CSCI-4530/6530 Advanced Computer Graphics

http://www.cs.rpi.edu/~cutler/classes/advancedgraphics/S13/

Barb Cutler
cutler@cs.rpi.edu
MRC 331A

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Luxo Jr.

Pixar Animation Studios, 1986

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Topics for the Semester

- Meshes
  - representation
  - simplification
  - subdivision surfaces
  - construction/generation
  - volumetric modeling
- Simulation
  - particle systems, cloth
  - rigid body, deformation
  - wind/water flows
  - collision detection
  - weathering
- Rendering
  - ray tracing, shadows
  - appearance models
  - local vs. global illumination
  - radiosity, photon mapping, subsurface scattering, etc.
- procedural modeling
- texture synthesis
- non-photorealistic rendering
- hardware & more …

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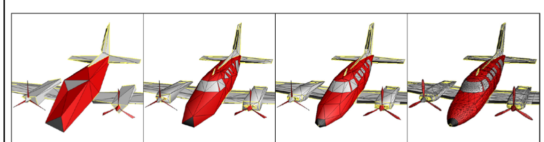
Mesh Simplification



(a) Base mesh M^0 (150 faces) (b) Mesh M^{175} (500 faces) (c) Mesh M^{425} (1,000 faces) (d) Original $\hat{M}=M^n$ (13,546 faces)

Hoppe "Progressive Meshes" SIGGRAPH 1996

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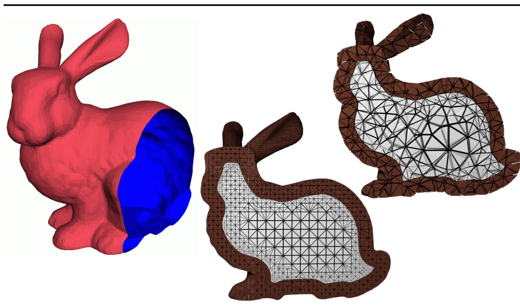
Mesh Generation & Volumetric Modeling



Cutler et al., "Simplification and Improvement of Tetrahedral Models for Simulation" 2004

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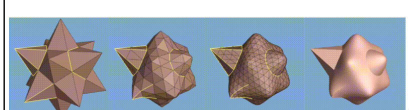
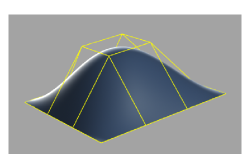
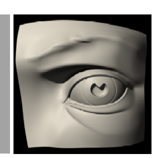
Modeling – Subdivision Surfaces



Hoppe et al., "Piecewise Smooth Surface Reconstruction" 1994





Geri's Game
Pixar 1997

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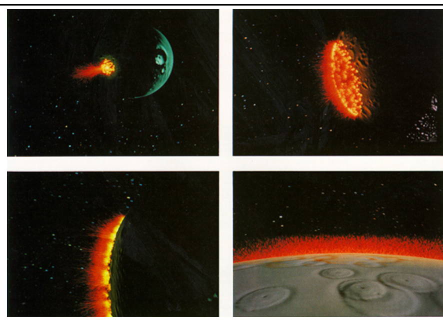
Particle Systems



Star Trek: The Wrath of Khan 1982

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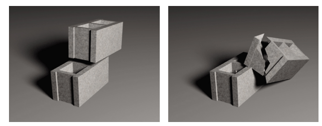
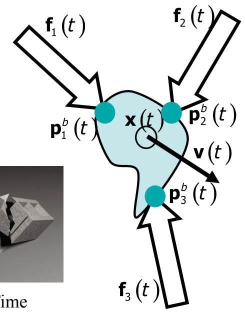
Physical Simulation

- Rigid Body Dynamics
- Collision Detection
- Fracture
- Deformation



Müller et al., "Stable Real-Time Deformations" 2002



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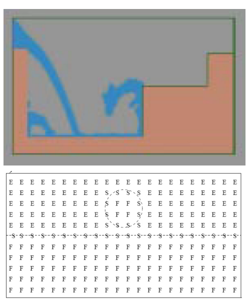
Fluid Dynamics



Foster & Mataxas, 1996

"Visual Simulation of Smoke"
Fedkiw, Stam & Jensen
SIGGRAPH 2001

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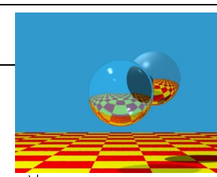
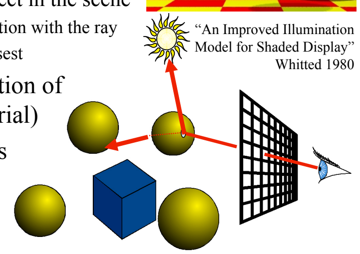
Ray Casting/Tracing

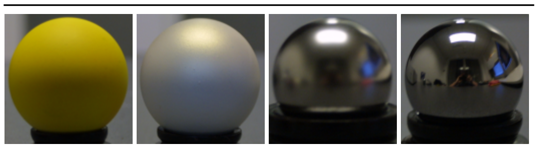
- For every pixel construct a ray from the eye
  - For every object in the scene
    - Find intersection with the ray
    - Keep the closest
- Shade (interaction of light and material)
- Secondary rays (shadows, reflection, refraction)



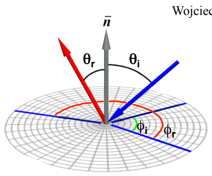
"An Improved Illumination Model for Shaded Display"
Whitted 1980

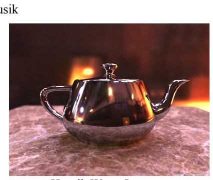


Appearance Models



Wojciech Matusik





Henrik Wann Jensen

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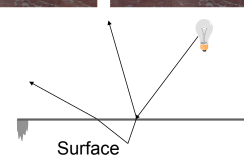
Subsurface Scattering



Jensen et al., "A Practical Model for Subsurface Light Transport" 2001

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Syllabus & Course Website

`http://www.cs.rpi.edu/~cutler/classes/advancedgraphics/S13/`

- Which version should I register for?
  - CSCI 6530 : 3 units of graduate credit, class ends at 3:20
  - CSCI 4530 : 4 units of undergraduate credit, class ends at 3:50

  (same lectures, assignments, quizzes, & grading criteria)
- This is an intensive course aimed at graduate students and undergraduates interested in graphics research, involving significant reading & programming each week. Taking this course in a 5 course overload semester is discouraged.
- Other Questions?

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Participation/Laptops in Class Policy

- Lecture is intended to be discussion-intensive
- Laptops, tablet computers, smart phones, and other internet-connected devices are not allowed
  - Except during the discussion of the day's assigned paper: students may use their laptop/tablet to view an electronic version of the paper
  - Other exceptions to this policy are negotiable; please see the instructor in office hours.

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Introductions – Who are you?

- name
- year/degree
- graphics background (if any)
- research/job interests, future plans
- something fun, interesting, or unusual about yourself

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Outline

- Course Overview
- Classes of Transformations
- Representing Transformations
- Combining Transformations
- Orthographic & Perspective Projections
- Example: Iterated Function Systems (IFS)
- OpenGL Basics

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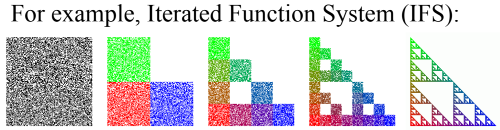
What is a Transformation?

- Maps points (x, y) in one coordinate system to points (x', y') in another coordinate system

$$x' = ax + by + c$$
$$y' = dx + ey + f$$

- For example, Iterated Function System (IFS):



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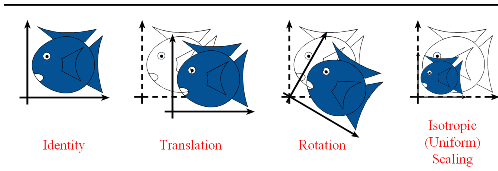
Simple Transformations



- Can be combined
- Are these operations invertible?

  Yes, except scale = 0

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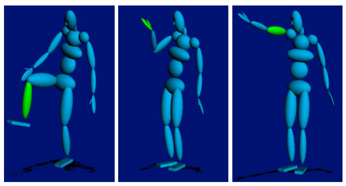
Transformations are used to:

- Position objects in a scene
- Change the shape of objects
- Create multiple copies of objects
- Projection for virtual cameras
- Describe animations



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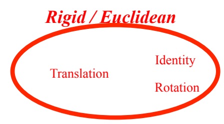
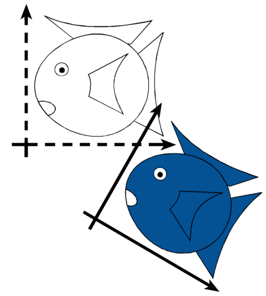
Rigid-Body / Euclidean Transforms

- Preserves distances
- Preserves angles





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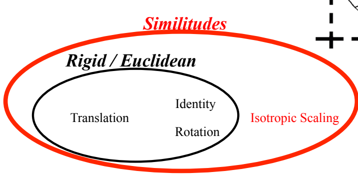
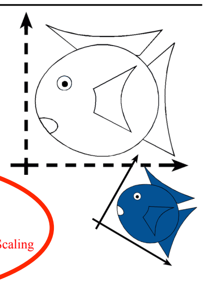
Similitudes / Similarity Transforms

- Preserves angles





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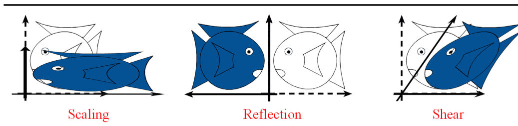
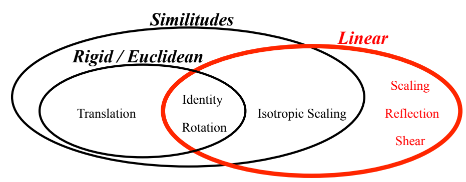
Linear Transformations





$L(p + q) = L(p) + L(q)$ $\qquad L(ap) = a\, L(p)$

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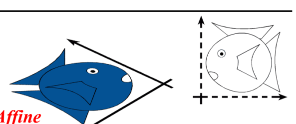
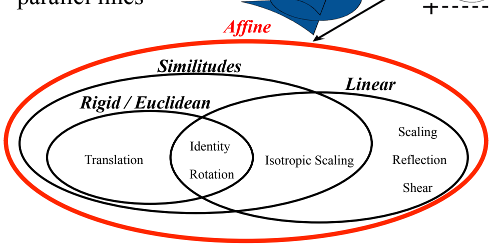
Affine Transformations

- preserves parallel lines





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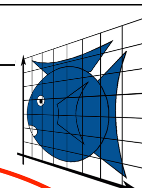
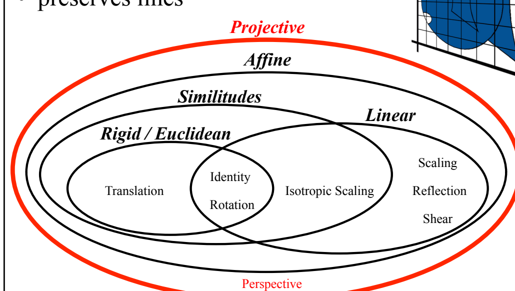
Projective Transformations

- preserves lines





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General (Free-Form) Transformation

- Does not preserve lines
- Not as pervasive, computationally more involved

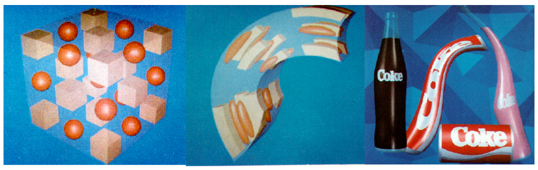

Fig 1. Undeformed Plastic

Fig 2. Deformed Plastic

Sederberg and Parry, Siggraph 1986

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How are Transforms Represented?

$$x' = ax + by + c$$
$$y' = dx + ey + f$$

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} a & b \\ d & e \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} + \begin{pmatrix} c \\ f \end{pmatrix}$$

$$p' = Mp + t$$

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Homogeneous Coordinates

- Add an extra dimension
  - in 2D, we use 3 x 3 matrices
  - In 3D, we use 4 x 4 matrices
- Each point has an extra value, w

$$\begin{pmatrix} x' \\ y' \\ z' \\ w' \end{pmatrix} = \begin{pmatrix} a & b & c & d \\ e & f & g & h \\ i & j & k & l \\ m & n & o & p \end{pmatrix} \begin{pmatrix} x \\ y \\ z \\ w \end{pmatrix}$$

$$p' = Mp$$

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Translation in homogeneous coordinates

$$x' = ax + by + c$$
$$y' = dx + ey + f$$

Affine formulation

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} a & b \\ d & e \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} + \begin{pmatrix} c \\ f \end{pmatrix}$$

$$p' = Mp + t$$

Homogeneous formulation

$$\begin{pmatrix} x' \\ y' \\ 1 \end{pmatrix} = \begin{pmatrix} a & b & c \\ d & e & f \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x \\ y \\ 1 \end{pmatrix}$$

$$p' = Mp$$

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Homogeneous Coordinates

- Most of the time w = 1, and we can ignore it

$$\begin{pmatrix} x' \\ y' \\ z' \\ 1 \end{pmatrix} = \begin{pmatrix} a & b & c & d \\ e & f & g & h \\ i & j & k & l \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix}$$

- If we multiply a homogeneous coordinate by an *affine matrix*, w is unchanged

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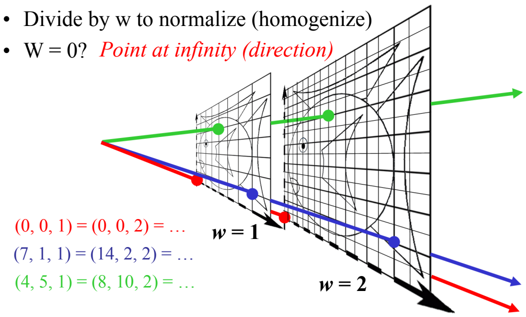
Homogeneous Visualization

- Divide by w to normalize (homogenize)
- W = 0? *Point at infinity (direction)*



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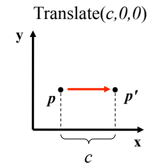
Translate (tx, ty, tz)



- Why bother with the extra dimension?
  Because now translations can be encoded in the matrix!

$$\begin{pmatrix} x' \\ y' \\ z' \\ 1 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & t_x \\ 0 & 1 & 0 & t_y \\ 0 & 0 & 1 & t_z \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix}$$

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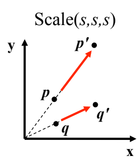
Scale (sx, sy, sz)



- Isotropic (uniform) scaling: $s_x = s_y = s_z$

$$\begin{pmatrix} x' \\ y' \\ z' \\ 1 \end{pmatrix} = \begin{pmatrix} s_x & 0 & 0 & 0 \\ 0 & s_y & 0 & 0 \\ 0 & 0 & s_z & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix}$$

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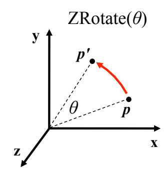
Rotation



- About z axis

$$\begin{pmatrix} x' \\ y' \\ z' \\ 1 \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta & 0 & 0 \\ \sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix}$$

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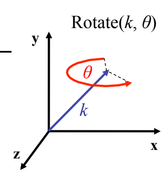
Rotation



- About (k_x, k_y, k_z), a unit vector on an arbitrary axis (Rodrigues Formula)

$$\begin{pmatrix} x' \\ y' \\ z' \\ 1 \end{pmatrix} = \begin{pmatrix} k_xk_x(1-c)+c & k_zk_x(1-c)-k_zs & k_xk_z(1-c)+k_ys & 0 \\ k_yk_x(1-c)+k_zs & k_zk_x(1-c)+c & k_yk_z(1-c)-k_xs & 0 \\ k_zk_x(1-c)-k_ys & k_zk_x(1-c)-k_xs & k_zk_z(1-c)+c & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix}$$

where $c = \cos\theta$ & $s = \sin\theta$

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Storage

- Often, w is not stored (always 1)
- Needs careful handling of direction vs. point
  - Mathematically, the simplest is to encode directions with $w = 0$
  - In terms of storage, using a 3-component array for both direction and points is more efficient
  - Which requires to have special operation routines for points vs. directions

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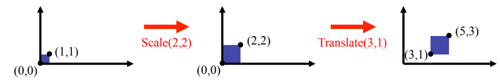
How are transforms combined?

Scale then Translate



Use matrix multiplication: p' = T (S p) = TS p

$$TS = \begin{pmatrix} 1 & 0 & 3 \\ 0 & 1 & 1 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 2 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} 2 & 0 & 3 \\ 0 & 2 & 1 \\ 0 & 0 & 1 \end{pmatrix}$$

Caution: matrix multiplication is NOT commutative!

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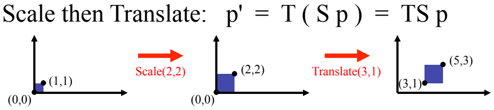
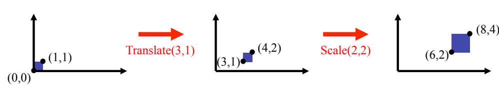
Non-commutative Composition

Scale then Translate: p' = T (S p) = TS p



Translate then Scale: p' = S (T p) = ST p



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Non-commutative Composition

Scale then Translate: p' = T (S p) = TS p

$$TS = \begin{pmatrix} 1 & 0 & 3 \\ 0 & 1 & 1 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 2 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} 2 & 0 & 3 \\ 0 & 2 & 1 \\ 0 & 0 & 1 \end{pmatrix}$$

Translate then Scale: p' = S (T p) = ST p

$$ST = \begin{pmatrix} 2 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 3 \\ 0 & 1 & 1 \\ 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} 2 & 0 & 6 \\ 0 & 2 & 2 \\ 0 & 0 & 1 \end{pmatrix}$$

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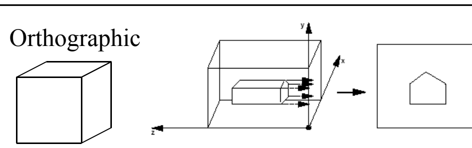
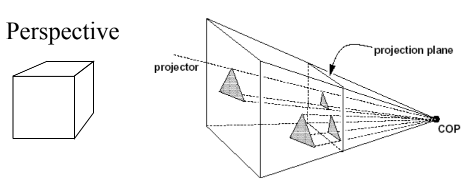
Orthographic vs. Perspective

- Orthographic



- Perspective



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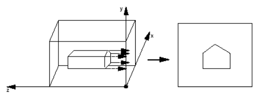
Simple Orthographic Projection

- Project all points along the z axis to the $z = 0$ plane

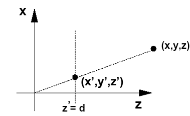


$$\begin{bmatrix} x \\ y \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

Simple Perspective Projection

- Project all points along the z axis to the $z = d$ plane, eyepoint at the origin:

By similar triangles:
x'/x = d/z
x' = (x*d)/z



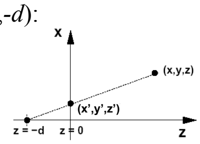
homogenize

$$\begin{bmatrix} x * d / z \\ y * d / z \\ d \\ 1 \end{bmatrix} = \begin{bmatrix} x \\ y \\ z \\ z / d \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 1/d & 0 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

Alternate Perspective Projection

- Project all points along the z axis to the $z = 0$ plane, eyepoint at the (0,0,-d):

By similar triangles:
x'/x = d/(z+d)
x' = (x*d)/(z+d)



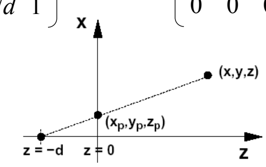
homogenize

$$\begin{bmatrix} x * d / (z + d) \\ y * d / (z + d) \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} x \\ y \\ 0 \\ (z + d) / d \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1/d & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

In the limit, as $d \to \infty$

this perspective projection matrix... → ...is simply an orthographic projection

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1/d & 1 \end{bmatrix} \rightarrow \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$



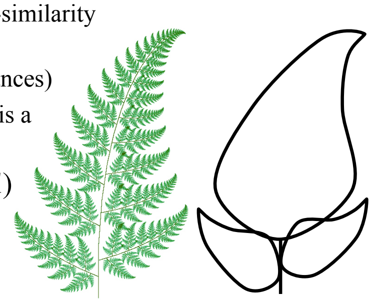
Outline

- Course Overview
- Classes of Transformations
- Representing Transformations
- Combining Transformations
- Orthographic & Perspective Projections
- Example: Iterated Function Systems (IFS)
- OpenGL Basics

Iterated Function Systems (IFS)

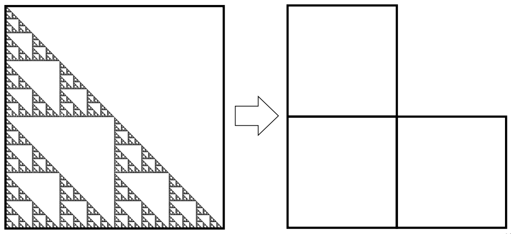
- Capture self-similarity
- Contraction (reduce distances)
- An attractor is a fixed point

$$A = \bigcup f_i(A)$$



Example: Sierpinski Triangle

- Described by a set of n affine transformations
- In this case, $n = 3$
  - translate & scale by 0.5



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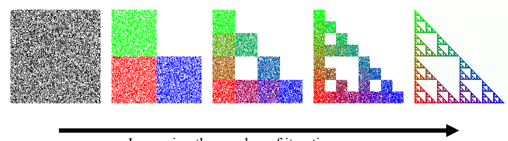
Example: Sierpinski Triangle

```
for "lots" of random input points (x_0, y_0)
   for j=0 to num_iters
      randomly pick one of the transformations
      (x_k+1, y_k+1) = f_i (x_k, y_k)
   display (x_k, y_k)
```



Increasing the number of iterations

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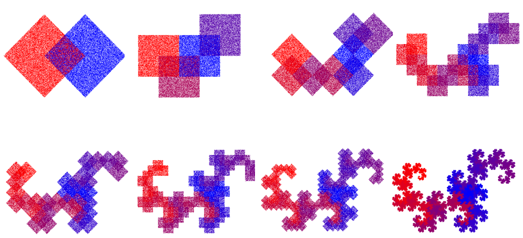
Another IFS: The Dragon



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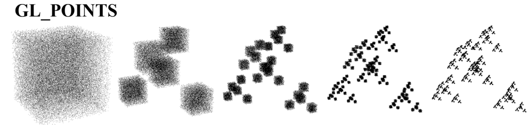
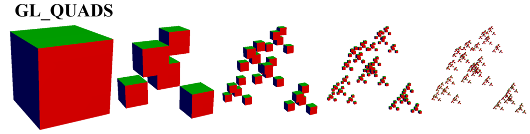
3D IFS in OpenGL

GL_POINTS



GL_QUADS



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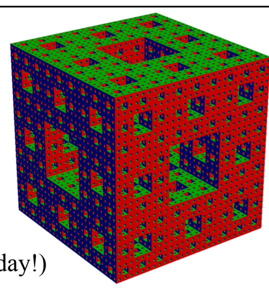
Assignment 0: OpenGL Warmup

- Get familiar with:
  - C++ environment
  - OpenGL
  - Transformations
  - simple Vector & Matrix classes
- Have Fun!
- Due ASAP (start it today!)
- ¼ of the points of the other HWs *(but you should still do it and submit it!)*



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OpenGL

- OpenGL is a “state machine”
- OpenGL has lots of finicky setup & execution function calls
  - omitting a function call, swapping the order of 2 function calls, or passing the “wrong” argument, can result in a blank screen, nothing happens/changes, craziness happens, bus error, seg fault, etc.
- Often usually more than one way to do things
  - often one way is much faster than another
- What is possible depends on your hardware

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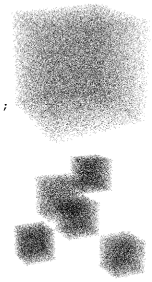
OpenGL Basics: Array Buffer

- **Some useful commands:**

```
/* store data in points array */
glGenBuffers(1, &points_VBO);
glBindBuffer(GL_ARRAY_BUFFER,points_VBO);
glBufferData(GL_ARRAY_BUFFER, ..., points);
glColor3f(0,0,0);
glPointSize(1);
glEnableClientState(GL_VERTEX_ARRAY);
glVertexPointer(...);
glEnableVertexAttribArray(...);
glVertexAttribPointer(...);
glDrawArrays(GL_POINTS, ...);
glDisableClientState(GL_VERTEX_ARRAY);
glDisableVertexAttribArray(...);
```



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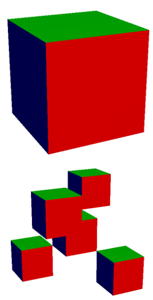
OpenGL Basics: Index Vertex Buffers

- **Some useful commands:**

```
/* store data in verts & faces arrays */
glBindBuffer(GL_ARRAY_BUFFER,cube_verts_VBO);
glBufferData(GL_ARRAY_BUFFER, cube_verts, ...);
glBindBuffer(GL_ELEMENT_ARRAY_BUFFER,
   cube_face_indices_VBO);
glBufferData(GL_ELEMENT_ARRAY_BUFFER,
   cube_face_indices, GL_STATIC_DRAW);
glEnableClientState(GL_VERTEX_ARRAY);
glVertexPointer(... BUFFER_OFFSET(0));
glEnableClientState(GL_NORMAL_ARRAY);
glNormalPointer(..., BUFFER_OFFSET(12));
glEnableClientState(GL_COLOR_ARRAY);
glColorPointer(..., BUFFER_OFFSET(24));
glBindBuffer(GL_ELEMENT_ARRAY_BUFFER,
   cube_face_indices_VBO);
glDrawElements(GL_QUADS, ...);
glDisableClientState(GL_NORMAL_ARRAY);
glDisableClientState(GL_COLOR_ARRAY);
glDisableClientState(GL_VERTEX_ARRAY);
```



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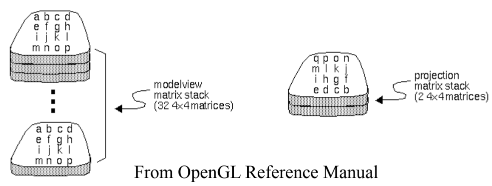
OpenGL Basics: Transformations

- Useful commands:

```
glMatrixMode(GL_MODELVIEW);
glPushMatrix();
glPopMatrix();
glMultMatrixf(…);
```



From OpenGL Reference Manual

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Questions?

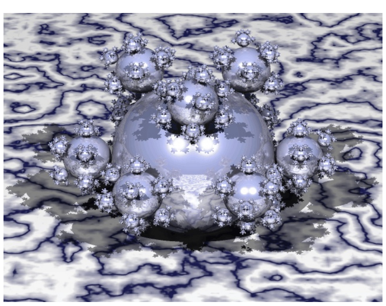

Image by Henrik Wann Jensen

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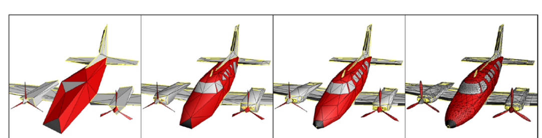
For Next Time:

- Read Hugues Hoppe “Progressive Meshes” SIGGRAPH 1996
- Post a comment or question on the course WebCT/LMS discussion by 10am on Friday



(a) Base mesh M^0 (150 faces) (b) Mesh M^{175} (500 faces) (c) Mesh M^{425} (1,000 faces) (d) Original $\hat{M}=M^n$ (13,546 faces)

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