Procedural Methods

CS 432 Interactive Computer Graphics
Prof. David E. Breen
Department of Computer Science
Shader Applications

• Moving vertices
  - Wave motion
  - Morphing
  - Particle systems
  - Newtonian dynamics
  - Fractals

• Lighting
  - More realistic models
  - Cartoon shaders
Wave Motion Vertex Shader

uniform float time;
uniform float xs, zs, // frequencies
uniform float h; // height scale
uniform mat4 ModelView, Projection;
in vec4 vPosition;

void main() {
    vec4 t = vPosition;
    t.y = vPosition.y
        + h*sin(time + xs*vPosition.x)
        + h*sin(time + zs*vPosition.z);
    gl_Position = Projection*ModelView*t;
}
Modeling

• Geometric
  - Meshes
  - Hierarchical
  - Curves and Surfaces

• Procedural
  - Particle Systems
  - Fractal
Introduction

• Most important of procedural methods
• Used to model
  - Natural phenomena
    • Clouds
    • Terrain
    • Plants
  - Crowd Scenes
  - Real physical processes
Particle Systems – A Technique for Modeling a Class of Fuzzy Objects

William T. Reeves, Lucasfilm
ACM Transactions on Graphics, 1983

Presented in CS536 by Walt Mankowski
19 October 2006
At the end of the universe lies the beginning of vengeance.

STAR TREK II
THE WRATH OF KHAN

FRANKLIN PICTURES PRESENTS "STAR TREK II: THE WRATH OF KHAN."

Starring: William Shatner, Leonard Nimoy, DeForest Kelley,
James Doohan, Walter Koenig, Nichelle Nichols, Adam West, and
many more. Directed by Leonard Nimoy. Produced by Temple
Porthole As a Visionary. Written by Roddenberry and Star Trek
Producer. Music by Jerry Goldsmith. Additional Editing by
Michael E. Selby. Co-Produced by Robert A. Draper and
Star Trek Producers. Distributed by Paramount Pictures.

Original score from "Star Trek: The Motion Picture."
Genesis Project Demo
Prior to Khan

State of the art in computer animation:

• Static geometric objects
• Primitive surface elements (e.g. polygons)
• Deterministic
• Simple affine transformations
Prior to Khan

State of the art in computer animation:

• Smooth surfaces
• Well-defined
• Shiny surfaces
What about “fuzzy” objects?

- Clouds, smoke, water, fire
- Irregular, ill-defined, complex
- Dynamic
- Fluid
Representation of “fuzzy” objects

• Cloud of primitive particles that define its volume
• Particles are born, move, change form, and die over time
• Stochastic processes are basis for all dynamics
Advantages of particles

• Simpler than polygons
• Easier and faster to compute
• Easier to motion-blur
• Model is procedural and random
• Less human modeling required
• Particle systems are “alive”
• More natural way to represent dynamic motion than polygons
High level view

• System is collection of many of tiny particles (25,000–750,000 in sample frames)
• Over time, particles are added to the system, move and change, and then are removed from the system
For each frame...

- New particles are “born” into the system
- Each new particle is assigned its own individual, random attributes
- Any particles that are too old “die” and are removed from the system
- Remaining particles move and are transformed according to their attributes
- Image is rendered to frame buffer
Particle generation

• For entire frame
  - \( N_{\text{Parts}_f} = \text{MeanParts}_f + \text{Rand}() \times \text{VarParts}_f \)

• For smaller screen area
  - \( N_{\text{Parts}_f} = (\text{MeanParts}_{\text{saf}} + \text{Rand}() \times \text{VarParts}_{\text{saf}}) \times \text{ScreenArea} \)

• Uniformly distributed over a range

• Dynamically change density \( \rightarrow \) Vary mean over all frames
  - \( \text{MeanParts}_f = \text{InitMeanParts} + \text{DeltaMeanParts} \times (f - f_0) \)
Particle attributes

For each new particle, must determine:

- initial position
- initial velocity
- initial size
- initial color
- initial transparency
- shape
- lifetime
Initial position

- sphere
- circle
- rectangle
- etc.

Fig. 1. Typical particle system with spherical generation shape.
Initial settings

- Initial speed is uniformly distributed:
  \[
  \text{InitialSpeed} = \text{MeanSpeed} + \text{Rand()} \times \text{VarSpeed}
  \]

- Color, size, transparency set the same way
Particle dynamics

- To move a particle, just add its velocity vector to its position.

- Can simulate gravity by using an acceleration factor.

- Color, transparency, size controlled by similar rate-of-change parameters.

- Everything is completely deterministic.

Fig. 3. Form of an explosion-like particle system.
Particle extinction

• Remove particles that exceed lifetime
• Can also remove particles that stray outside a window
Particle rendering

Two simplifying assumptions:

• Particles don’t interact with other objects
  - They’re composited in later
  - Added “glow” on planet from the fire with an additional light source

• Each particle is a point light source
  - No hidden surfaces
  - Each particle only contributes to the color of the pixel it covers
Particle hierarchy

- Maintain a tree of particle systems.

- Allows more global control over system.

- In Genesis Demo:
  - Top level was point of impact
  - Particles it generates are themselves other particle systems.

Fig. 2. Distribution of particle systems on the planet's surface.
Motion blur

• Computer animation up to then produced one static image at an instant in time
• This can lead to aliasing and strobing
• They motion-blurred the particles:
  - Calculate position at start of frame and half way through
  - Draw an antialiased line between points
• Stills look blurry but video looks better
• Go to videos

- Making of the Genesis Sequence from Star Trek II
- Particle Dreams
  • Karl Sims
Other applications

Fireworks

Grass
Future directions (circa 1982)

• Clouds
  - difficult to model
  - can throw shadows on themselves
  - very large number of particles

• Water

• More sophisticated motion-blur
Newtonian Particle

- Particle system is a set of particles
- Each particle is an ideal point mass
- Six degrees of freedom
  - Position
  - Velocity
- Each particle obeys Newton's law
  \[ f = ma \]
Particle Equations

\[ \mathbf{p}_i = (x_i, y_i, z_i) \]
\[ \mathbf{v}_i = \frac{d\mathbf{p}_i}{dt} = \mathbf{p}_i' = (dx_i/dt, dy_i/dt, z_i/dt) \]

\[ m \mathbf{v}_i' = \mathbf{f}_i \]

Hard part is defining force vector
Force Vector

• Independent Particles
  - Gravity
  - Wind forces
  - O(n) calculation

• Coupled Particles O(n)
  - Meshes
  - Spring-Mass Systems

• Coupled Particles O(n^2)
  - Attractive and repulsive forces
float time, delta state[6n], force[3n];
state = initial_state();
for(time = t0; time<final_time;
    time+=delta) {
    force = force_function(state, time);
    state = ode(force, state, time,
                              delta);
    render(state, time)
}

• Consider force on particle \( i \)
  \[
f_i = f_i(p_i, v_i)
\]
• Gravity \( f_i = g \)
  \[
g_i = (0, -g, 0)
\]
• Wind forces
• Drag
  - \( f(-v_i) \)

\[ p_i(t_0), v_i(t_0) \]
uniform vec3 init_vel;
uniform float g, m, t;
uniform mat4 Projection, ModelView;
in vPosition;
void main(){
    vec3 object_pos;
    object_pos.x = vPosition.x + vel.x*t;
    object_pos.y = vPosition.y + vel.y*t - g/(2.0*m)*t*t;
    object_pos.z = vPosition.z + vel.z*t;
gl_Position = Projection*ModelView*vec4(object_pos,1);
}
Meshes

• Connect each particle to its closest neighbors
  - $O(n)$ force calculation

• Use spring-mass system
Spring Forces

• Assume each particle has unit mass and is connected to its neighbor(s) by a spring
• Hooke’s law: force proportional to distance \( d = \| \mathbf{p} - \mathbf{q} \| \) between the points

\[ q \quad \mathbf{p} \]
Hooke’s Law

- Let $s$ be the distance when there is no force

$$f = -k_s(|d| - s) \frac{d}{|d|}$$

$k_s$ is the spring constant

$\frac{d}{|d|}$ is a unit vector pointed from $p$ to $q$

- Each interior point in mesh has four forces applied to it
Spring Damping

- A pure spring-mass will oscillate forever.
- Must add a damping term.

\[ f = -(k_s(|d| - s) + k_d \frac{\vec{d} \cdot \vec{d}}{|d|})\frac{d}{|d|} \]

- Must project velocity.
Repulsion

- Inverse square law
  \[ f = \frac{k}{d^2} \]

- General case requires \( O(n^2) \) calculation

- In most problems, the drop off is such that not many particles contribute to the forces on any given particle

- Sorting problem: is it \( O(n \log n) \)?
Boxes

• Spatial subdivision technique
• Divide space into boxes
• Particle can only interact with particles in its box or the neighboring boxes
• Must update which box a particle belongs to after each time step
Linked Lists

- Each particle maintains a linked list of its neighbors
- Update data structure at each time step
- Must amortize cost of building the data structures initially
Solution of ODEs

• Particle system has 6n ordinary differential equations
• Write set as $\frac{du}{dt} = g(u,t)$
• Solve by approximations using Taylor’s Thm
Euler’s Method

\[ u(t + h) \approx u(t) + h \frac{du}{dt} = u(t) + hg(u, t) \]

Per step error is \( O(h^2) \)

Require one force evaluation per time step

Problem is numerical instability

Depends on step size
Improved Euler

\[ u(t + h) \approx u(t) + \frac{h}{2}(g(u, t) + g(u, t+h)) \]

Per step error is \( O(h^3) \)
Also allows for larger step sizes
But requires two function evaluations per step
Also known as Runge-Kutta method of order 2
Contraints

• Easy in computer graphics to ignore physical reality
• Surfaces are virtual
• Must detect collisions separately if we want exact solution
• Can approximate with repulsive forces
Collisions

Once we detect a collision, we can calculate new path
Use coefficient of restitution
Reflect vertical component
May have to use partial time step
Contact Interactions

• Sliding contact
• Normal force that prevents particle from penetrating surface
• Friction force in the tangential direction
Flocks, Herds, and Schools: A Distributed Behavioral Model

Craig W. Reynolds
SIGGRAPH 1987
Presented by Duc Nguyen
November 15, 2007
Simulated Flocks of “Boids”

- Simulate motion of flocks of birds or other animals following individual behaviors
- Extends particle systems
- More realistic (and easier!) than scripting the paths of the individual birds
Prior work

• *Eurythmy* (1985)
  - Flocking simulations used force-fields around each bird and around each object.
  - The animator sets the initial positions, headings, and velocities.

• Other behavioral control work by Karl Sims was based around groups of single objects, not flocks.
Particle Systems

- Particle System is a collection of large number of particles each with their own behaviors
  - At the time of the paper, they were used to model fire, smoke, clouds and ocean waves.
- A Boid is a generalization of a particle
  - Each boid follows a flight model
Boid Model

- Local coordinate system
- Direction of flight
- Bank angle
- Affected by
  - Gravity
  - Centrifugal force
Boid Simulation

- Create a boid model that supports flight
- Add individual behaviors that interact with each other:
  - Separation
  - Alignment
  - Cohesion
  - Obstacle Avoidance
- Boids must be able to arbitrate conflicting behaviors as well
Boid Neighborhood

Only sense boids
  • within a certain distance
  • that are in “front” of you
Boid Behavior: Separation

• Keep a certain distance from neighboring boids
• Steer toward the general heading of neighboring boids
Boid Behavior: Cohesion

• Move toward the average position of neighboring boids
Avoiding Obstacles

• Independently model shape for rendering and collision avoidance
• Boids model uses a *steer-to-avoid* as opposed to force-field approach
Putting it all together

• Simulated flocking behavior that mimics real life flocks, schools and herds
• Combined with a low priority goal seeking results in a scripted path of the flock
• Go to videos

- Boids demo
- Stanley & Stella in Breaking the Ice
Summary

• Boids is a model of group motion of flocks based on actions of individual boids
• Boid simulation is an example of emergent behavior
  - Simple local rules lead to complex global behavior
• This paper (from 1987!) has spawned the field of collective behavior modeling/analysis in physics, biology, artificial life and computer science
Fractals

CS 432 Interactive Computer Graphics
Prof. David E. Breen
Department of Computer Science
Overview

- Fractal representations
- Algorithms for drawing fractals
- Mandelbrot Set
- Brownian Motion
Introduction to Fractals

• Term Fractal coined by Benoit Mandelbrot

• Properties of fractal:
  - Self-similarity (small portion looks like the whole object)
  - Have fractional dimensions
  - Non-differentiable
  - Infinite length

Construction of Koch Curve

Compiled from Gary W. Flake "The Computational Beauty of Nature"
Length of the Fractals

- Lewis Richardson (1961) measured length of coastlines
- Total length increase as measurement stick reduced
- Does this mean coastlines are infinite in length?
Koch Curve

ITERATION NUMBER: 0

http://www.arcytech.org/java/fractals/
Properties of Koch Curve

• Has no tangent at any point
• Length of the curve at iteration $n$ is $(4/3)^n$

<table>
<thead>
<tr>
<th>Step</th>
<th>Num of segments</th>
<th>Length of segment</th>
<th>Total length</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>0.3333333</td>
<td>1.3333333</td>
</tr>
<tr>
<td>2</td>
<td>16</td>
<td>0.1111111</td>
<td>1.7777778</td>
</tr>
<tr>
<td>100</td>
<td>$1.04858 \times 10^{60}$</td>
<td>$1.94033 \times 10^{-48}$</td>
<td>$3.11798 \times 10^{12}$</td>
</tr>
</tbody>
</table>

• Koch curve is 1.26186 ... dimensional object

Compiled from Gary W. Flake “The Computational Beauty of Nature”
Fractal Dimensions

- 1D line of unit length divided into $n$ segments looks like the whole line scaled by $1/n$
- 2D square of unit area divided into $n$ segments looks like the whole square scaled by $1/n^{1/2}$
  - i.e. 4 segments, each one 1/2 the size of the original
- Divide an object into $n$ segments where each segment is scaled by $1/s$
- $s = n^{1/d}$  \quad $d = \log(n)/\log(s)$  \quad $2 = \log(4)/\log(2)$
- The square is divided into 4 parts and each part is 1/2 the size of the original
- $d = \log(4)/\log(2) = 2$
Fractal Dimensions

- \( s = n^{1/d} \quad d = \log(n)/\log(s) \)
- Koch curve divides line into 4 parts, each part is 1/3 the size of the original
- Therefore the dimension of the Koch curve is:

\[
4^{\frac{1}{d}} = 3, \quad n^{1/d} = s
\]

\[
d = \frac{\log(4)}{\log(3)} = \frac{\log(n)}{\log(s)} = 1.26186 \ldots
\]
Space Filling Fractals

- Peano curve (1890)
- Fills a 2D region
- Fractal dimension - 2
- \( s = n^{1/d} \), 9 segments, 1/3 original size
- \( d = \log(9)/\log(3) = 2 \)

Construction of Peano Curve

Compiled from Gary W. Flake "The Computational Beauty of Nature"
Sierpinski Gasket

Rule based:

Repeat n times. As $n \to \infty$
Area $\to 0$
Perimeter $\to \infty$
Not a normal geometric object
Sierpinski Gasket

http://www.arcytech.org/java/fractals/
Examples

• Koch Curve
  - Scale by 3 each time
  - Create 4 new objects
  - $d = \frac{\ln 4}{\ln 3} = 1.26186$

• Sierpinski gasket
  - Scale by
  - Create 3 new objects
  - $d = \frac{\ln 3}{\ln 4} = 1.58496$
Volumetric Examples

d = \ln 4 / \ln 2 = 2

D = \ln 20 / \ln 3 = 2.72683
Naturally Occurring Fractals

- Fractals often occur in nature
- All natural fractals are *grown*
- We can model natural objects with fractals

Compiled from Gary W. Flake “The Computational Beauty of Nature”
In 1968 A. Lindenmayer developed a formalism describing plant growth

Called L-system

L-system consists of:
- Seed cell (axiom)
- Production rules

Axiom: $B$

Rules: $B \Rightarrow F[-B][+B]$
$F \Rightarrow FF$

Compiled from Gary W. Flake “The Computational Beauty of Nature”
<table>
<thead>
<tr>
<th>Species</th>
<th>Angle</th>
<th>Axiom</th>
<th>Rule(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Twig</td>
<td>20</td>
<td>$F$</td>
<td>$F = [[-F]+F]$</td>
</tr>
<tr>
<td>Weed-1</td>
<td>25</td>
<td>$F$</td>
<td>$F = F[-F]F[-F]F$</td>
</tr>
<tr>
<td>Plantlike Fractals 2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Weed-3</th>
<th>Angle: 20</th>
<th>Axiom: F</th>
<th>Rule(s): $F = [[-F][+F][-F]F$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bush-1</th>
<th>Angle: 25</th>
<th>Axiom: F</th>
<th>Rule(s): $F = FF + [+F - F - F] - [-F + F + F]$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Compiled from Gary W. Flake “The Computational Beauty of Nature”
<table>
<thead>
<tr>
<th>Tree-1</th>
<th>Angle: 20</th>
<th>Axiom: $F$</th>
<th>Rule(s): $F = \mathbb{I}[3 - F][3 + F][(3 - F)] + F][F$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td><img src="image1.jpg" alt="Tree-1 Diagram" /></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><img src="image2.jpg" alt="Tree-1 Diagram" /></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><img src="image3.jpg" alt="Tree-1 Diagram" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tree-2</th>
<th>Angle: 8</th>
<th>Axiom: $F$</th>
<th>Rule(s): $F = \mathbb{I}[5 + F][7 - F] - \mathbb{I}[4 + F][6 - F] - \mathbb{I}[3 + F][5 - F] - F$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td><img src="image4.jpg" alt="Tree-2 Diagram" /></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><img src="image5.jpg" alt="Tree-2 Diagram" /></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><img src="image6.jpg" alt="Tree-2 Diagram" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tree-3</th>
<th>Angle: 20</th>
<th>Axiom: $F$</th>
<th>Rule(s): $F = \mathbb{I}[-F][+F] - F$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td><img src="image7.jpg" alt="Tree-3 Diagram" /></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><img src="image8.jpg" alt="Tree-3 Diagram" /></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><img src="image9.jpg" alt="Tree-3 Diagram" /></td>
</tr>
</tbody>
</table>

Compiled from Gary W. Flake “The Computational Beauty of Nature”
Affine Transformation Fractals

• Fractal often described to contain miniature versions of itself.
• We can use affine transformations to describe where these miniatures should be placed
  - Translation
  - Rotation
  - Scaling
• Self-affine fractals may have different scaling factors in different dimensions
Multiple Reduction Copy Machine Algorithm

- Can be simulated with real copy machine
- Copy machine takes a seed image
- Creates several transformed copies of it as an output.
- Procedure is recursive

Compiled from Gary W. Flake "The Computational Beauty of Nature"
MRCM Examples
Problems with MRCM

- To get good image we must compute MRCM to large depth
- Computing time grows exponentially with depth
- Problem amplified when the reduction in size during one iteration is small
Iterated Functional System

- Fractal consist entirely of points
- Randomly and recursively apply affine transformation $L_i(p)$ to point $p$
- Converges to a fractal

500 points  5000 points

Compiled from Gary W. Flake “The Computational Beauty of Nature”
IFS Algorithm

• Pick random point of the seed image
• Randomly pick one of the affine transformations
• Transform the point
• Continue recursively
IFS Generated Tree

Compiled from Gary W. Flake "The Computational Beauty of Nature"
Iteration in the Complex Plane

\[ z_0, z_1 = F(z_0), z_2 = F(z_1), z_3 = F(z_2) \]
Mandelbrot Set

• $x_n = x_{n-1}^2 + c$ for some complex number $c$
  - For some $c$, $x \to 0$ as $n \to \infty$
    $\in$ Mandelbrot Set
  - For some $c$, $x \to \infty$ as $n \to \infty$
  - For others neither

For each $c$ in the complex plane
$x_0 = 0$
for $(n=1$ to $n_{max})$
\{ 
  $x_n = x_{n}^2 + c$
  if ($|x_n| > 2$) break
\}
If $(n < n_{max})$ color $c = \text{white}$
else color $c = \text{black}$

Magnified region from http://www.astro.su.se/~alexis/fractals/
Mandelbrot Set
Mandelbrot Set
Newton Set

\[ f(x) = x^3 - 1 \quad x_{n+1} = x_n - \frac{f(x)}{f'(x)} \]
Phoenix Set

\[ z_{n+1} = z_n^2 + \text{Re}(c) + \text{Im}(c) \cdot z_{n-1} \]
Brownian Motion

- The dance of pollen grains in a water drop (Robert Brown in 1827)
- Explained by Albert Einstein in 1905
- Self-similar motion
- Infinite length
- Used to simulate rivers, mountains, and other random natural phenomena
Fractional Brownian Motion

- Fractional BM (fBM) is a generalization of BM to include memory
  - Integral on progress of random walk
- fBM characterized by its power spectrum
  - BM has $1/f^2$ power spectrum
  - fBM had $1/f^\beta$ power spectrum
    with $1.0 \leq \beta \leq 3.0$
- Think of $\beta$ as controlling terrain roughness
• Landscape generated by the **XMOUNTAINS** program by Steven Booth
• Realistic, self-similar image
XMOUNTAINS: Changing Fractal Dimension
Random Midpoint Displacement

- fBM computations are time consuming
- RMD are faster to compute but less realistic
- Basic idea:
  - Start with 2 (2D) 4 (3D) random points.
  - Compute the midpoint for each interval
  - Displace the midpoint at random but based on the difference between end points
• Generate points $a$ and $b$ at random

$$ y_{mid} = (1/2)(y(a) + y(b)) + r $$

$$ r = s \cdot (|b-a|) \cdot r_g() $$

$s$ - is a surface roughness parameter

$r_g()$ - returns a Gaussian random value (mean = 0, variance = 1)

In 3D version:

$$ y_m = (1/4)(y(a) + y(b) + y(c) + y(d)) + r $$
Controlling the Topography

- To model real environments we want to control the placement of peaks and valleys
- We can do it by setting up Control Surfaces.
- Calculate random elevations based on:
  - Elevation of control surface
  - Average elevation of the midpoint
Fractal Mountains
by Ken Musgrave
Cellular Automata

- Invented by John von Neumann in 1940s
- Thoroughly studied by Wolfram
- Mechanism to study reproduction
- Dynamic system
  - Discrete in space
  - Discrete in time

Compiled from Gary W. Flake “The Computational Beauty of Nature”
• Process which creates seashells has been linked to a one-dimensional CA
Conus Textile Seashell

Source: wikipedia.org