Computer Graphics 543
Lecture 2(Part 3): Fractals

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What are Fractals?

- Mathematical expressions to generate pretty pictures
- Evaluate math functions to create drawings
  - approach infinity -> converge to image
- Utilizes recursion on computers
- Popularized by Benoit Mandelbrot (Yale university)
- Dimensional:
  - Line is 1-dimensional
  - Plane is 2-dimensional
- Defined in terms of self-similarity
Fractals: Self-similarity

- See similar sub-images within image as we zoom in
- Example: surface roughness or profile same as we zoom in
- Types:
  - Exactly self-similar
  - Statistically self-similar
Examples of Fractals

- Clouds
- Grass
- Fire
- Modeling mountains (terrain)
- Coastline
- Branches of a tree
- Surface of a sponge
- Cracks in the pavement
- Designing antennae (www.fractenna.com)
Example: Mandelbrot Set
Example: Mandelbrot Set
Example: Fractal Terrain

Courtesy: Mountain 3D Fractal Terrain software
Example: Fractal Terrain
Example: Fractal Art

Courtesy: Internet Fractal Art Contest
Application: Fractal Art

Courtesy: Internet Fractal Art Contest
Recall: Sierpinski Gasket Program

- Popular fractal
Koch Curves

- Discovered in 1904 by Helge von Koch
- Start with straight line of length 1
- Recursively:
  - Divide line into 3 equal parts
  - Replace middle section with triangular bump, sides of length 1/3
  - New length = 4/3
Koch Curves

$S_0$, $S_1$, $S_2$, $S_3$, $S_4$, $S_5$, $S_6$
Koch Snowflakes

- Can form Koch snowflake by joining three Koch curves
- Perimeter of snowflake grows exponentially:

\[ P_i = 3 \left( \frac{4}{3} \right)^i \]

where \( P_i \) is perimeter of the \( i \)th snowflake iteration
- However, area grows slowly and \( S_\infty = \frac{8}{5} \)
- Self-similar:
  - zoom in on any portion
  - If \( n \) is large enough, shape still same
  - On computer, smallest line segment > pixel spacing
Koch Snowflakes

Pseudocode, to draw $K_n$:

If (n equals 0) draw straight line
Else{
    Draw $K_{n-1}$
    Turn left 60°
    Draw $K_{n-1}$
    Turn right 120°
    Draw $K_{n-1}$
    Turn left 60°
    Draw $K_{n-1}$
}
L-Systems: Lindenmayer Systems

- Express complex curves as simple set of **string-production** rules
- Example rules:
  - ‘F’: go forward a distance 1 in current direction
  - ‘+’: turn right through angle $A$ degrees
  - ‘-’: turn left through angle $A$ degrees
- Using these rules, can express koch curve as: “F-F++F-F”
- Angle $A = 60$ degrees
L-Systems: Koch Curves

- Rule for Koch curves is $F \rightarrow F-F++F-F$
- Means each iteration replaces every ‘F’ occurrence with “F-F++F-F”
- So, if initial string (called the atom) is ‘F’, then
  - $S_1 = “F-F++F-F”$
  - $S_2 = “F-F++F-F- F-F++F-F++ F-F++F-F- F-F++F-F”$
  - $S_3 = .....
- Gets very large quickly
Iterated Function Systems (IFS)

- Recursively call a function
- Does result converge to an image? What image?
- IFS’s converge to an image
- Examples:
  - The Fern
  - The Mandelbrot set
The Fern
Mandelbrot Set

- Based on iteration theory
- Function of interest:

\[ f(z) = (s)^2 + c \]

- Sequence of values (or orbit):

\[
\begin{align*}
  d_1 &= (s)^2 + c \\
  d_2 &= ((s)^2 + c)^2 + c \\
  d_3 &= (((s)^2 + c)^2 + c)^2 + c \\
  d_4 &= ((((s)^2 + c)^2 + c)^2 + c)^2 + c
\end{align*}
\]
Mandelbrot Set

- Orbit depends on $s$ and $c$
- Basic question:
  - For given $s$ and $c$,
    - does function stay finite? (within Mandelbrot set)
    - explode to infinity? (outside Mandelbrot set)
- Definition: if $|d| < 1$, orbit is finite else infinite
- Examples orbits:
  - $s = 0, c = -1$, orbit = $0, -1, 0, -1, 0, -1, 0, -1, ...$ \textit{finite}
  - $s = 0, c = 1$, orbit = $0, 1, 2, 5, 26, 677, ...$ \textit{explodes}
Mandelbrot Set

- Mandelbrot set: use complex numbers for $c$ and $s$
- Always set $s = 0$
- Choose $c$ as a complex number
- For example:
  - $s = 0, c = 0.2 + 0.5i$
- Hence, orbit:
  - $0, c, c^2 + c, (c^2 + c)^2 + c, \ldots$
- Definition: Mandelbrot set includes all finite orbit $c$
Mandelbrot Set

- Some complex number math:
  \[ i \cdot i = -1 \]

- Example:
  \[ 2i \cdot 3i = -6 \]

- Modulus of a complex number, \( z = ai + b \):
  \[ |z| = \sqrt{a^2 + b^2} \]

- Squaring a complex number:
  \[ (x + yi)^2 = (x^2 - y^2) + (2xy)i \]
Mandelbrot Set

- Calculate first 3 terms
  - with $s=2$, $c=-1$
  - with $s = 0$, $c = -2+i$
Mandelbrot Set

- Calculate first 3 terms
  - with $s=2$, $c=-1$, terms are
    
    \[
    \begin{align*}
    2^2 - 1 &= 3 \\
    3^2 - 1 &= 8 \\
    8^2 - 1 &= 63 \\
    \end{align*}
    \]

- with $s = 0$, $c = -2+i$

  \[
  (x + yi)^2 = (x^2 - y^2) + (2xy)i \\
  \begin{align*}
  0 + (-2 + i) &= -2 + i \\
  (-2 + i)^2 + (-2 + i) &= 1 - 3i \\
  (1 - 3i)^2 + (-2 + i) &= -10 - 5i \\
  \end{align*}
  \]
Mandelbrot Set

● **Fixed points:** Some complex numbers converge to certain values after $x$ iterations.

● **Example:**
  - $s = 0$, $c = -0.2 + 0.5i$ converges to $-0.249227 + 0.333677i$ after 80 iterations
  - **Experiment:** square $-0.249227 + 0.333677i$ and add $-0.2 + 0.5i$

● Mandelbrot set depends on the fact the convergence of certain complex numbers
Mandelbrot Set Routine

- Math theory says calculate terms to infinity
- Cannot iterate forever: our program will hang!
- Instead iterate 100 times
- **Math theorem:**
  - if no term has exceeded 2 after 100 iterations, never will!
- Routine returns:
  - 100, if modulus doesn’t exceed 2 after 100 iterations
  - Number of times iterated before modulus exceeds 2, or

\[ s, c \quad \rightarrow \quad \text{Mandelbrot function} \quad \rightarrow \quad \begin{cases} 
\text{Number} < 100 \quad & (\text{first term} > 2) \\
\text{Number} = 100 \quad & (\text{did not explode}) 
\end{cases} \]
Mandelbrot dwell( ) function

\[(x + yi)^2 = (x^2 - y^2) + (2xy)i\]
\n\[(x + yi)^2 + (c_x + c_yi) = [(x^2 - y^2) + c_x] + (2xy + c_y)i\]

```c
int dwell(double cx, double cy)
{
    // return true dwell or Num, whichever is smaller
    #define Num 100 // increase this for better pics
    double tmp, dx = cx, dy = cy, fsq = cx*cx + cy*cy;
    for(int count = 0; count <= Num && fsq <= 4; count++)
    {
        tmp = dx; // save old real part
        dx = dx*dx - dy*dy + cx; // new real part
        dy = 2.0 * tmp * dy + cy; // new imag. Part
        fsq = dx*dx + dy*dy;
    }
    return count; // number of iterations used
}
```
Mandelbrot Set

- Map real part to x-axis
- Map imaginary part to y-axis
- Decide range of complex numbers to investigate. E.g:
  - X in range [-2.25: 0.75], Y in range [-1.5: 1.5]
Mandelbrot Set

- Set world window (ortho2D) range of complex numbers to investigate. E.g
  - X in range [-2.25: 0.75], Y in range [-1.5: 1.5]
- Choose your viewport (glviewport). E.g:
  - Viewport = [V.L, V.R, V.B, V.T] = [60,380,80,240]
Mandelbrot Set

- So, for each pixel:
  - For each point \( c \) in world window call your \( \text{dwell}(\ ) \) function
  - Assign color \(<\text{Red},\text{Green},\text{Blue}>\) based on \( \text{dwell}(\ ) \) return value
- Choice of color determines how pretty
- Color assignment:
  - Basic: In set (i.e. \( \text{dwell}(\ ) = 100 \)), color = black, else color = white
  - Discrete: Ranges of return values map to same color
    - E.g 0 – 20 iterations = color 1
    - 20 – 40 iterations = color 2, etc.
  - Continuous: Use a function
Mandelbrot Set

Use continuous function
Hilbert Curve

- Discovered by German Scientist, David Hilbert in late 1900s
- Space filling curve
- Drawn by connecting centers of 4 sub-squares, make up larger square.
- Iteration 0: To begin, 3 segments connect 4 centers in upside-down U shape

![Iteration 0](image-url)
Hilbert Curve: Iteration 1

- Each of 4 squares divided into 4 more squares
- U shape shrunk to half its original size, copied into 4 sectors
- In top left, simply copied, top right: it's flipped vertically
- In the bottom left, rotated 90 degrees clockwise,
- Bottom right, rotated 90 degrees counter-clockwise.
- 4 pieces connected with 3 segments, each of which is same size as the shrunken pieces of the U shape (in red)
Hilbert Curve: Iteration 2

- Each of the 16 squares from iteration 1 divided into 4 squares
- Shape from iteration 1 shrunk and copied.
- 3 connecting segments (shown in red) are added to complete the curve.
- Implementation? Recursion is your friend!!
Gingerbread Man

- Each new point $q$ is formed from previous point $p$ using the equation

$$q.x = M(1 + 2L) - p.y + |p.x - LM|;$$
$$q.y = p.x.$$

- For 640 x 480 display area, use

$M = 40$  $L = 3$

- A good starting point is (115, 121)
FREE SOFTWARE

- Free fractal generating software
  - Fractint
  - FracZoom
  - Astro Fractals
  - Fractal Studio
  - 3DFract
References