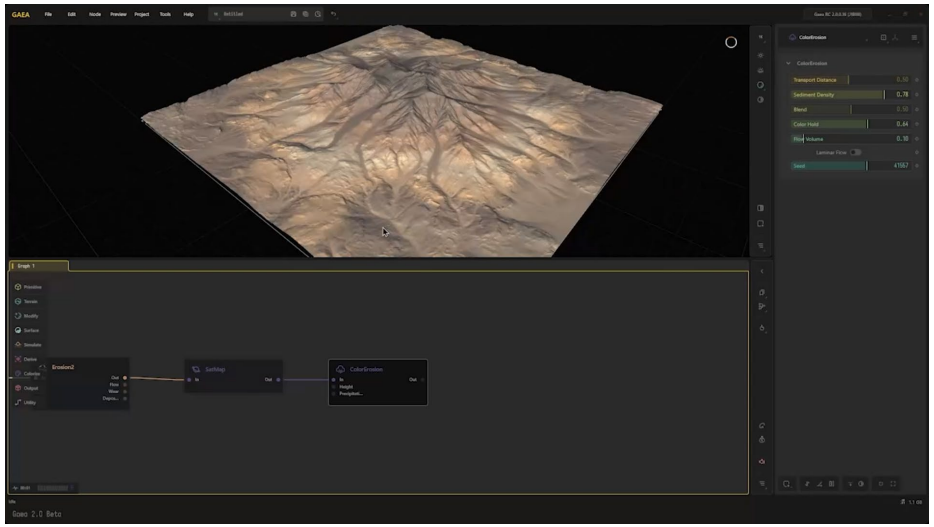


Overview

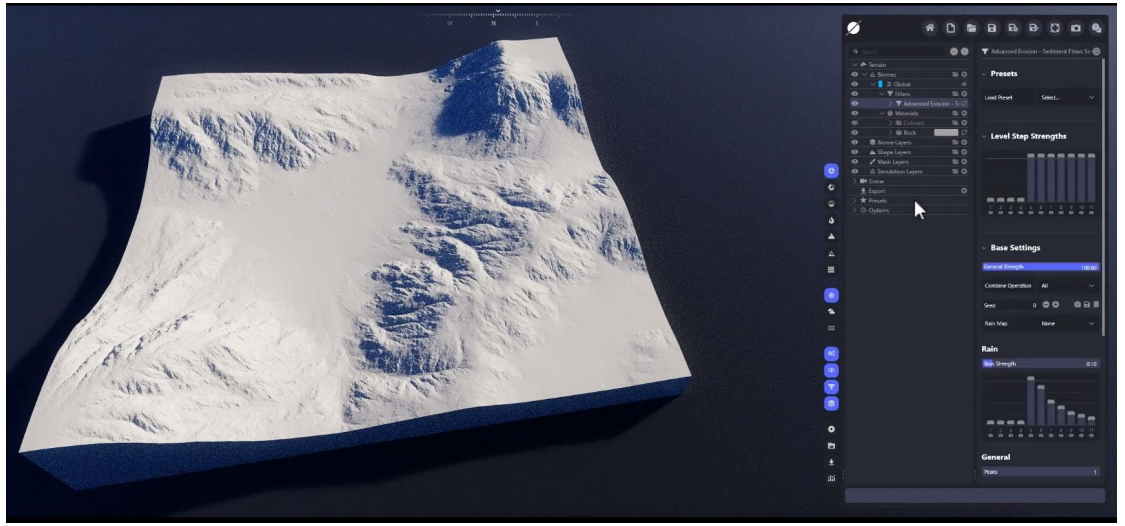
Heightfields as industry standard

As with texture & material generation, **node-based systems** are popular

- Key difference: more simulation/physics algorithms in terrain modeling
- Hydraulic Erosion, Tectonic Erosion, Thermal weathering etc…

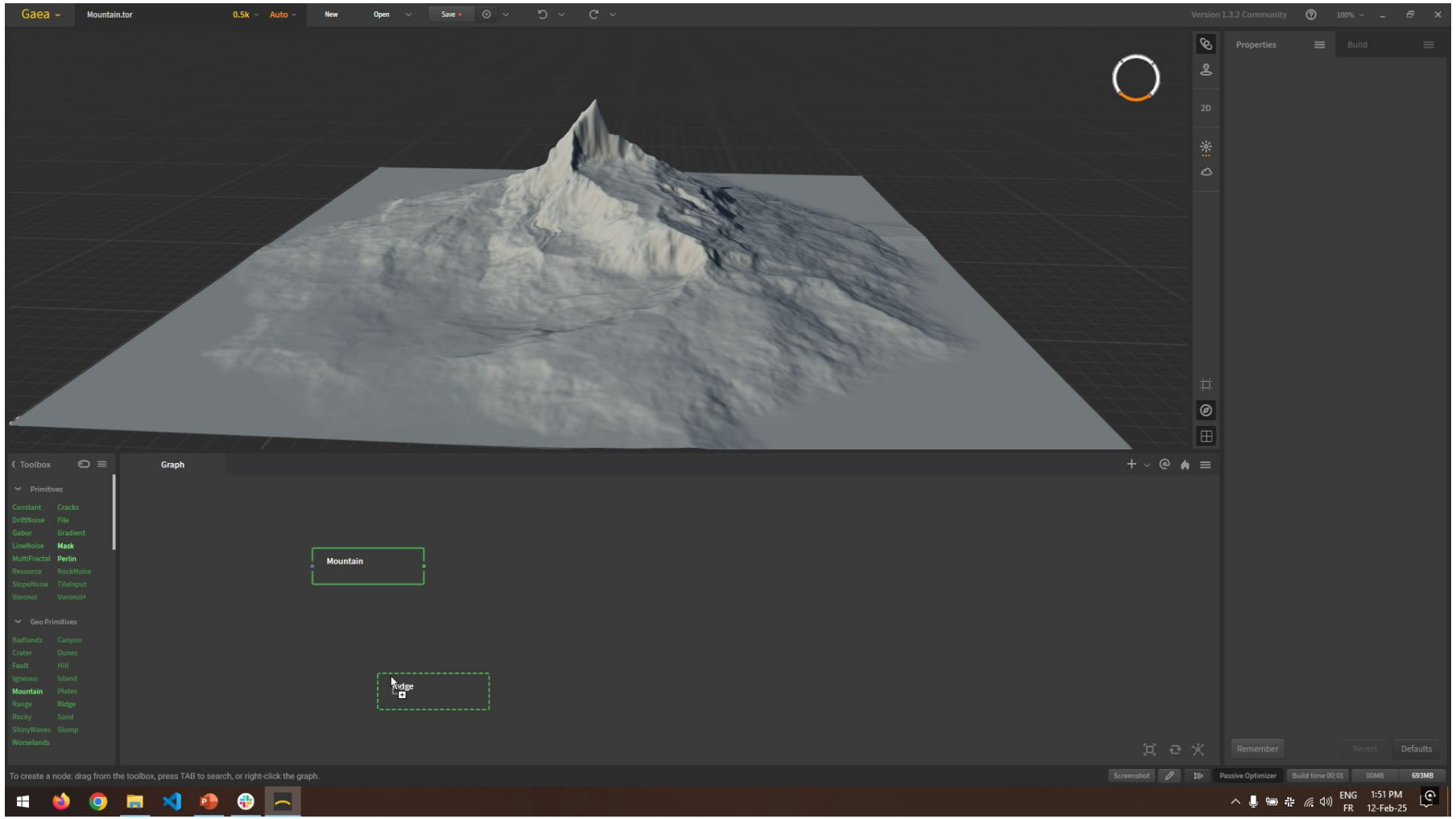


Gaea



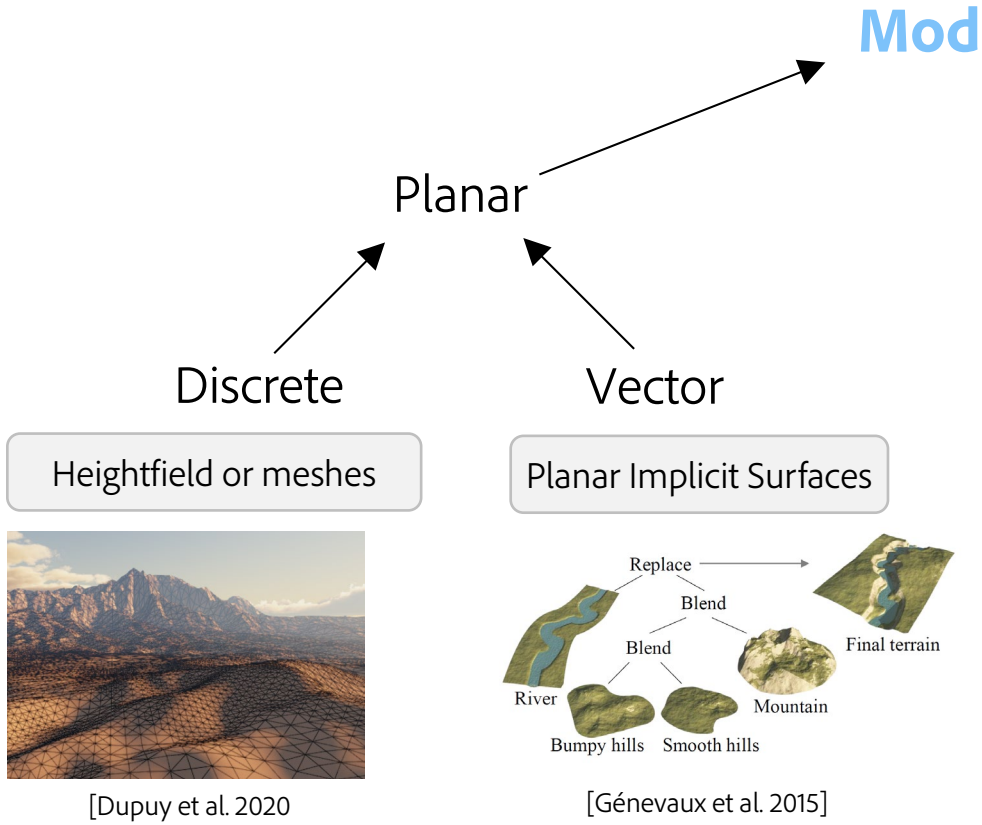
World Creator

Heightfields as industry standard



Personal note: terrain modeling softwares often do not provide any explicit manipulation tool (3D Gizmos) for their primitives ☹

Planar representations: limitations



[Dupuy et al. 2020

[Génevaux et al. 2015]

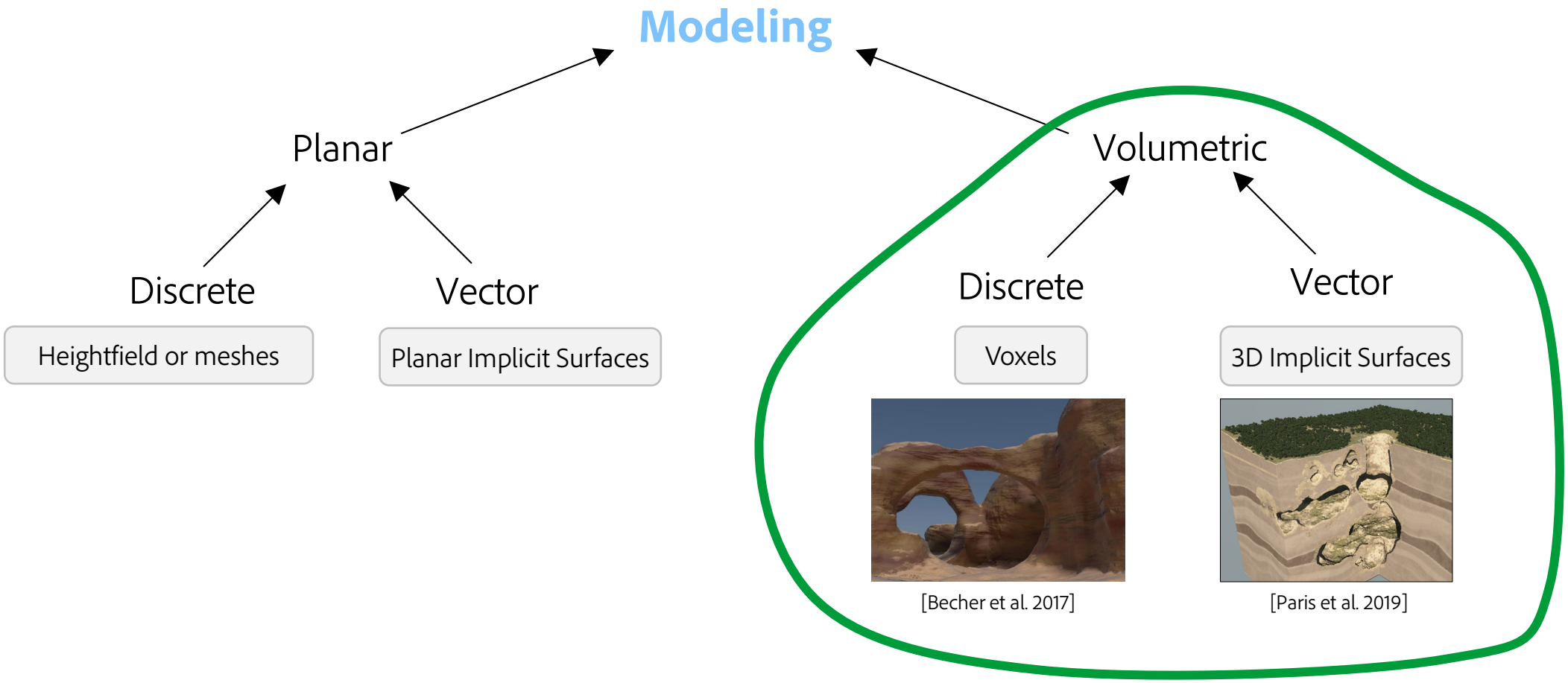
Planar representation (heightfields) are handy…

Scalable, easy meshing, level of detail…

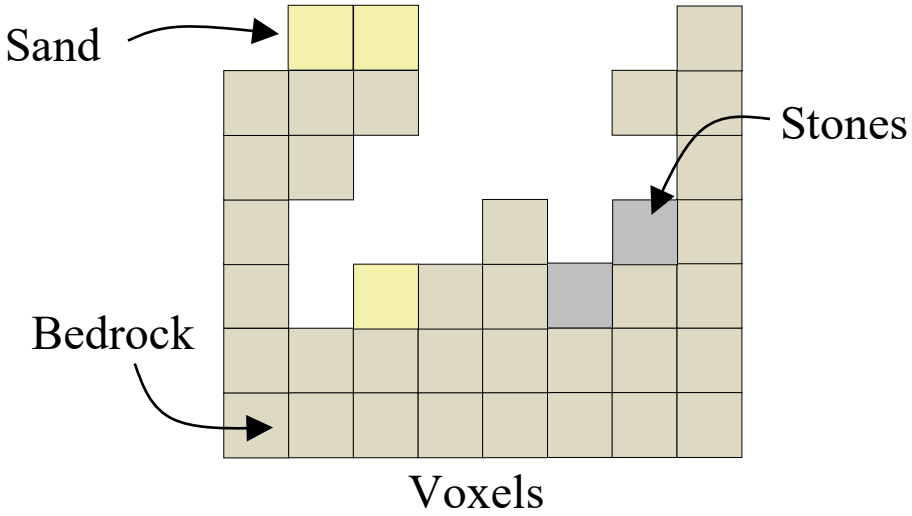
…But they **cannot represent volumetric features**

Overhangs, caves, arches…

Volumetric models to the rescue

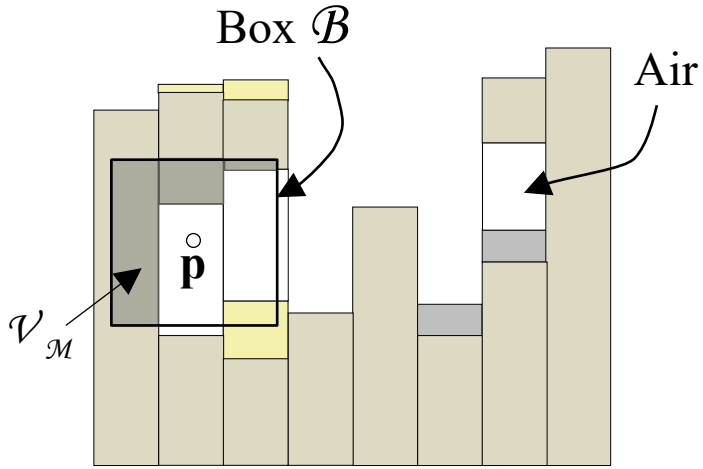


Modeling: volumetric terrains



Voxels

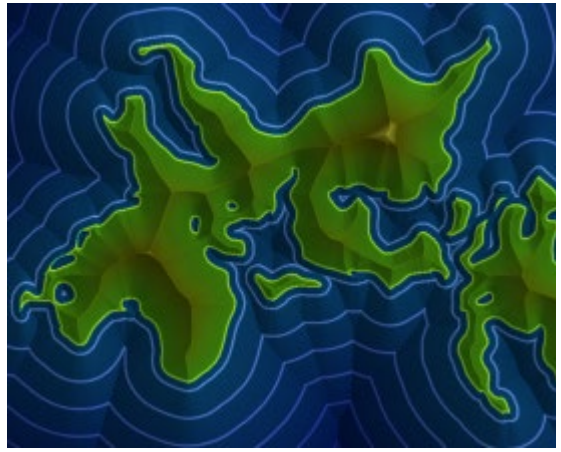
Easy to manipulate
Limited resolution
High memory footprint



Layer Stacks

Easy to manipulate
High memory footprint
More computationally demanding

Peytavie et al. 2009



[Source]

Implicit

Compact in memory
Intuitive manipulation
Computationally intensive!

Paris et al. 2019

Lots of attention
in general
these past years

Generation for volumetric models

Some work on Voxel models [Ito 2003, Beardall 2007, Jones 2010, Becher 2018]

Jones et al. 2010

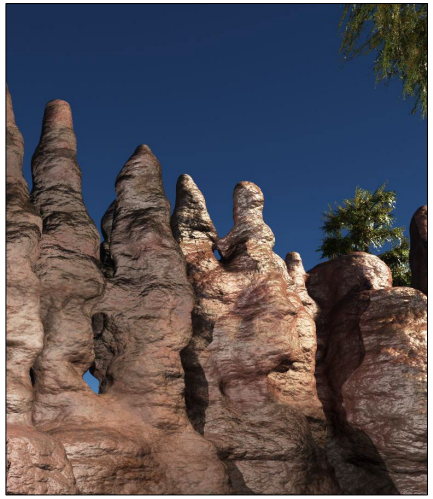
Recent: lots of generation technique for **implicit terrains**

Main topic of my PhD

Invasion-Percolation

Paris et al. 2019

Open Shape Grammar



Cave Networks

Paris et al. 2021

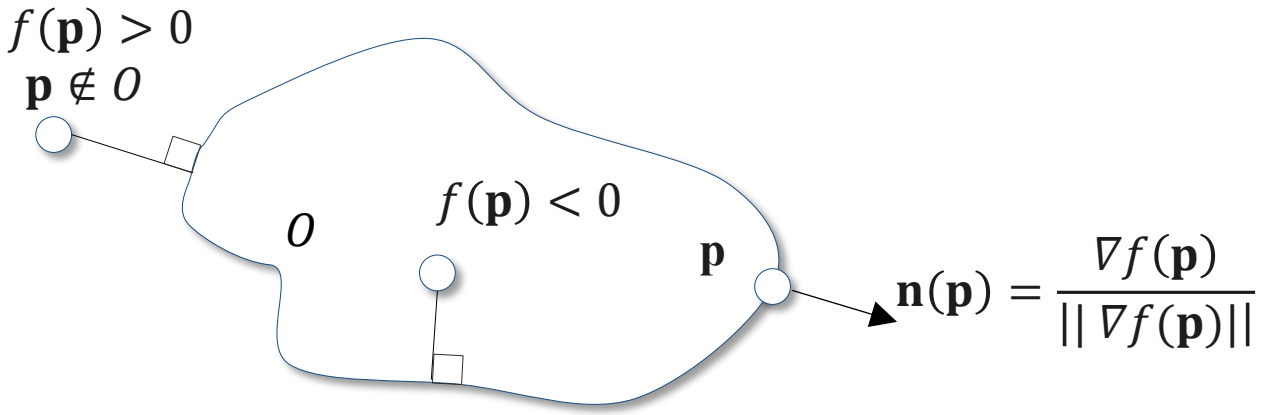
Block structures

Paris et al. 2020

Focus: Volumetric Implicit Terrains

Fundamentals
Procedural implicit surfaces
$S = \{\mathbf{p} \in \mathbf{R}^3 \mid f(\mathbf{p}) = 0\}$

Set aside discrete implicit surfaces [Frisken 2000]



Compact in memory
Expressive modeling
Infinite precision

Focus: Volumetric Implicit Terrains

Signed distance fields (SDFs)

$$f(\mathbf{p}) = \begin{cases} d(\mathbf{p}) & \text{if } \mathbf{p} \notin O \\ 0 & \text{if } \mathbf{p} \in S \\ -d(\mathbf{p}) & \text{otherwise.} \end{cases} \qquad d(\mathbf{p}) = \min_{\mathbf{q} \in S} ||\mathbf{p} - \mathbf{q}||$$

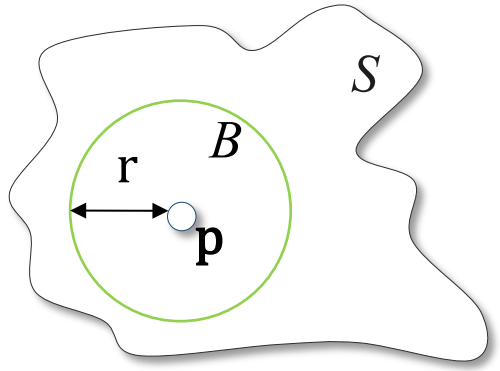
Euclidean distance to the surface

Lipschitz Property

$$\forall (\mathbf{p}, \mathbf{q}) \in \Omega \times \Omega,$$
$$|f(\mathbf{p}) - f(\mathbf{q})| \leq \lambda \, \|\mathbf{p} - \mathbf{q}\|$$

Exclusion criteria

$$\forall \mathbf{p} \in \mathbf{R}^3,$$
$$B(\mathbf{p}, |f(\mathbf{p})|) \cap S = \emptyset$$



$$\mathrm{r} = \frac{|f(\mathbf{p})|}{\lambda}$$

1-Lipschitz SDF $(\lambda = 1)$

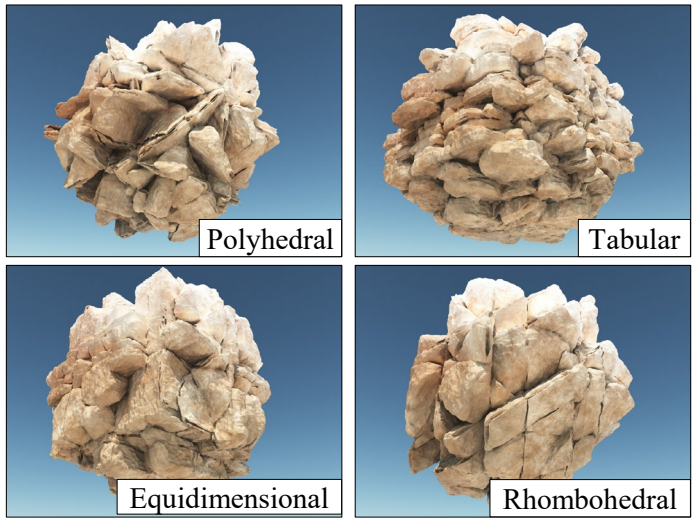
$$\forall \mathbf{p} \in \mathbf{R}^3, \; |b(\mathbf{p})| \leq |f(\mathbf{p})|$$

Lower distance bound to the surface

Focus: Volumetric Implicit Terrains

Problem: generating a variety of volumetric landforms

Approach: different algorithms & primitives for **distinct geological scales**



Micro (few meters)

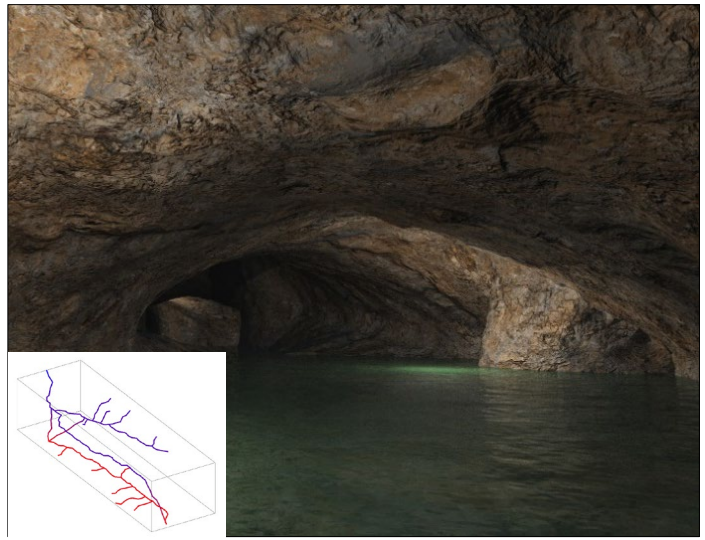
Cliff & blocks

Paris et al. 2020

Méso (a few dozen meters)

Arch, overhangs

Paris et al. 2019



Macro (> 50m)

Deep cave networks

Paris et al. 2022

Volumetric Terrains in the industry

Voxels are common in video games
Can represent large worlds with proper implementation

Volumetric Terrains in the industry

Voxels are common in video games
Can represent large worlds with proper implementation

Not used in Terrain Modeling Softwares!

Lack of standard representation
No interoperability

Volumetric Terrains in the industry

Voxels are common in video games
Can represent large worlds with proper implementation

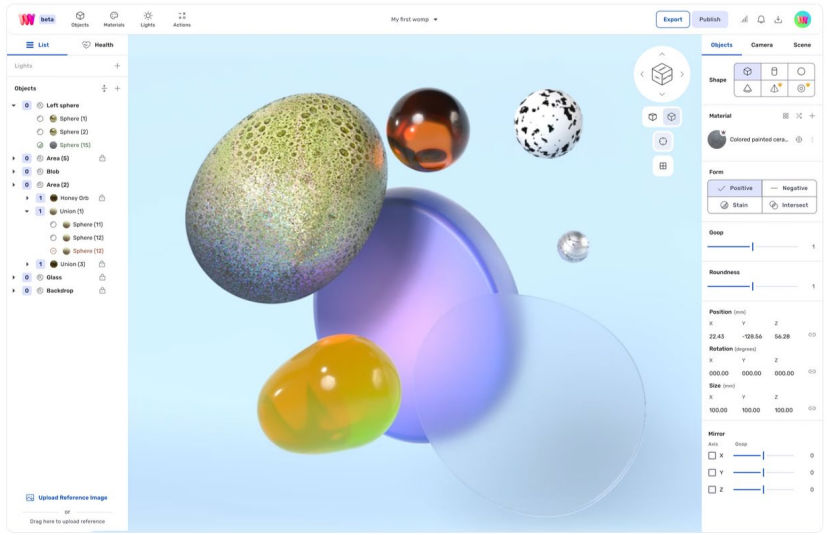
Not used in Terrain Modeling Softwares!

Lack of standard representation
No interoperability

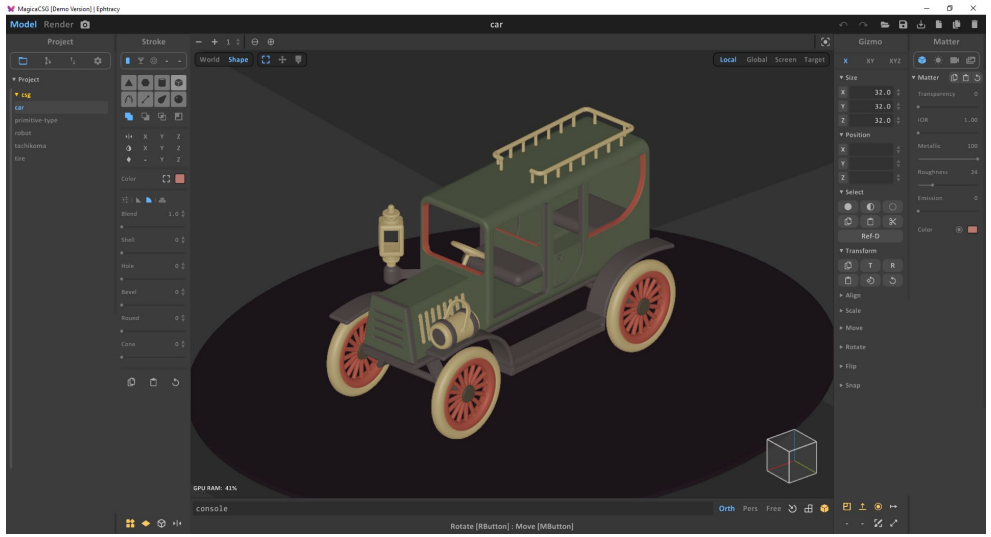
So, implicit surfaces, maybe?

No standard either ☺
But there are implicit modeling softwares!
… often with just export to meshes

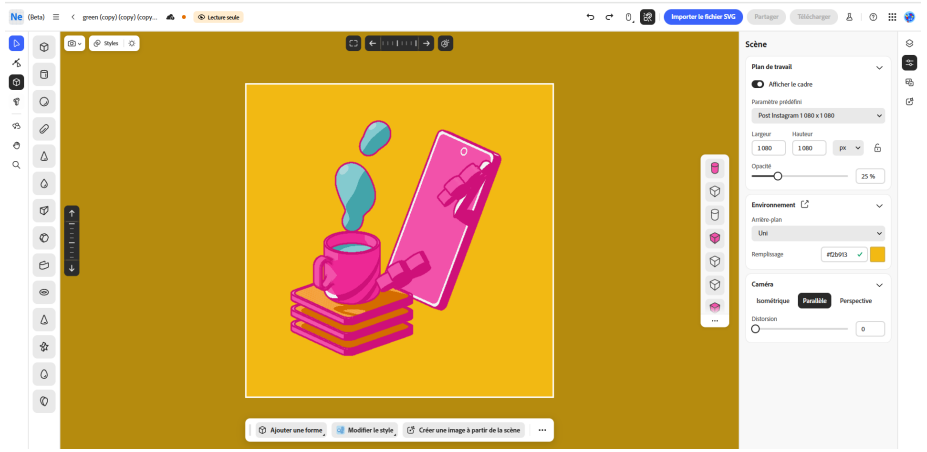
Latest trends: Implicit Modeling everywhere?



Womp3D



Magica CSG



Adobe Neo

All of these have their own format

What’s next?

Trends in Large-scale GenAI

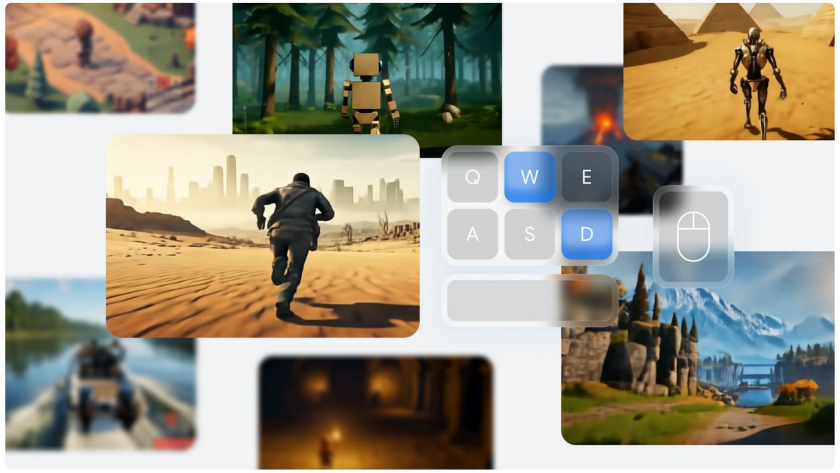
Hot topic for the past two years!

One-click to generate explorable worlds

One-prompt to generate images, videos, 3D worlds…

[Source]

World Labs Image-to-3D-World



[Source]

Genie 2: A large-scale foundation world model

Trends in Large-scale GenAI

Hot topic for the past two years!

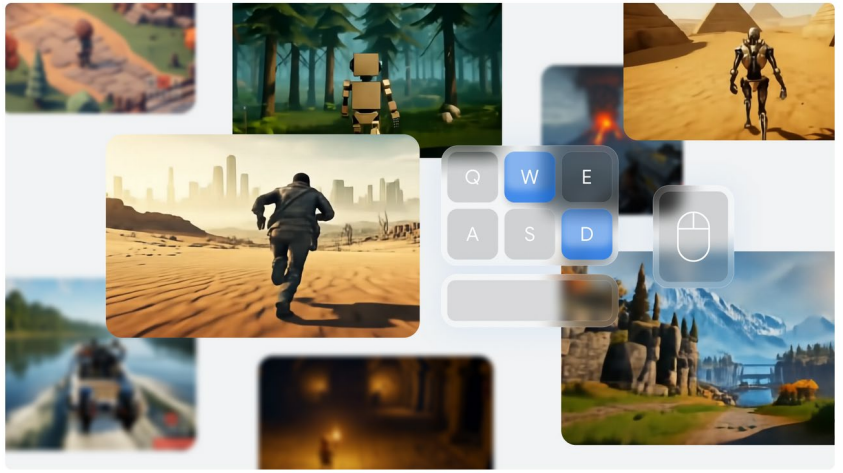
One-click to generate explorable worlds

One-prompt to generate images, videos, 3D worlds…

[Source]

World Labs Image-to-3D-World

Early results



[Source]

Genie 2: A large-scale foundation world model

Not released yet

Trends in Large-scale GenAI

Hot topic for the past two years!

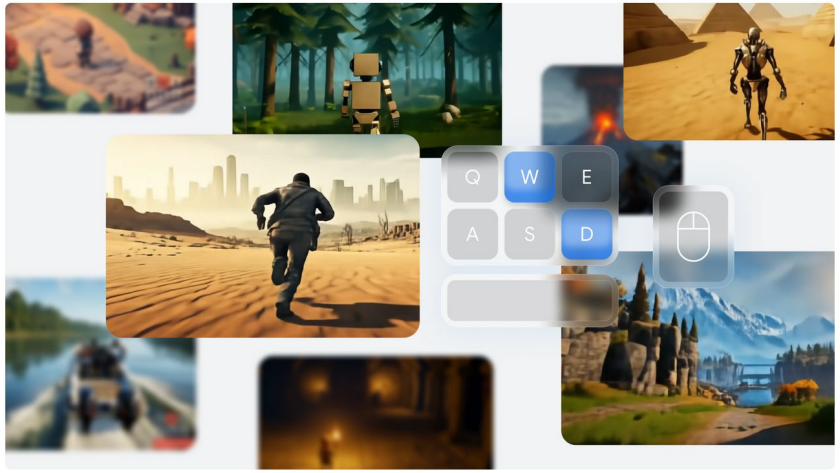
One-click to generate explorable worlds

One-prompt to generate images, videos, 3D worlds…

[Source]

World Labs Image-to-3D-World

Early cherry-picked results



[Source]

Genie 2: A large-scale foundation world model

Not released yet

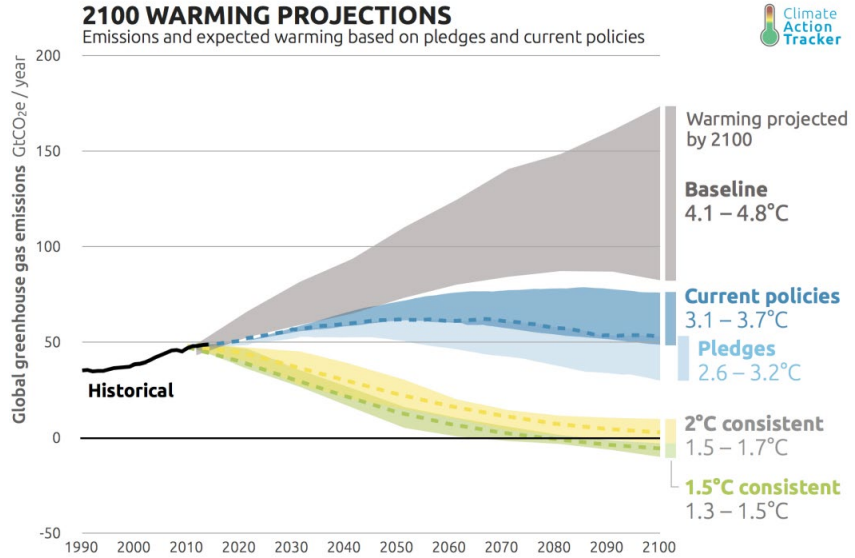
All of this is **very impressive**!

But where is the **control**?

And what's the **cost of all** of this?

Trends in Large-scale GenAI: the not-so-hidden cost

Climate change is a real thing and not looking very good



AI of the last years has **a real impact**

*Compagnies are **failing** at their climate targets*

[Source] July 2, 2024

Carbon reduction continues to be an area of focus, especially as we work to address Scope 3 emissions. In 2023, we saw our Scope 1 and 2 emissions decrease by 6.3% from our 2020 baseline. This area remains on track to meet our goals. But our indirect emissions (Scope 3) increased by 30.9%. In aggregate, across all Scopes 1–3, Microsoft's emissions are up 29.1% from the 2020 baseline.

The rise in our Scope 3 emissions primarily comes from the construction of more datacenters and the associated embodied carbon in building materials, as well as hardware components such as semiconductors, servers, and racks. Our challenges are in part unique to our position as a leading cloud supplier that is expanding its datacenters. But even more, we reflect the challenges the world must overcome to develop and use greener concrete, steel, fuels, and chips. These are the biggest drivers

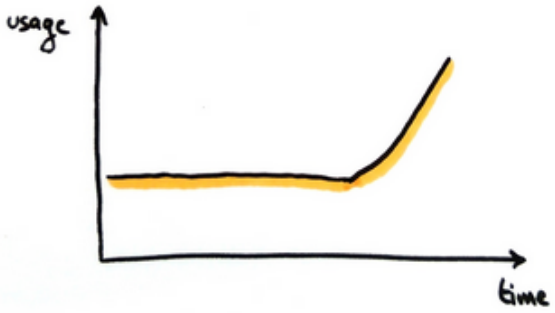
[Source] Microsoft on FY2023

…But this will get optimized, right?

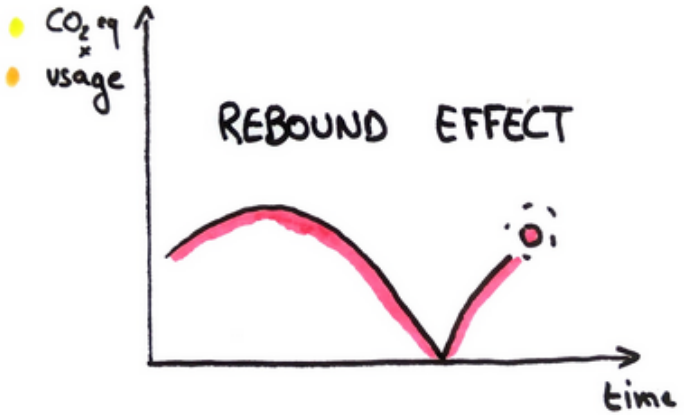
Trends in Large-scale GenAI: the not-so-hidden cost

Here comes the **rebund effect!**

1. Technology gets ***more efficient***



2. ***Usage*** *increases*



3. Global impact gets ***worst***

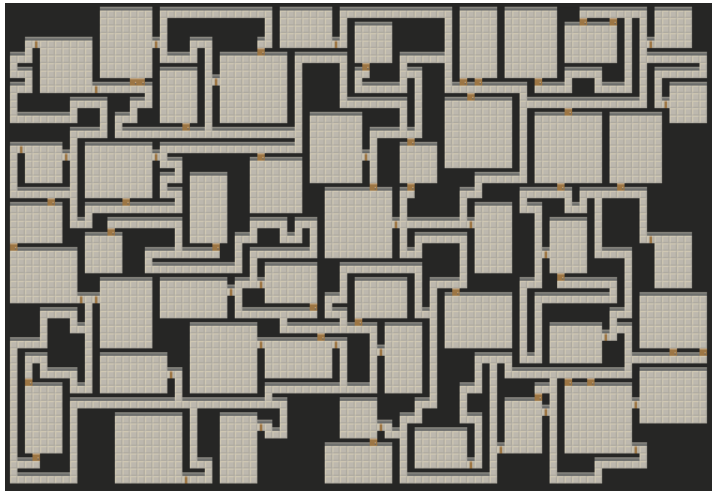
My opinion: we all have a role to play!

Our responsibility as researchers (and people!)

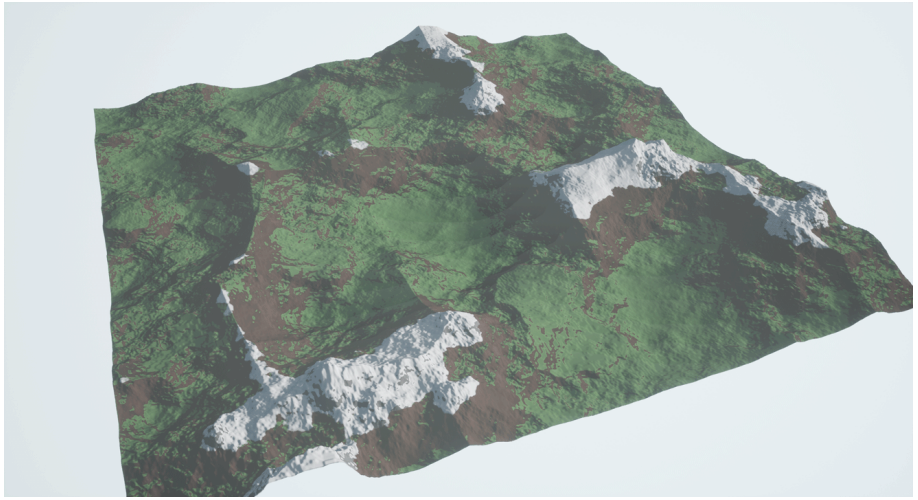
- Do graphics research for **climate-related topics**
  Climate & Ecosystem, Radiative transfers, hurricanes and tornadoes simulation…
- Do research on **lower-end devices**
  Researchers tend to use the latest, cool hardware – inciting other people to renew as well!
- As reviewers: **ask for environmental/energy consumption** reporting in paper
  This is how our community moves forward.
- Ask yourself if AI (and GenAI) is the **right solution** for your problem
- **Don't ignore the issue!**
  When writing annual or multi-year plans, when writing PhD/internship topics, when picking next project

From "The Environmental Impact of Computer Graphics"
Axel Paris, Octave Crespel, Elie Michel
SIGGRAPH 2024 BoF
https://eliemichel.github.io/EnvironmentalImpactsOfComputerGraphics/

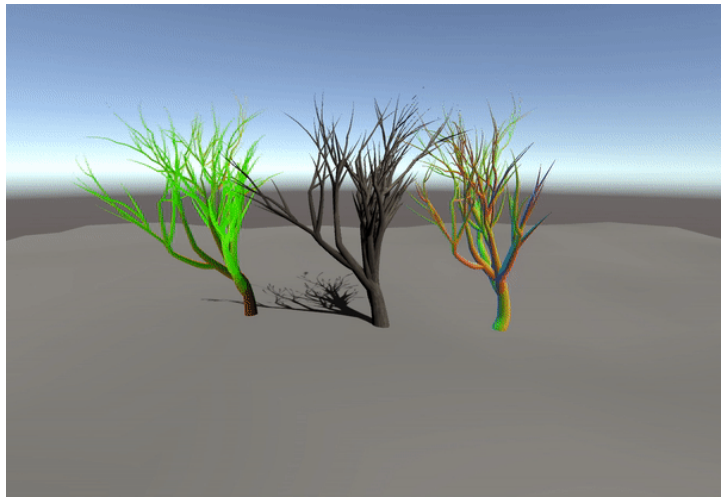
Terrain & World Generation: alternatives



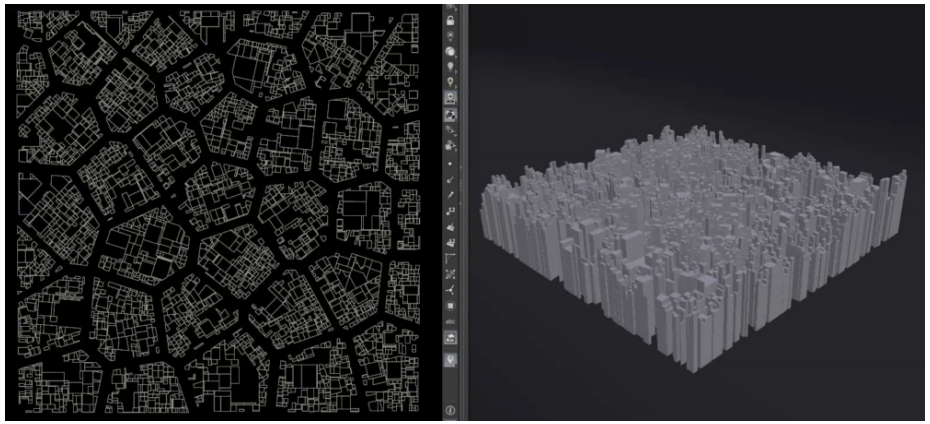
https://imgur.com/this-procedural-dungeon-generator-fRFKp6N



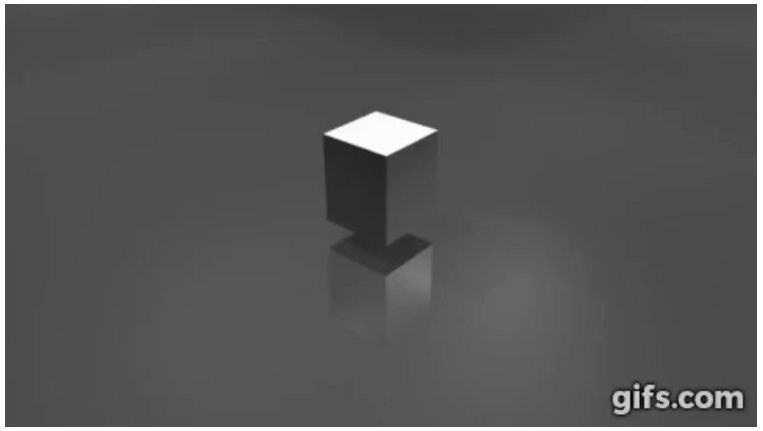
https://imgur.com/HVO6cuL



https://raw.githubusercontent.com/mattatz/unity-procedural-tree/master/Captures/Demo.gif



https://www.artstation.com/artwork/8eQX6R



https://github.com/ldo/blender_spaceship_generator

https://blendermarket.com/products/river-generator

Conclusion

Future work on Terrain Modeling & Generation

Bridge the gap between planar and volumetric models

Work on controllable algorithms & simulations

Collaborate with other scientists: geologists, hydrologists, artists…

Towards an industry standard?
For implicits? For HeightField + Voxels?

Conclusion

Future work on Terrain Modeling & Generation

Towards an industry standard?
For implicits? For HeightField + Voxels?

Bridge the gap between planar and volumetric models
Work on controllable algorithms & simulations
Collaborate with other scientists: geologists, hydrologists, artists…

3D Worlds & GenAI

*Has a **significant environmental impact***
Won't solve everything (or at what cost?)
*Can be a immensely valuable **tool***

As for me: happy to chat & collaborate on those topics!

Thank you!