CSE 167:
Introduction to Computer Graphics
Lecture #17: Procedural Modeling

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Fall Quarter 2020

Announcements

- Tomorrow, Wednesday, November 25th at 1pm:
  - Discussion Project 4
- Sunday, November 29th at 11:59pm:
  - Homework Project 3 due
- Sunday, December 6th at 11:59pm:
  - Homework Project 3 late deadline

Lecture Overview

- Procedural Modeling
  - Concepts
  - Algorithms

3D Modeling

- Creating 3D objects/scenes and defining their appearance (texture, etc.)
- So far we created:
  - triangles with C++ code
  - triangle meshes from OBJ files
- For realistic scenes, we need extremely complex models containing millions or billions of primitives

Alternatives

- Data-driven modeling
  - Scan model geometry from real world examples
  - Use laser scanners or similar devices
  - Use photographs as textures

Photograph Rendering

[Levoy et al.]

- Procedural modeling
  - Construct 3D models and/or textures algorithmically

Procedural Modeling

- Wide variety of techniques for algorithmic model creation
- Used to create models too complex (or tedious) to build manually
  - Terrain, clouds
  - Plants, ecosystems
  - Buildings, cities

[Deussen et al.]

- Usually defined by a small set of data, or rules, that describes the overall properties of the model
  - Example: tree defined by branching properties and leaf shapes
- Model is constructed by an algorithm
  - Often includes randomness to add variety
  - E.g., a single tree pattern can be used to model an entire forest

Example: No Man's Sky

- Players are free to perform within the entirety of a procedurally generated deterministic open world universe, which includes over 18 quintillion (10^{18}) planets. Through the game's procedural generation system, planets have their own ecosystems with unique forms of flora and fauna, and various sentient alien species may engage the player in combat or trade within planetary systems.
- https://www.youtube.com/watch?v=nLtmEjqzg7M

Randomness

- Use some sort of randomness to make models more interesting, natural, less uniform
- *Pseudorandom* number generation algorithms
  - Produce a sequence of (apparently) random numbers based on some initial seed value
  - **rand()** generates random number between 0 and 1
- Pseudorandom sequences are repeatable, as one can always reset the sequence
  - **srand(seed)** initializes the random number generator
  - If the seed value is changed, a different sequence of numbers will be generated
  - Non-repeatable sequences can be generated with srand((unsigned)time(NULL));

Lecture Overview

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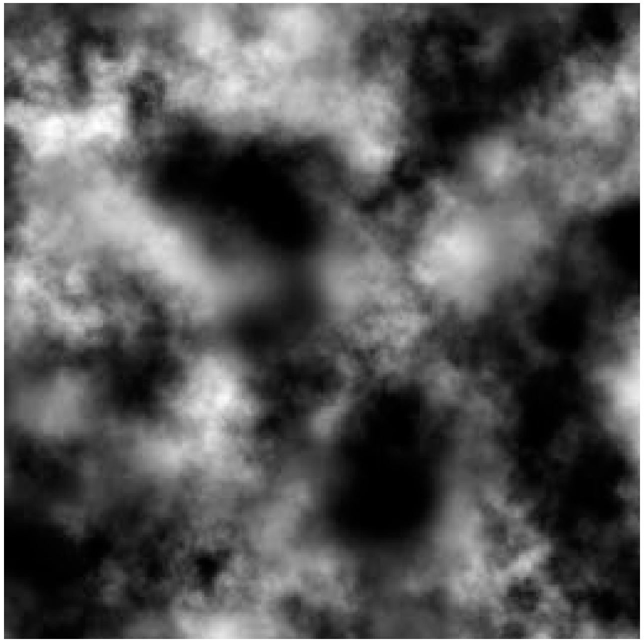
Height Fields

Height Fields

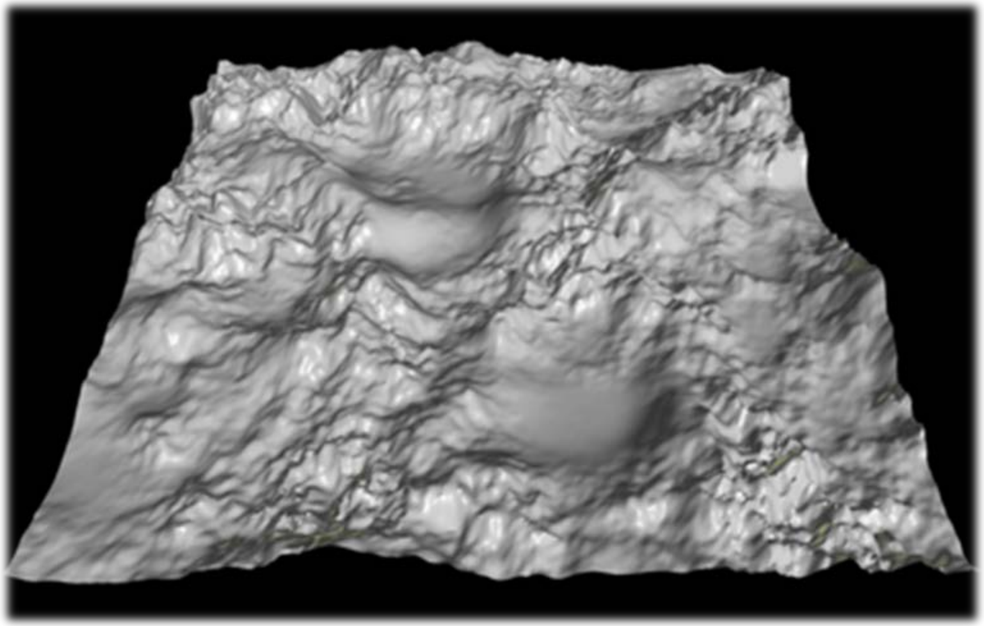
- Landscapes are often constructed as *height fields*
- Regular grid on the ground plane
- Store a height value at each point
- Can store large terrain in memory
  - No need to store all grid coordinates: inherent connectivity
- Shape terrain by operations that modify the height at each grid point

Height Map

- Can generate height from gray scale values
  - Allows using image processing tools to create terrain height



Height map



Height map converted to a 3D mesh

Source: https://en.wikipedia.org/wiki/Heightmap

Coloring

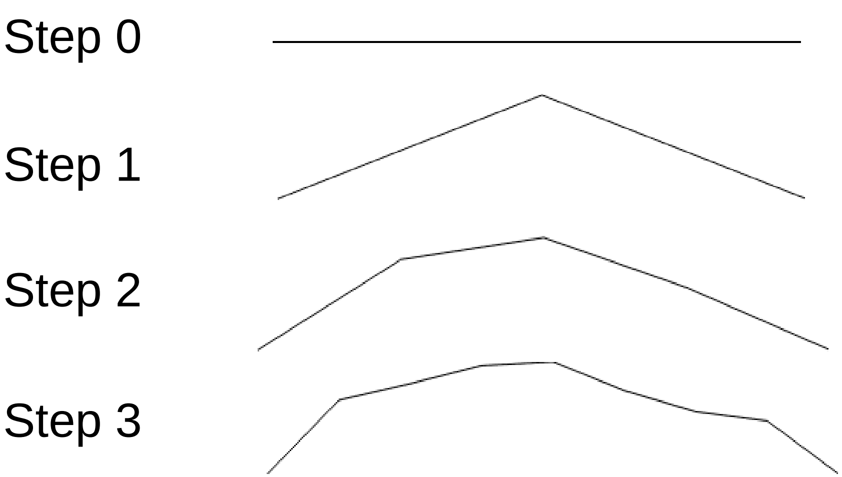
- Elevation based colors:
  - Different elevation ranges get different colors
    - E.g., blue for water, green for vegetation, gray for rocks, white for snow

Midpoint Displacement Algorithm

- Random midpoint displacement algorithm (one-dimensional)

```
Start with single horizontal line segment.
Repeat for sufficiently large number of times
{
   Repeat over each line segment in scene
   {
      Find midpoint of line segment.
      Displace midpoint in Y by random amount.
      Reduce range for random numbers.
   }
}
```

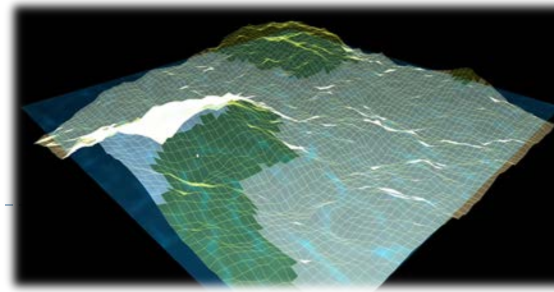
- Similar for triangles, quadrilaterals



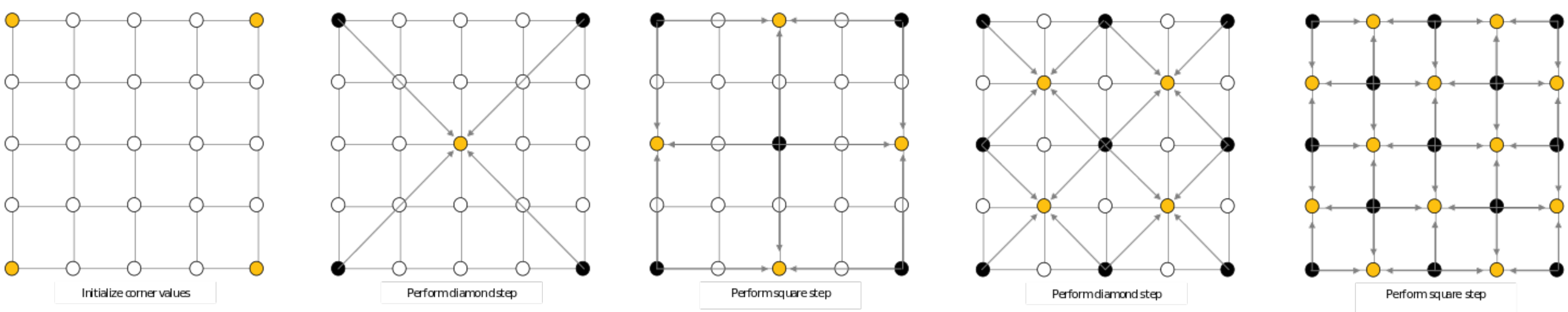
Result: Mountain Range

Source: http://gameprogrammer.com/fractal.html#midpoint

Diamond Square Algorithm

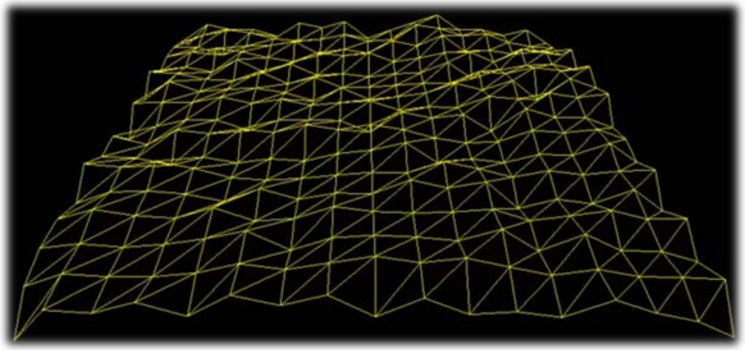


- Begins with a 2D array of size $2^n + 1$
- Four corner points must be set to initial values.
- Perform diamond and square steps alternatingly:
  - The diamond step: for each square in the array, set the midpoint of that square to be the average of the four corner points plus a random value.
  - The square step: for each diamond in the array, set the midpoint of that diamond to be the average of the four corner points plus a random value.
    - Points located on edges of the array will have only three adjacent values set rather than four: take their average.
- At each iteration, the magnitude of the random value should be reduced.

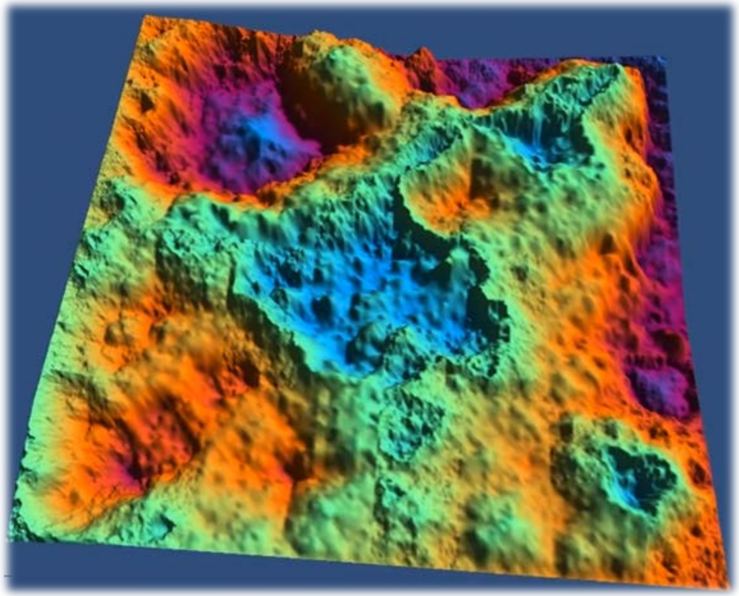


Diamond Square Algorithm: Example

- Increasing mesh sizes:
  - https://www.youtube.com/watch?v=Vx2Rt4Mxk6M



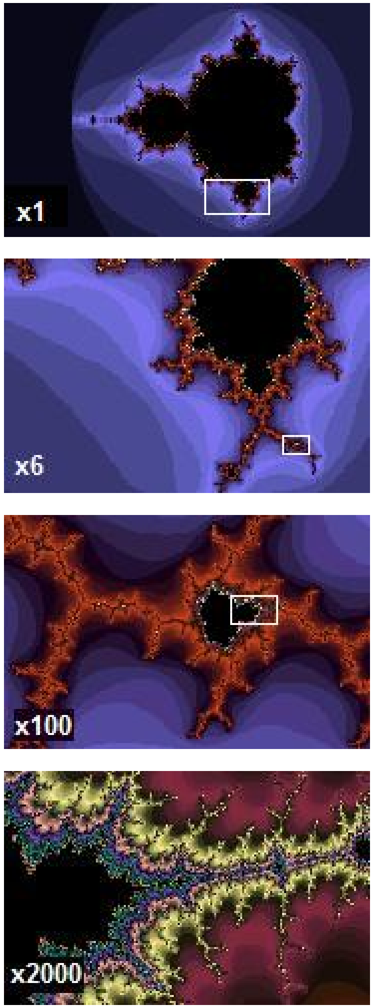
- Terrain examples:
  - https://www.youtube.com/watch?v=5NIs1Ww0N1M



Fractals

Fractals

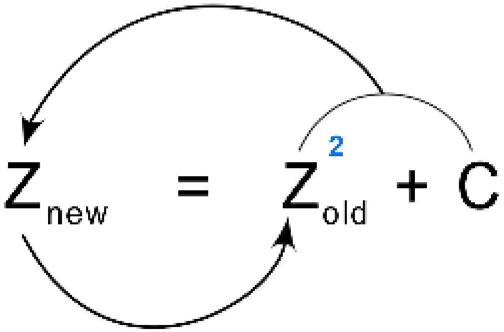
- Fractal:
  Fragmented geometric shape which can be split into parts, each of which is (at least approximately) a smaller size copy of the whole
- Self-similarity



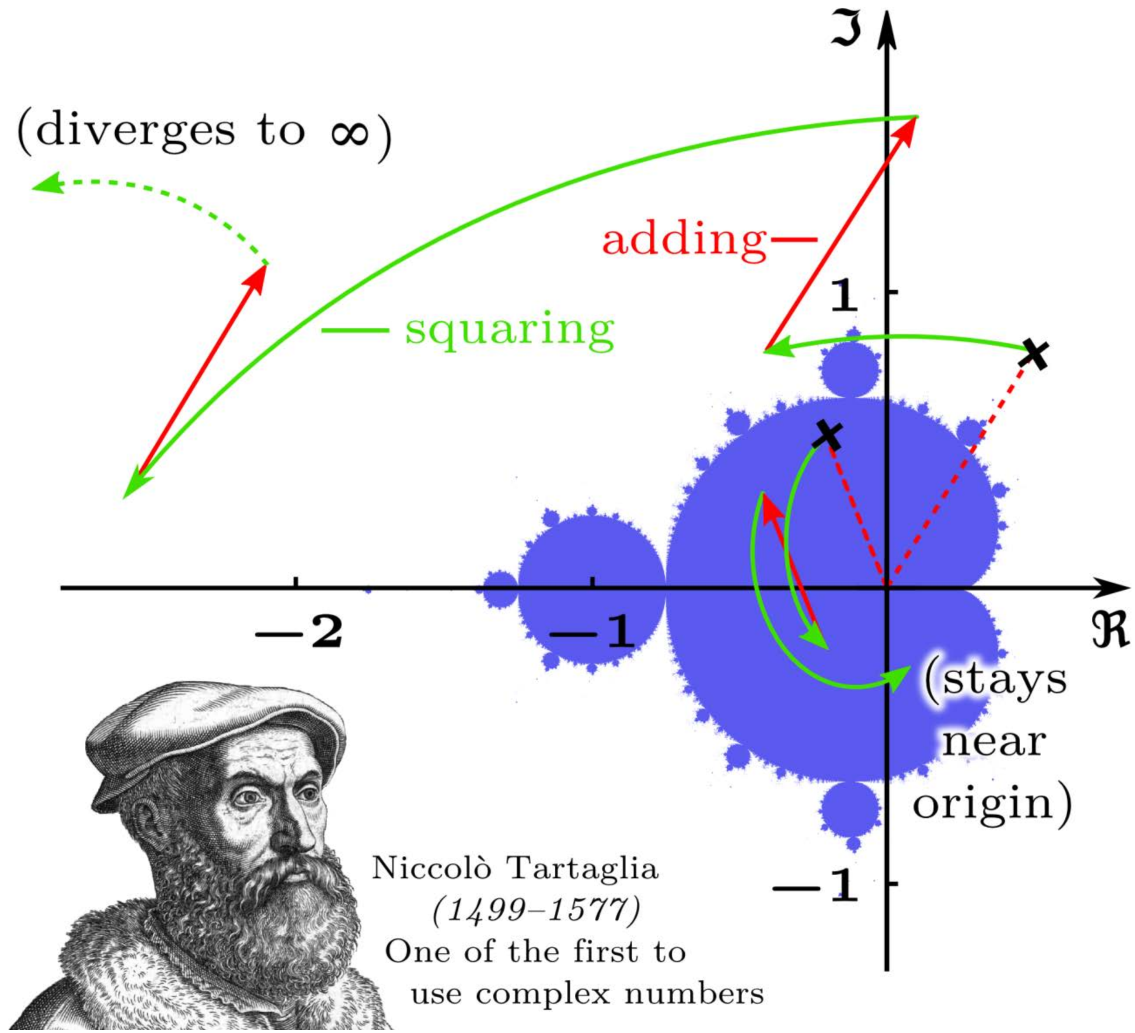
From Wikipedia

Mandelbrot Set

- Z and C are complex numbers
- Initialize Z with 0+0i
- Pick any C



- If C is diverting to infinity it is not part of the Mandelbrot set
- Otherwise it is



Demo: http://www.scale18.com/canvas2.html

Mandelbrot Set: Video

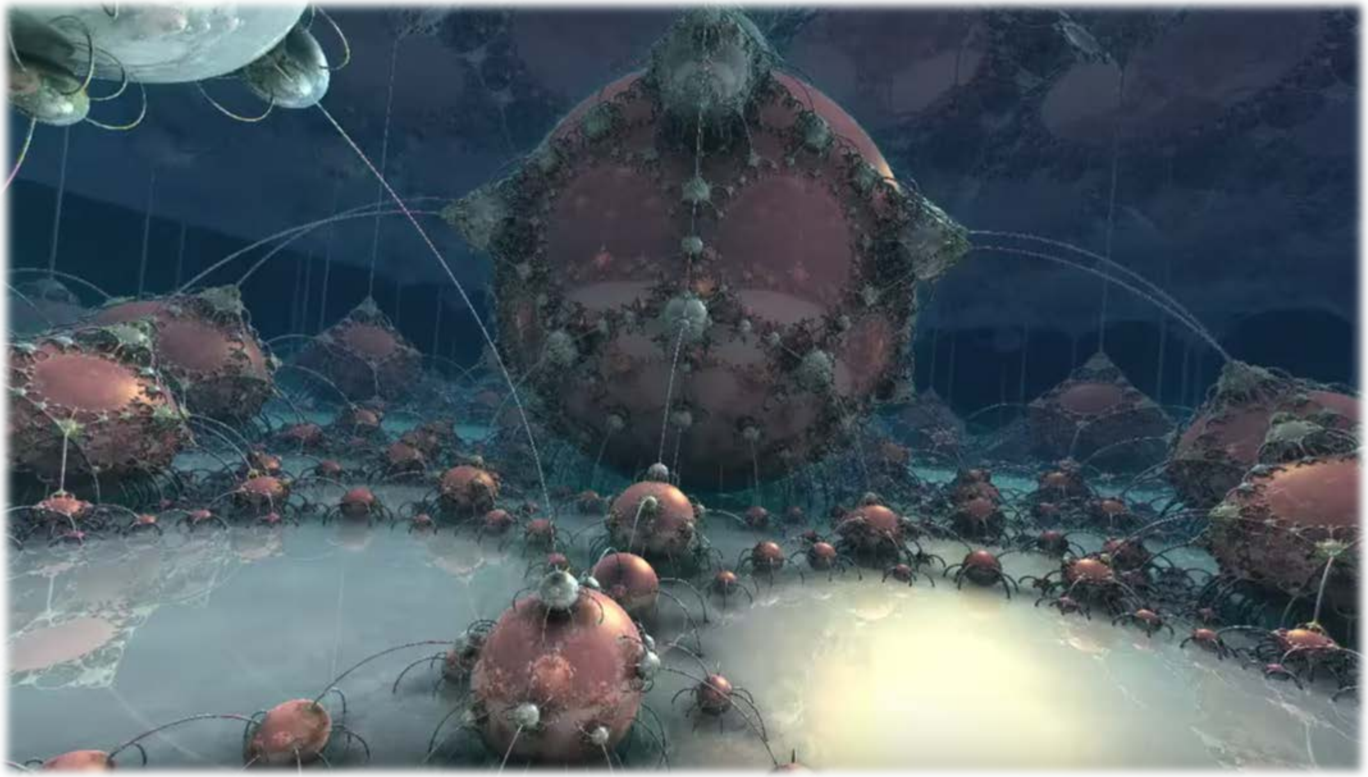
- The Hardest Mandelbrot Zoom in 2017 – New record, 750 000 000 iterations
  - https://www.youtube.com/watch?v=aSg2Db3jF_4

Mandelbox

- A fractal with a boxlike shape found by Tom Lowe in 2010
- Defined in a similar way to the Mandelbrot set
- Can be defined in any number of dimensions, typically drawn in three dimensions for illustrative purposes
- Video
  - http://www.youtube.com/watch?v=0clz6WLfWaY

Real-Time Fractal Rendering

- Trip inside a 3D fractal (Kleinian) GPU realtime rendering
  - https://www.youtube.com/watch?v=XIzScwydxOE



Fractal Landscapes

- Add textures, material properties; use nice rendering algorithm
- Example: Terragen Classic (free software)
  http://www.planetside.co.uk/terragen/

[http://www.planetside.co.uk/gallery/f/tg09]

L-Systems

L-Systems

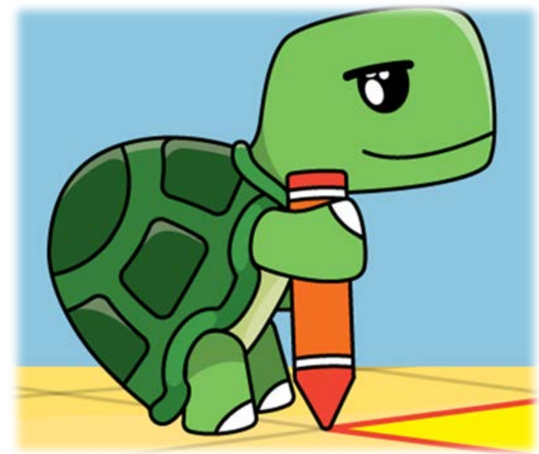
- Developed by biologist Aristid Lindenmayer in 1968 to study growth patterns of algae
- Defined by grammar

$$\mathbf{G} = \{V, S, \omega, P\}$$

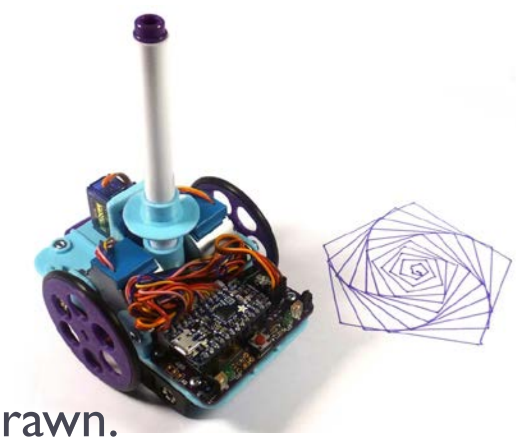
  - V = alphabet, set of symbols that can be replaced (variables)
  - S = set of symbols that remain fixed (constants)
  - ω = string of symbols defining initial state
  - P = production rules
- Stochastic L-system
  - If there is more than one production rule for a symbol, randomly choose one

Turtle Interpretation for L-Systems

- Origin: functional programming language Logo
  - Dialect of Lisp
  - Turtle Graphics for education:
    drove a mechanical turtle as an output device



- Turtle interpretation of strings
  - State of turtle defined by (x, y, α) for position and heading
  - Turtle moves by step size d and angle increment δ



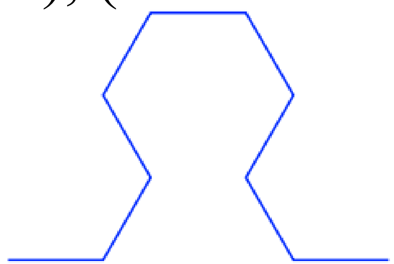
- Sample Grammar
  - F: move forward a step of length d
    New turtle state: (x', y', α)
    $x' = x + d \cos \alpha$
    $y' = y + d \sin \alpha$
    A line segment between points (x, y) and (x', y') is drawn.
  - +: Turn left by angle δ. Next state of turtle is $(x, y, \alpha+\delta)$
    Positive orientation of angles is counterclockwise.
  - −: Turn right by angle δ. Next state of turtle is $(x, y, \alpha-\delta)$

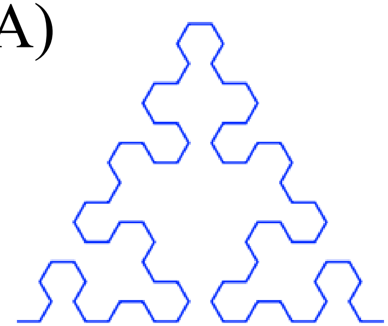
Example: Sierpinski Triangle

- Variables: A, B
  - Draw forward
- Constants: + , -
  - Turn left, right by 60 degrees
- Start: A
- Rules: (A→B-A-B), (B→A+B+A)

1 iteration: B-A-B
2 iterations:
A+B+A - B-A-B - A+B+A

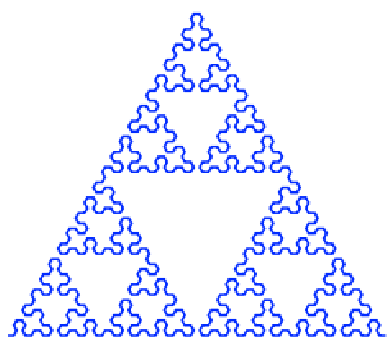
2 iterations

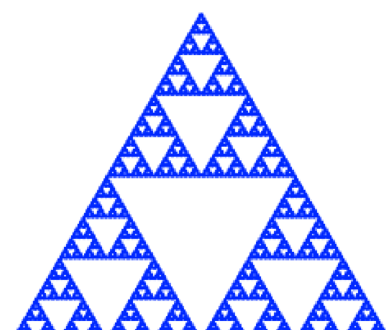




4 iterations

6 iterations





9 iterations

Example: Fern

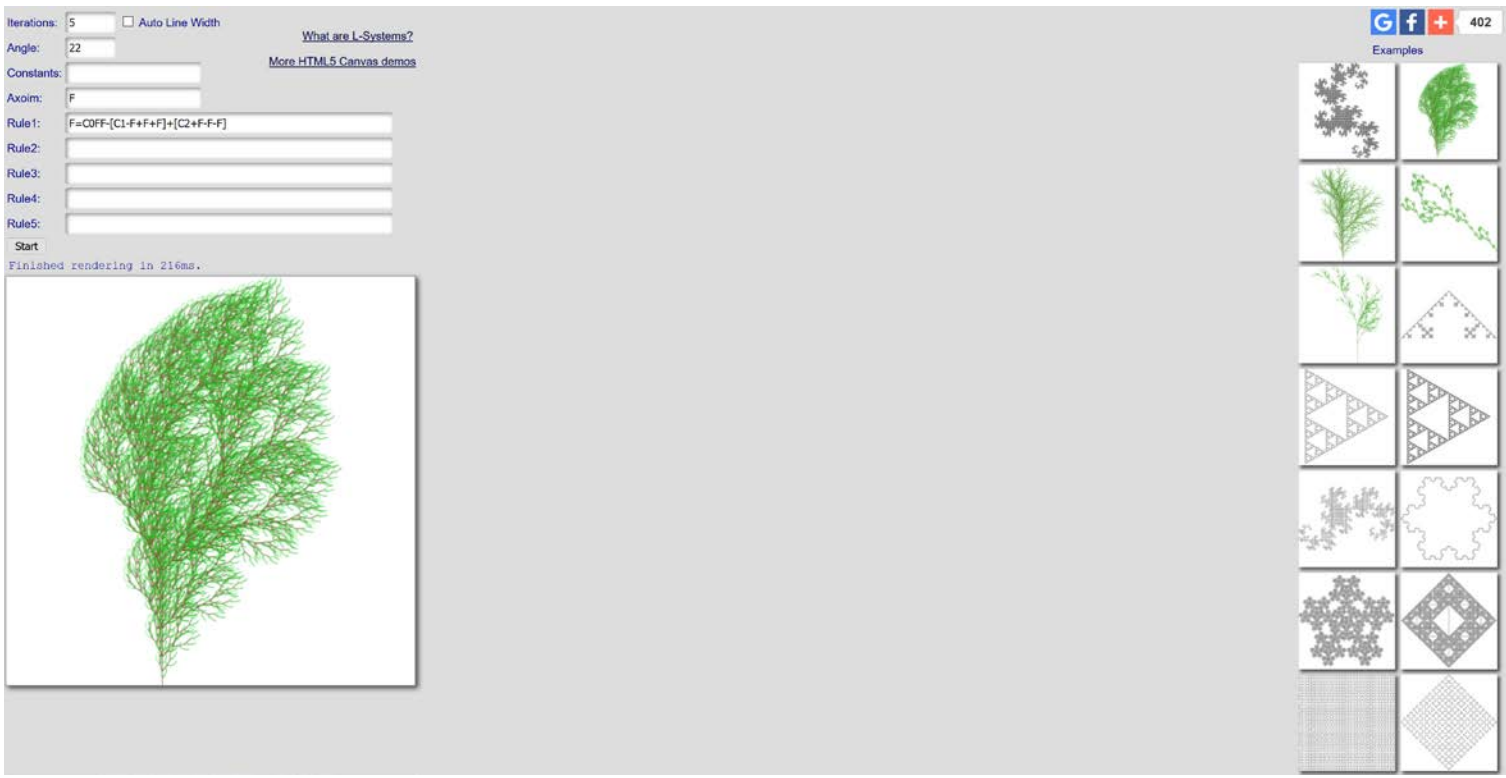
[Wikipedia]

- Variables: X, F
  - X: no drawing operation
  - F: move forward
- Constants: +, −, [,]
  - +: turn left
  - -: turn right
  - [: push current position and angle onto stack
  -] : pop stack and set current position and angle to stack values
- Start: X
- Rules:

$$(X \rightarrow F\text{-}[[X]+X]+F[+FX]\text{-}X),(F \rightarrow FF)$$

Demo

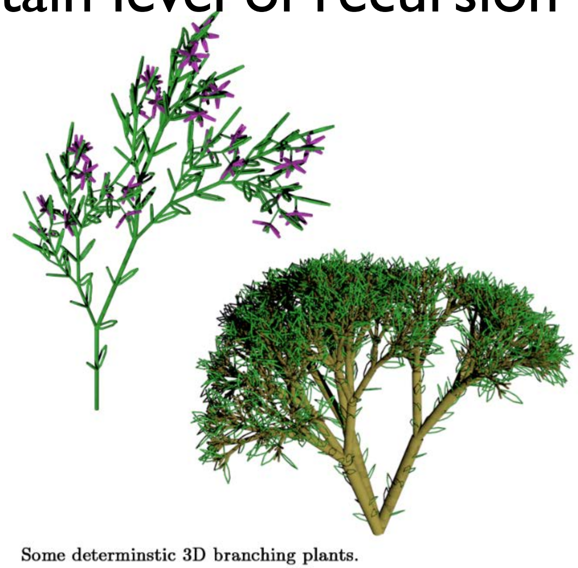
- http://www.kevs3d.co.uk/dev/lsystems/



Fractal Trees

- Paper on recursive generation of L-Systems in 3D: "Real-time 3D Plant Structure Modeling by L-System with Actual Measurement Parameters" by Rawin Viruchpintu and Noppadon Khiripet
- Model trunk and branches as cylinders
- Change color from brown to green at certain level of recursion

Dragon Curve Tree



Source: Allen Pike

Shape Grammar

Shape Grammar

- Shape Rules
  - Defines how an existing shape can be transformed
- Generation Engine
  - Performs the transformations
- Working Area
  - Displays created geometry

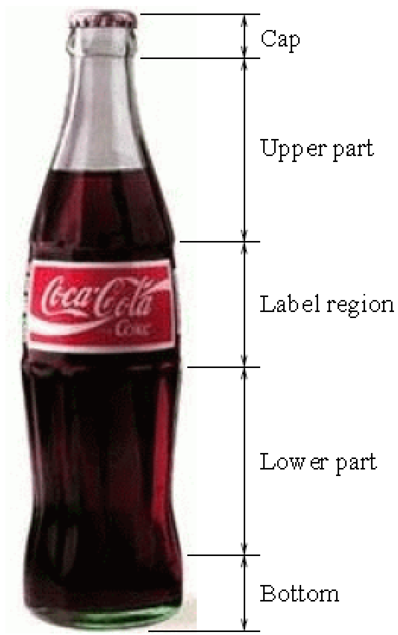
Related Toys

- Mix and match puzzles

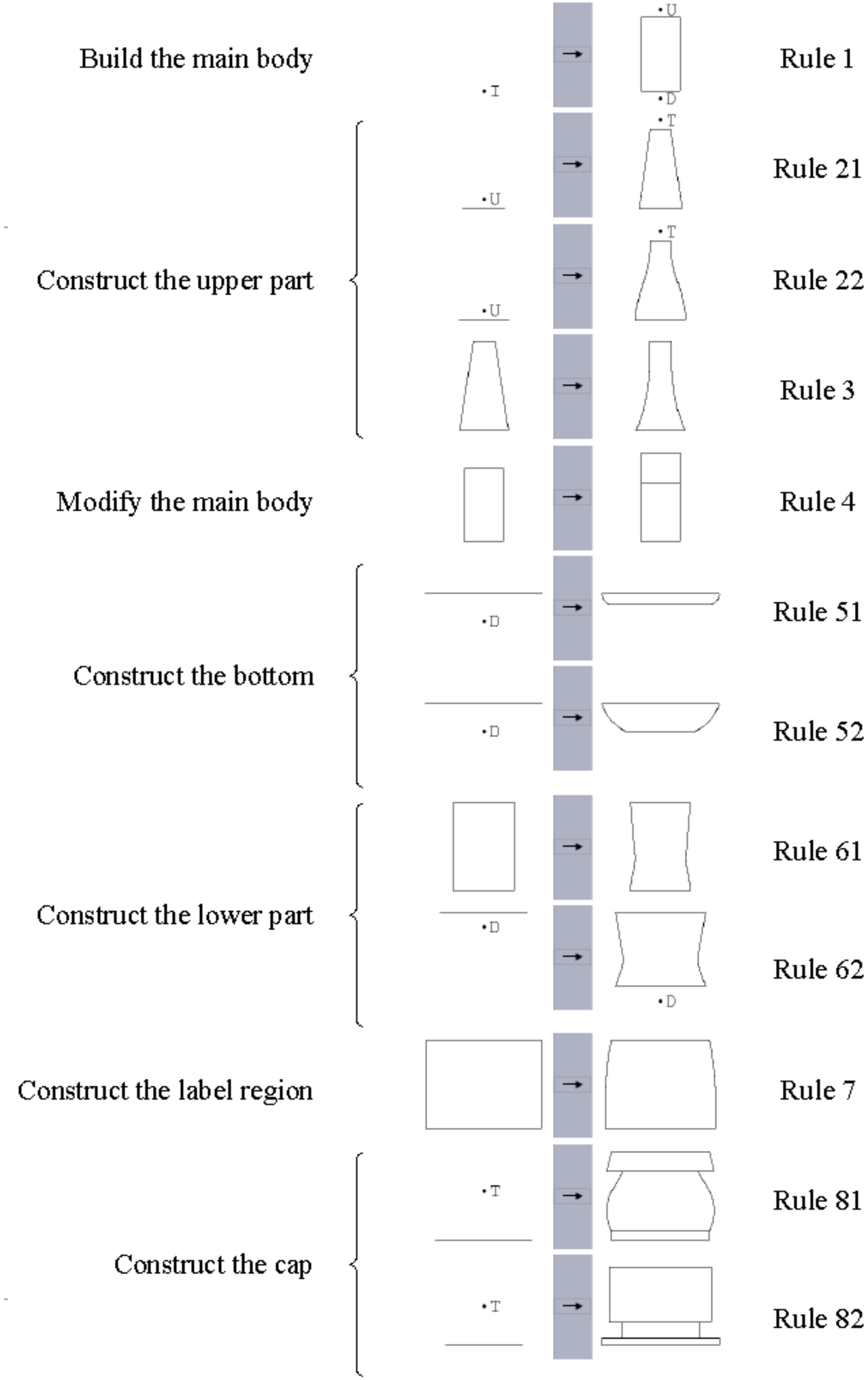
- Lego figures

Example: Coca-Cola Bottle

Evolution of Coca-Cola bottles

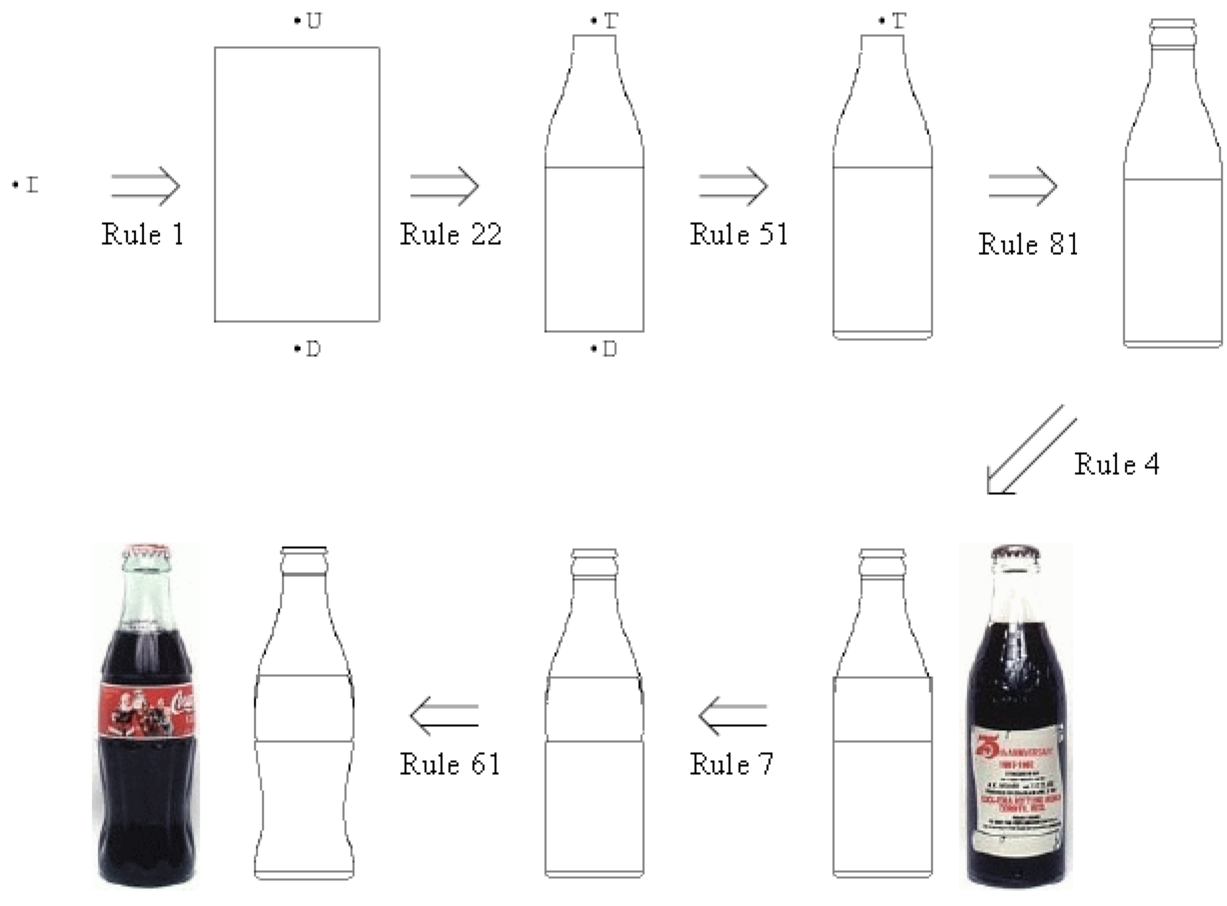


Division of a Coca-Cola bottle



Shape Computation Example

- Shape computation for two existing Coca-Cola bottles



Source: Chau et al.: “Evaluation of a 3D Shape Grammar Implementation”, *Design Computing and Cognition'04,* pp. 357-376

City Modeling

Video

- Procedurally Crafting Manhattan for Marvel's Spider-Man
  - https://www.youtube.com/watch?v=4aw9uyj9MAE

Real-Time Procedural Modeling Demos

- Chaos Theory by DMA
  - Best 4k Intro at Assembly 2011 in Finland
  - https://www.youtube.com/watch?v=2aQtgPv84wE

- Uncovering Static by Fairlight & Alcatraz
  - Best 64k Intro at Assembly 2011 in Finland
  - https://www.youtube.com/watch?v=6sJfMmBtG0k

- More demos at:
  - http://awards.scene.org