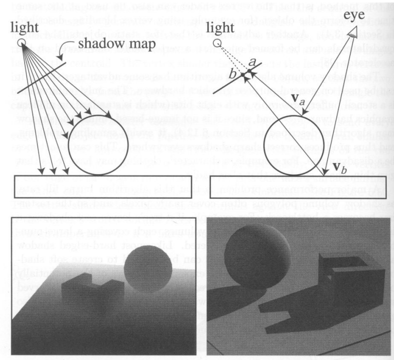
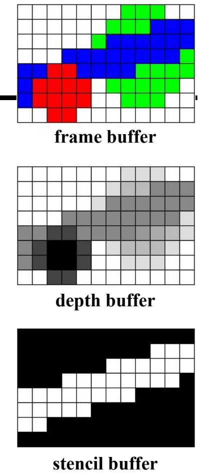
Shaders and Procedural Modeling

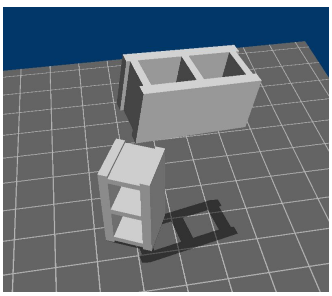
For the Birds, Pixar, 2000

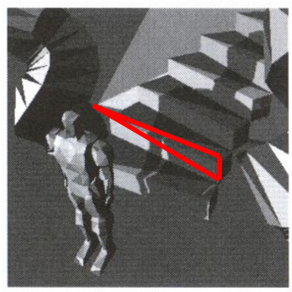
Last Time?

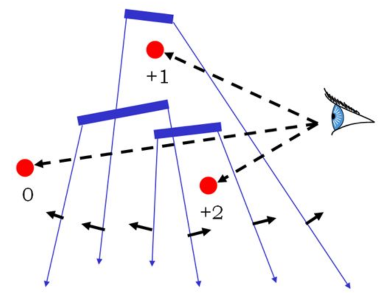
- Planar Shadows
- Projective Texture Shadows
- Shadow Maps
- Shadow Volumes
  - Stencil Buffer











Today

- Worksheet on Real-Time Shadows
- Texture Mapping & Other "Mapping" Techniques
  - Bump Mapping
  - Displacement Mapping
  - Environment Mapping
  - Light Mapping
  - Normal Mapping
  - Parallax Mapping
  - Parallax Occlusion Mapping
- Programmable Shader Examples
  - Modern Graphics Hardware
  - Per-Pixel Shading
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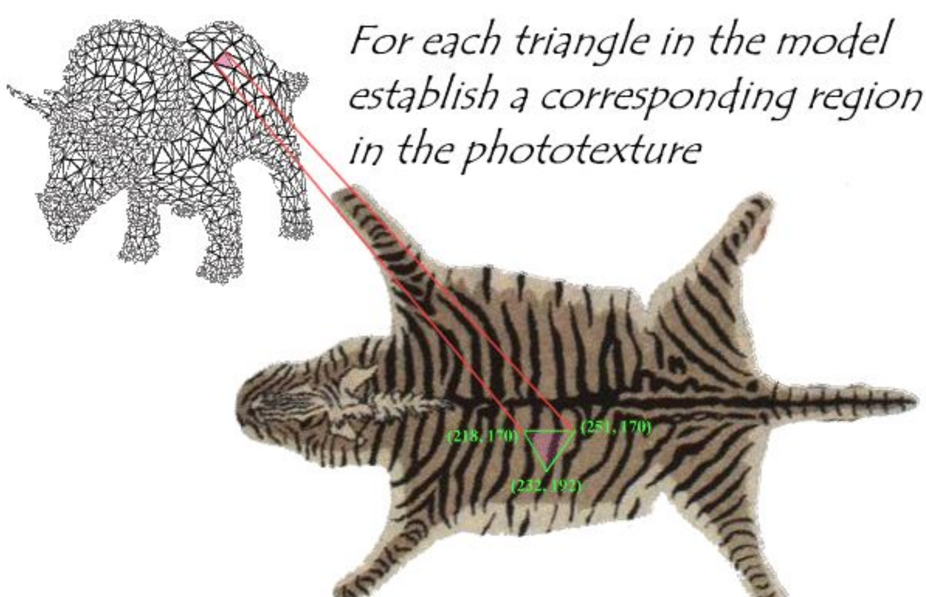
Texture Mapping

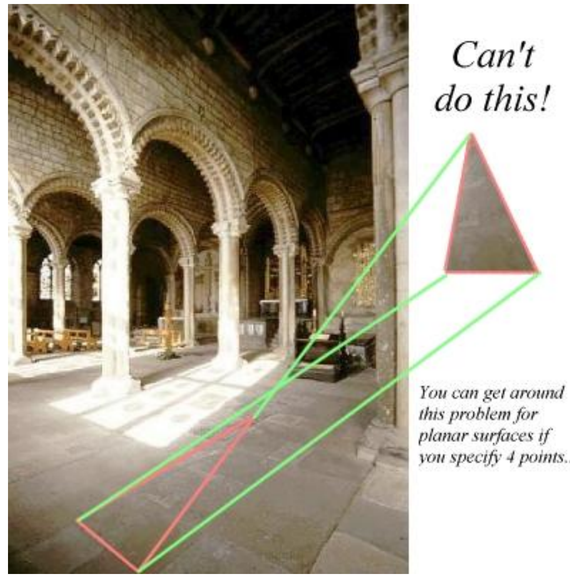


For each triangle in the model establish a corresponding region in the phototexture

During rasterization interpolate the coordinate indices into the texture map

Texture Mapping Difficulties

- Tedious to specify texture coordinates
- Acquiring textures is surprisingly difficult
  - Photographs have projective distortions
  - Variations in reflectance and illumination
  - Tiling problems

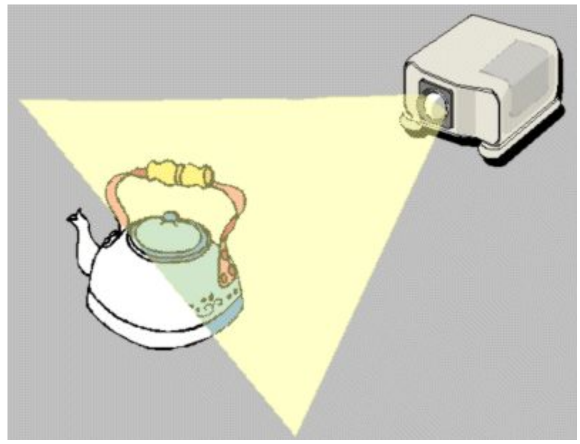


Common Texture Coordinate Mappings

- Orthogonal
- Cylindrical
- Spherical
- Perspective Projection
- Texture Chart

Projective Textures

- Use the texture like a slide projector
- No need to specify texture coordinates explicitly



Projective Texture Example

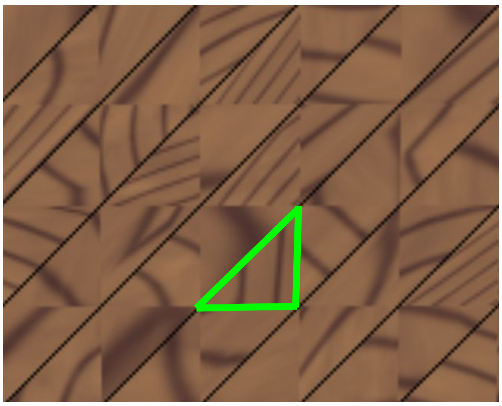
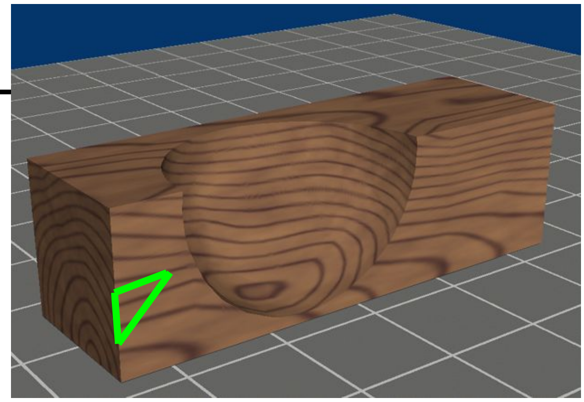
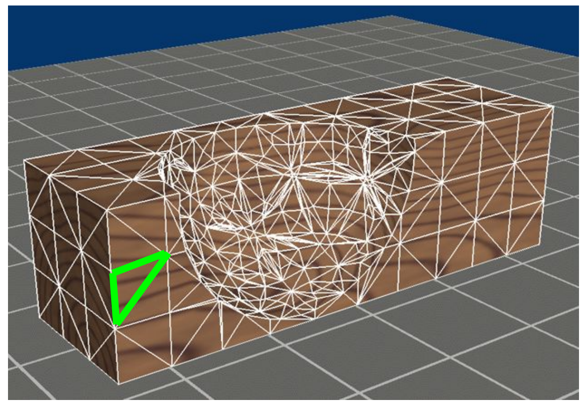
- Modeling from photographs
- Using input photos as textures

Original photograph with marked edges | Recovered model | Model edges projected onto photograph | Synthetic rendering

Figure from Debevec, Taylor & Malik
http://www.debevec.org/Research

Texture Chart

- Pack triangles into a single image

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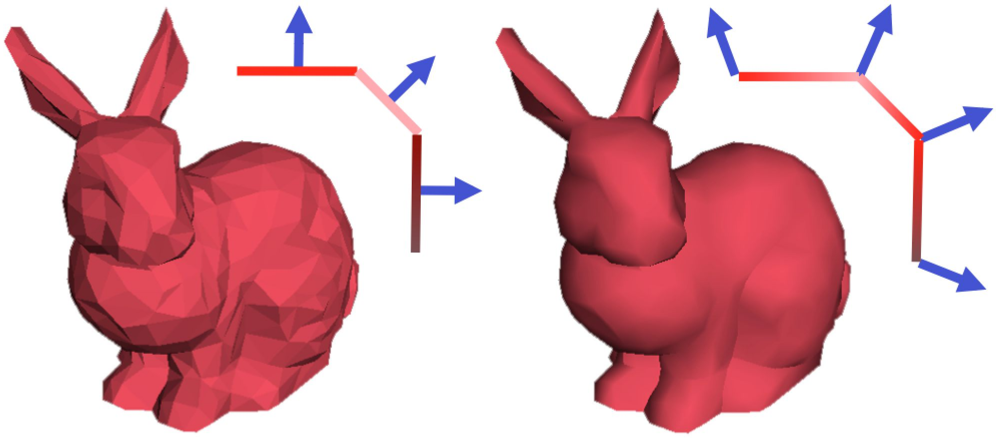
Remember Gouraud Shading?

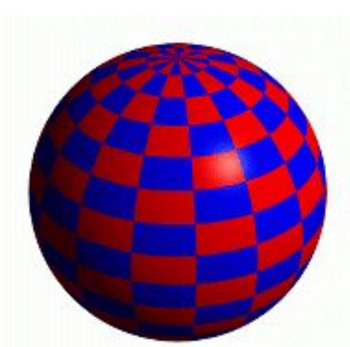
- Instead of shading with the normal of the triangle, we'll shade the vertices with the *average normal* and *interpolate the shaded color* across each face
  - Gives the *illusion of a smooth surface* with smoothly varying normals



Cheat normals to DISGUISE actual geometry

Bump Mapping / Normal Mapping

- Use textures to alter the surface normal
  - Does not change the actual shape of the surface
  - Just shaded as if it were a different shape



Sphere w/Diffuse Texture

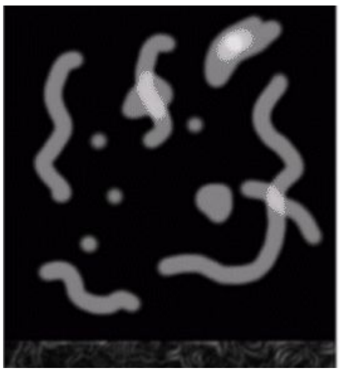
Swirly Bump Map

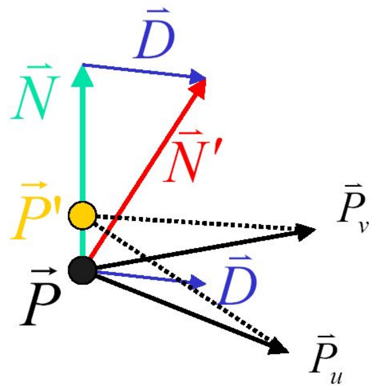
Sphere w/Diffuse Texture & Bump Map

Cheat normals to give illusion of ADDITIONAL/FAKE geometric detail

Bump Mapping

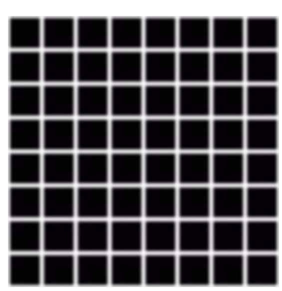
- Treat a greyscale texture as a single-valued height function
- Compute the normal from the partial derivatives in the texture





Another Bump Map Example

Cylinder w/Diffuse Texture Map

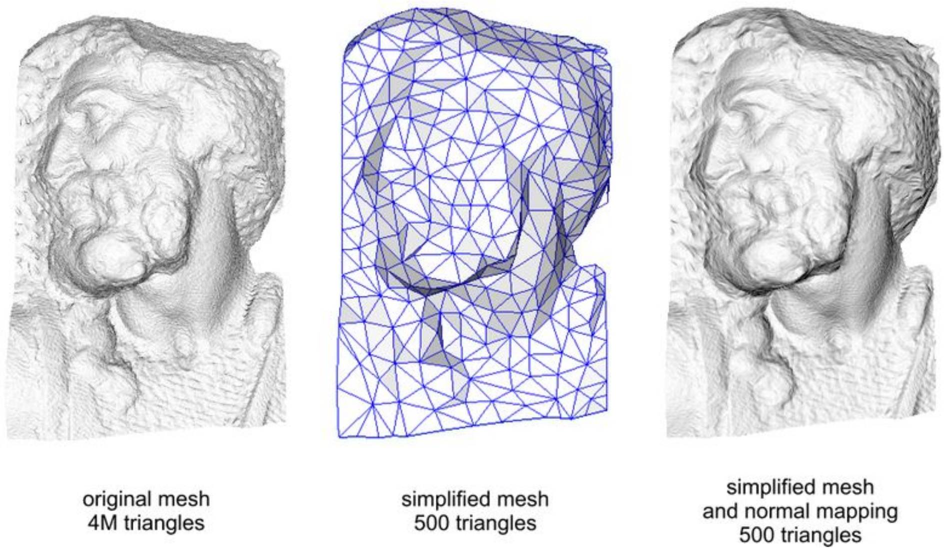


Bump Map

Cylinder w/Texture Map & Bump Map

Normal Mapping

- Variation on Bump Mapping:
  Use an RGB texture to directly encode the normal

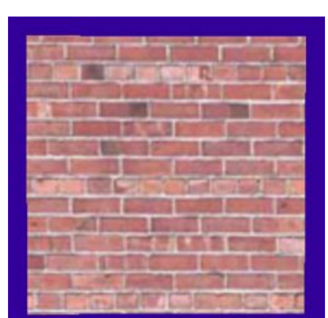


http://en.wikipedia.org/wiki/File:Normal_map_example.png

What's Missing?

- There are no bumps on the silhouette of a bump-mapped or normal-mapped object

- Bump/Normal maps don’t allow self-occlusion or self-shadowing



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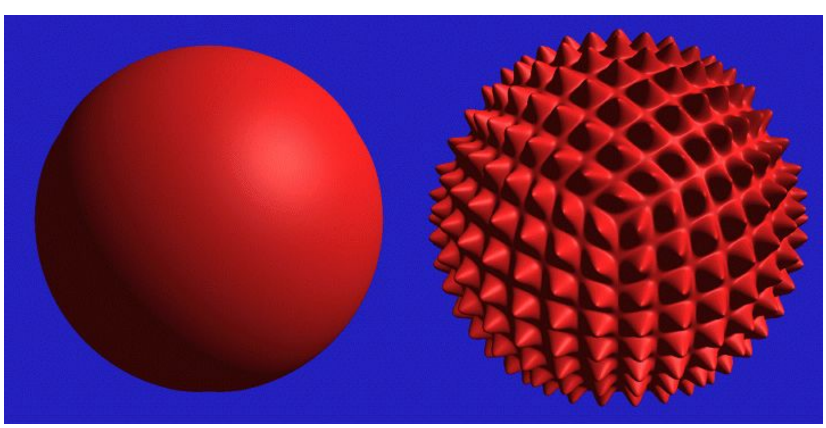
Displacement Mapping

- Use the texture map to actually move the surface point
- The geometry must be displaced before visibility is determined



Originally a CPU-only, post-user-modeling step

Displacement Mapping

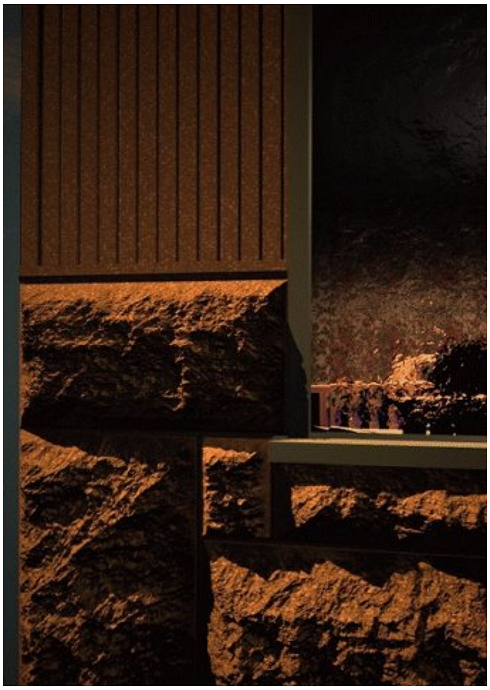
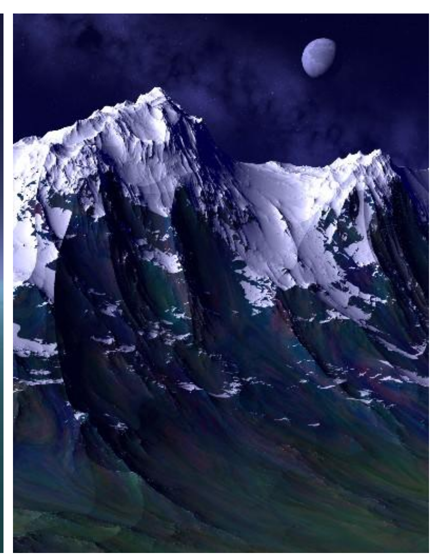


Image from:

Geometry Caching for Ray-Tracing Displacement Maps
EGRW 1996
Matt Pharr and Pat Hanrahan

note the accurate and detailed shadows cast by the stones

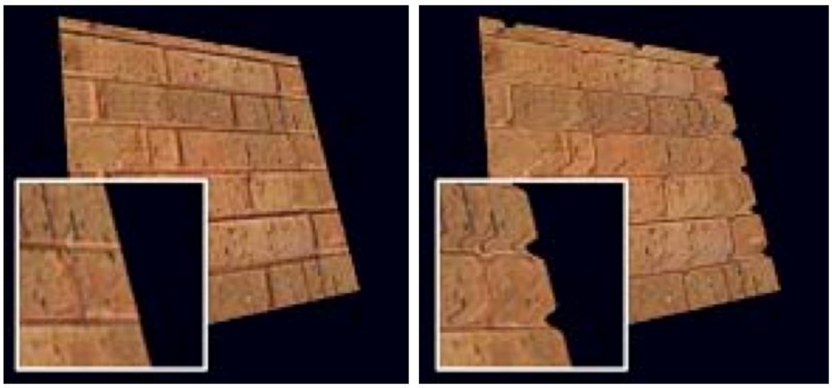
Procedural Displacement Mapping



Ken Musgrave
www.kenmusgrave.com

Parallax Mapping a.k.a. Offset Mapping or Virtual Displacement Mapping

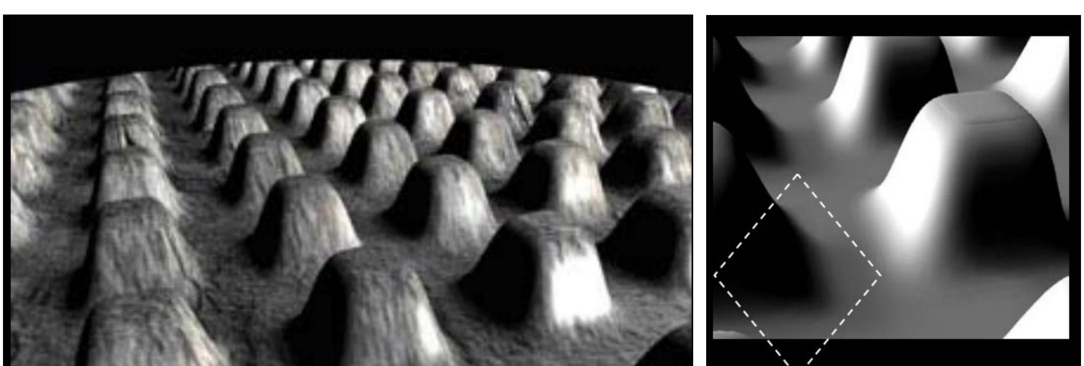
- Displace the texture coordinates for each pixel based on view angle and value of the height map at that point
- At steeper view-angles, texture coordinates are displaced more, giving *illusion of depth* due to parallax effects



“Detailed shape representation with parallax mapping”, Kaneko et al. ICAT 2001

Parallax Occlusion Mapping

- Brawley & Tatarchuk 2004
- Per pixel ray tracing of the heightfield geometry
- Occlusions & soft shadows



http://developer.amd.com/media/gpu_assets/ Tatarchuk-ParallaxOcclusionMapping-Sketch-print.pdf

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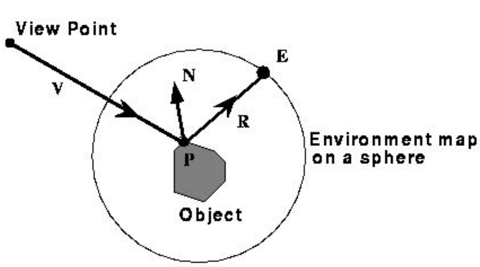
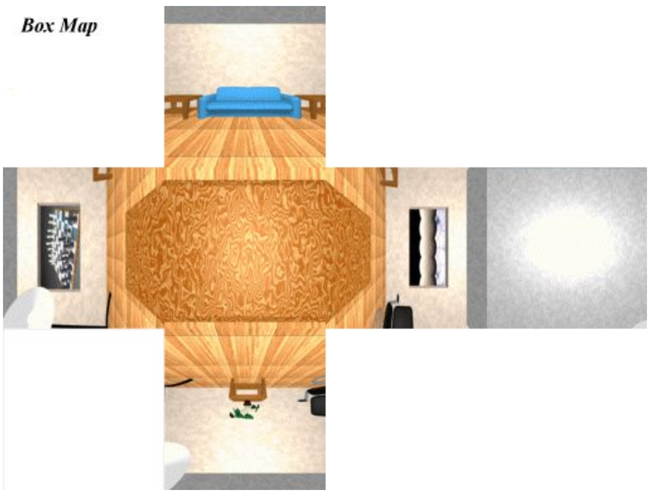
Environment Maps

- We can simulate reflections by using the direction of the reflected ray to index a spherical texture map at "infinity".
- Assumes that all reflected rays begin from the same point.



What's the Best Chart?



Environment Mapping Example

Terminator II

Texture Maps for Illumination

- Also called "Light Maps"

Quake

Questions?

Image by Henrik Wann Jensen
Environment map by Paul Debevec

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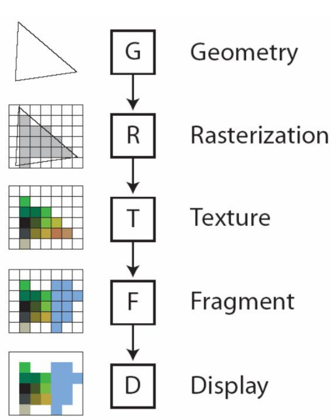
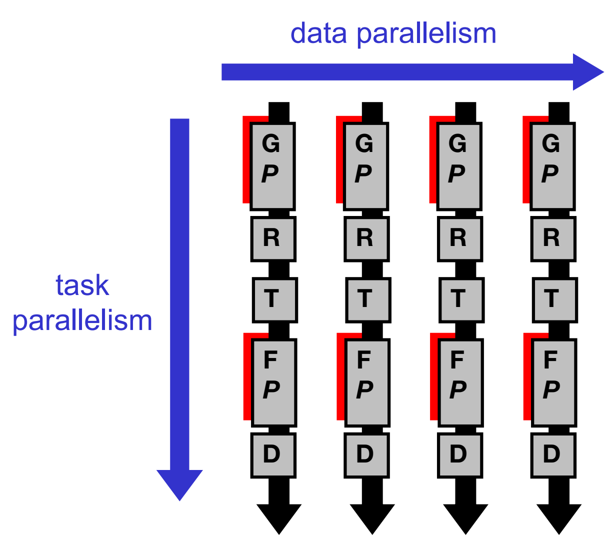
Modern Graphics Hardware

- Increased parallelism
- Programmable geometry and pixel/fragment stages
- General-purpose computation on GPU (GPGPU)

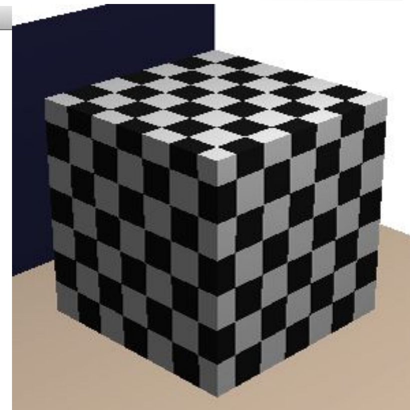




GLSL example: hw4_shader.vs

hw4_shader.vs

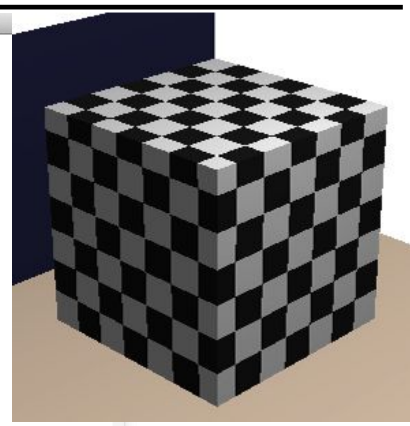
```
#version 330 core

// Input vertex data, different for all executions of this shader.
layout(location = 0) in vec3 vertexPosition_modelspace;
layout(location = 1) in vec3 vertexNormal_modelspace;
layout(location = 2) in vec3 vertexColor;

// Output data
out vec3 vertexPosition_worldspace;
out vec3 vertexNormal_worldspace;
out vec3 vertexNormal_cameraspace;
out vec3 EyeDirection_cameraspace;
out vec3 myColor;

// Values that stay constant for the whole mesh.
uniform mat4 MVP;
uniform mat4 V;
uniform mat4 M;
uniform vec3 LightPosition_worldspace;

void main(){

  // Output position of the vertex, in clip space : MVP * position
  gl_Position =  MVP * vec4(vertexPosition_modelspace,1);

  // Position of the vertex, in worldspace : M * position
  vertexPosition_worldspace = (M * vec4(vertexPosition_modelspace,1)).xyz;

  // Vector that goes from the vertex to the camera, in camera space.
  // In camera space, the camera is at the origin (0,0,0).
  vec3 vertexPosition_cameraspace = ( V * M * vec4(vertexPosition_modelspace,1)).xyz;

  EyeDirection_cameraspace = vec3(0,0,0) - vertexPosition_cameraspace;

  vertexNormal_worldspace = normalize (M * vec4(vertexNormal_modelspace,0)).xyz;

  // pass color to the fragment shader
  myColor = vertexColor;
}
```



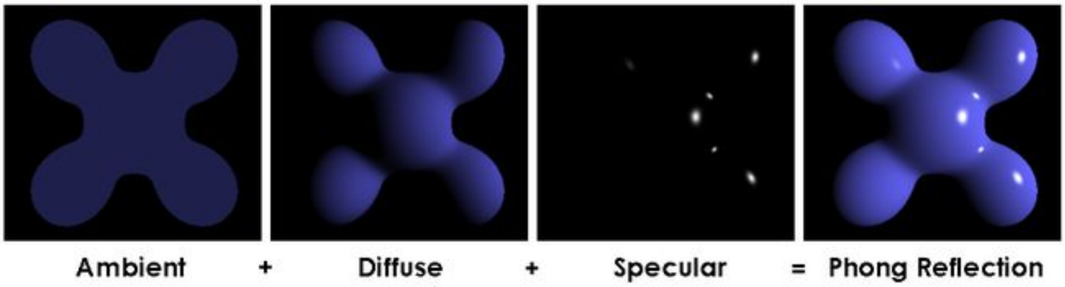
GLSL example: hw4_shader.fs

hw4_shader_checkerboard.fs

```
in vec3 vertexNormal_worldspace;

// Ouput data
out vec3 color;

// Values that stay constant for the whole mesh.
uniform vec3 LightPosition_worldspace;
uniform int colormode;
uniform int whichshader;

// -----------------------------------------------
// a shader for a black & white checkerboard
vec3 checkerboard(vec3 pos) {
  // determine the parity of this point in the 3D checkerboard
  int count = 0;
  if (mod(pos.x,0.3)> 0.15) count++;
  if (mod(pos.y,0.3)> 0.15) count++;
  if (mod(pos.z,0.3)> 0.15) count++;
  if (count == 1 || count == 3) {
    return vec3(0.1,0.1,0.1);
  } else {
    return vec3(1,1,1);
  }
}

// -----------------------------------------------
void main(){

  vec3 LightColor = vec3(1,1,1);
  float LightPower = 4.0f;

  // surface normal
  vec3 surface_normal =  vertexNormal_worldspace;

  // Material properties
  vec3 MaterialDiffuseColor = myColor;
  if (whichshader == 1) {
    MaterialDiffuseColor = checkerboard(vertexPosition_worldspace);
  } else if (whichshader == 2) {
    vec3 normal2;
    MaterialDiffuseColor = orange(vertexPosition_worldspace,surface_normal);
  } else if (whichshader == 3) {
    MaterialDiffuseColor = wood(vertexPosition_worldspace,surface_normal);
```



Phong Reflection/Lighting Model

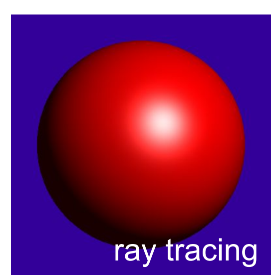


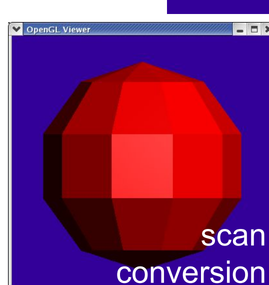
$$I_{\mathrm{p}} = k_{\mathrm{a}} i_{\mathrm{a}} + \sum_{m \in \text{lights}} (k_{\mathrm{d}} (\hat{L}_m \cdot \hat{N}) i_{m,\mathrm{d}} + k_{\mathrm{s}} (\hat{R}_m \cdot \hat{V})^{\alpha} i_{m,\mathrm{s}})$$

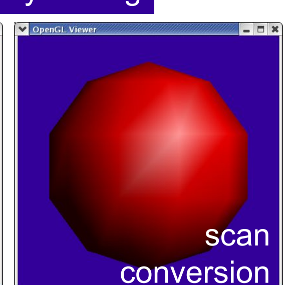
Color & Normal Interpolation

- It's easy in OpenGL to specify different colors and/or normals at the vertices of triangles:
- Why is this useful?

Originally, all we could afford to do in hardware was interpolate colors

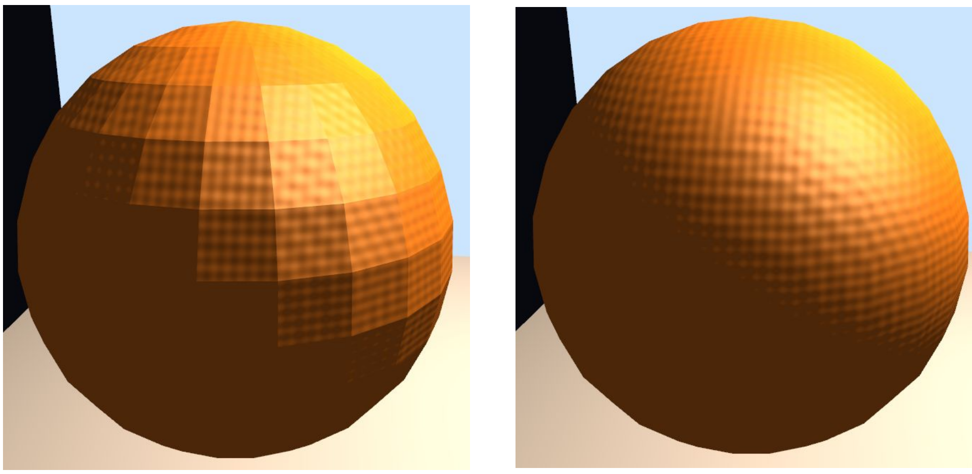






Per-Pixel Shading!

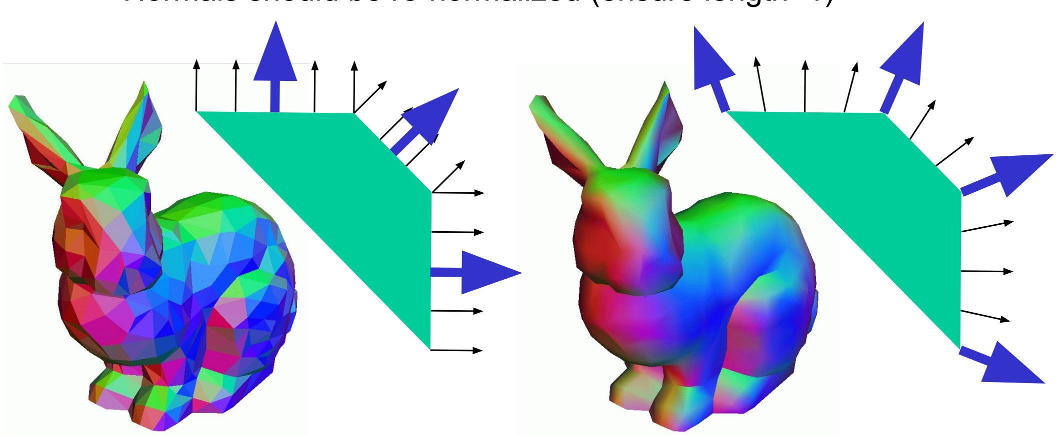
- We are not just interpolating the color
- Phong Reflection/Lighting can be calculated per pixel, not just per vertex



Phong Normal Interpolation

Not Phong Reflection Model

- *Interpolate the average vertex normals* across the face and compute *per-pixel shading*
  - Normals should be re-normalized (ensure length=1)

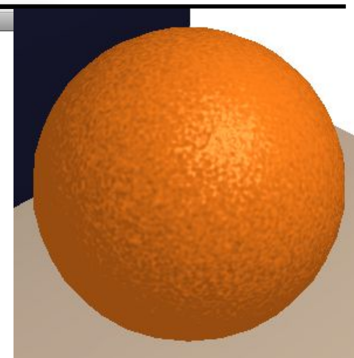


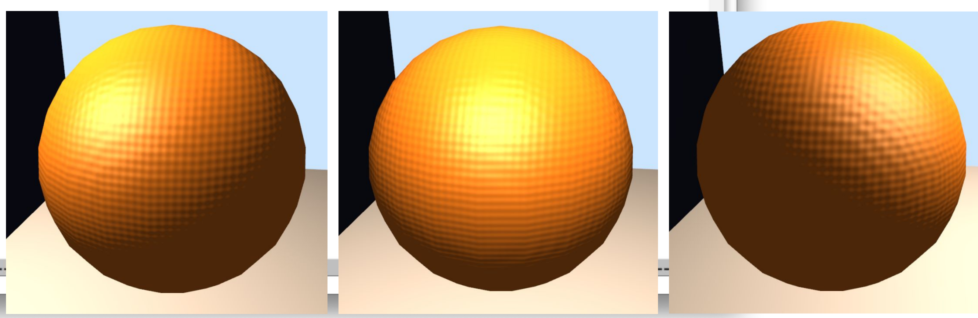
- Before shaders, per-pixel shading was not possible in hardware (Gouraud shading is actually a decent substitute!)

Another GLSL example: orange.vs

Emacs@tony.dyn.cs.rpi.edu

```
varying vec3 normal;
varying vec3 position_eyespace;
varying vec3 position_worldspace;

// a shader that looks like orange peel

void main(void) {

  // the fragment shader requires both the world space position (for
  // consistent bump mapping) & eyespace position (for the phong
  // specular highlight)
  position_eyespace = vec3(gl_ModelViewMatrix * gl_Vertex);
  position_worldspace = gl_Vertex.xyz;

  // pass along the normal
  normal = normalize(gl_NormalMatrix * gl_Normal);

  gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;
 }
```



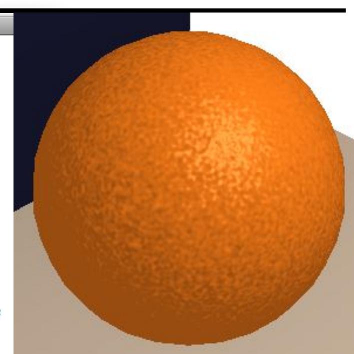


Another GLSL example: orange.fs

Emacs@tony.dyn.cs.rpi.edu

```
varying vec3 normal;
varying vec3 position_eyespace;
varying vec3 position_worldspace;

// a shader that looks like orange peel

void main (void) {

  // the base color is orange!
  vec3 color = vec3(1.0,0.5,0.1);

  // high frequency noise added to the normal for the bump map
  vec3 normal2 = normalize(normal+0.4*noise3(70.0*position_worldspace));

  // direction to the light
  vec3 light = normalize(gl_LightSource[1].position.xyz - position_eyespace);
  // direction to the viewer
  vec3 eye_vector = normalize(-position_eyespace);
  // ideal specular reflection
  vec3 reflected_vector = normalize(-reflect(light,normal2));

  // basic phong lighting
  float ambient = 0.6;
  float diffuse = 0.4*max(dot(normal2,light),0.0);
  float specular = 0.2 * pow(max(dot(reflected_vector,eye_vector),0.0),10.0);
  vec3 white = vec3(1.0,1.0,1.0);
  color = ambient*color + diffuse*color + specular*white;
  gl_FragColor = vec4 (color, 1.0);
}
```

--:--- orange.fs All L1 CVS-1.1 (C/l Abbrev)------------------------------



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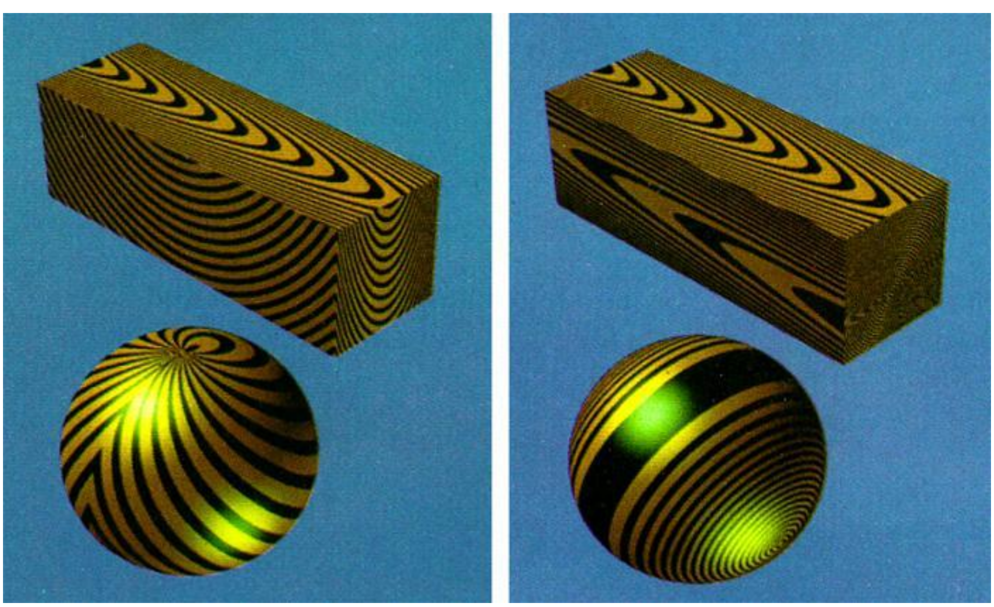
Texture Map vs. Solid Texture



“Solid Texturing of Complex Surfaces”,
Peachey, SIGGRAPH 1985

Procedural Textures

$f(x,y,z) \rightarrow$ color

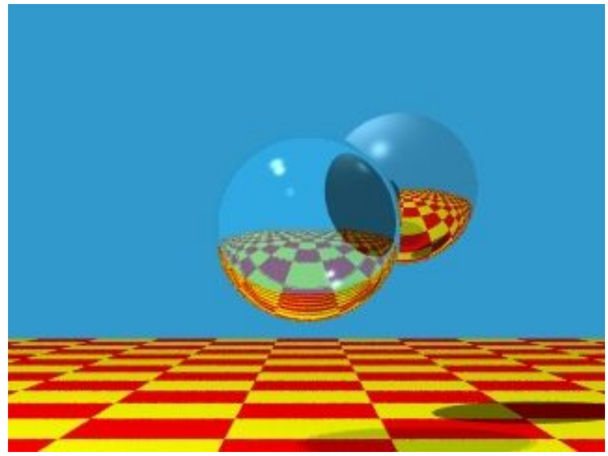
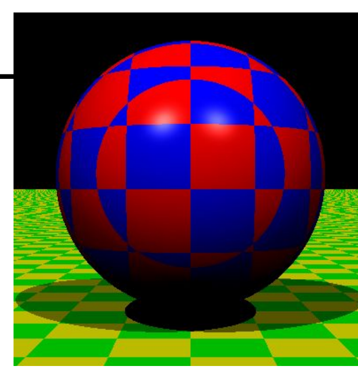
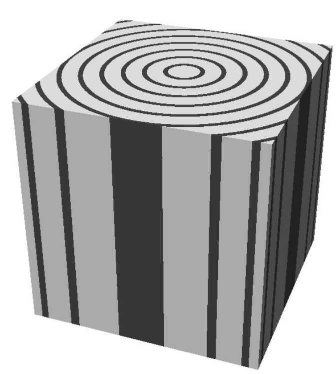


Image by Turner Whitted

Procedural Textures



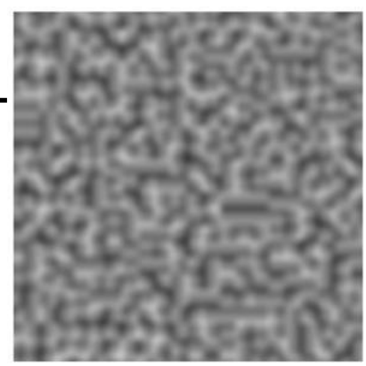
- Advantages:
  - easy to implement in ray tracer
  - more compact than texture maps (especially for solid textures)
  - infinite resolution
- Disadvantages
  - non-intuitive
  - difficult to match existing texture



Reading for Today

- “An Image Synthesizer”, Perlin, SIGGRAPH 1985 & “Improving Noise”, Perlin, SIGGRAPH 2002

Perlin Noise



- Properties:
  - Looks “random”, but is deterministic (always returns the same answer for a specific coordinate)
  - Small memory footprint & fast to compute
  - Known amplitude & frequency
  - Smooth interpolation when zoomed in
- Can be combined/layered:
  - Add multiple noise functions w/ different frequencies and amplitudes
  - Simple arithmetic operations (thresholding, sine waves, etc.)

“Shade Trees”, Cook, SIGGRAPH 1984

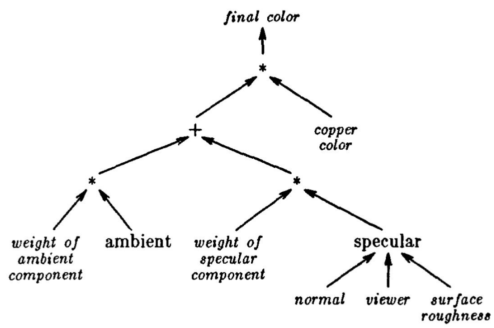


Figure 1a. Shade tree for copper.

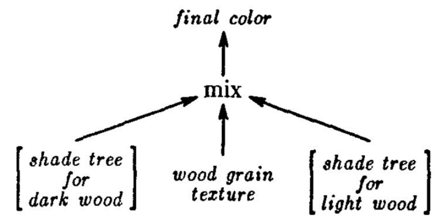
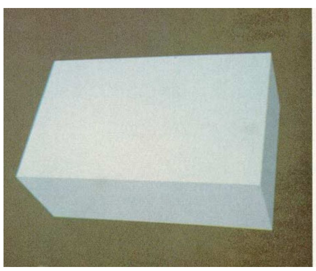
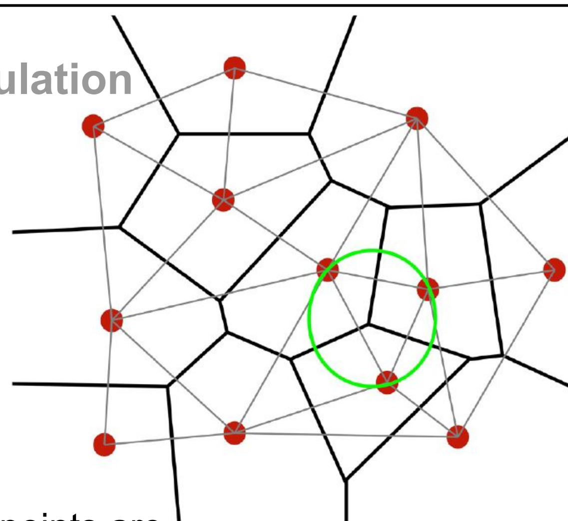
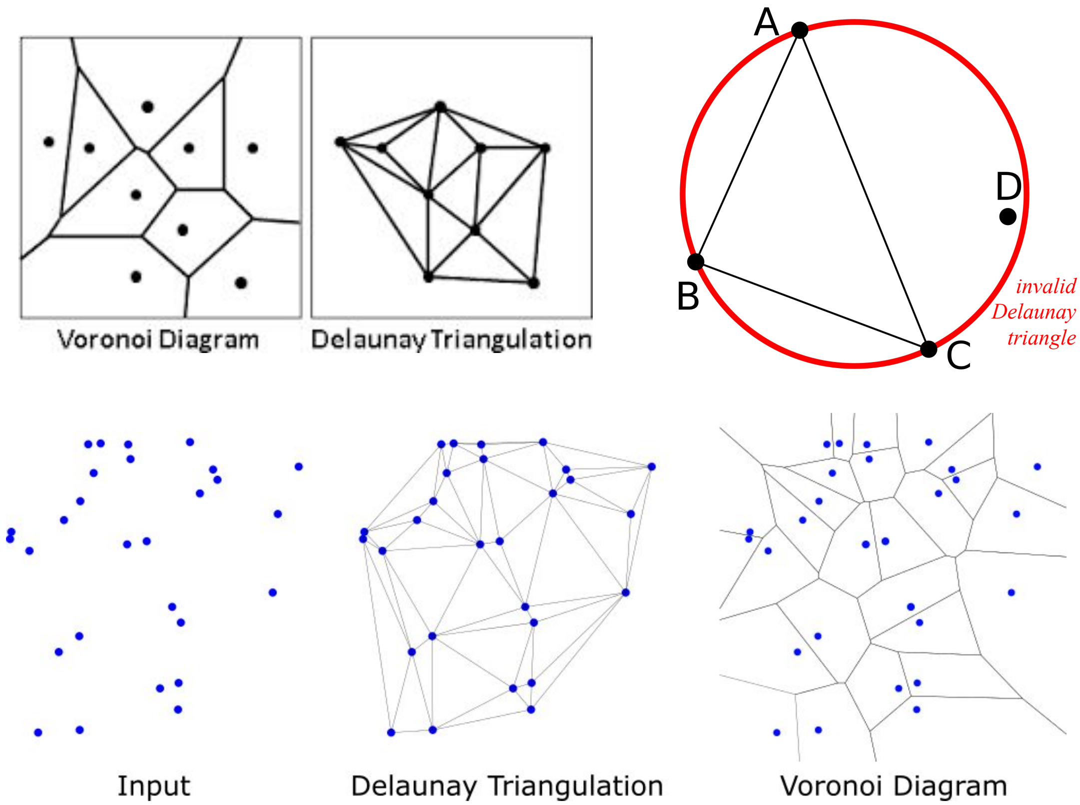


Figure 1b. The mix node in a shade tree for wood.



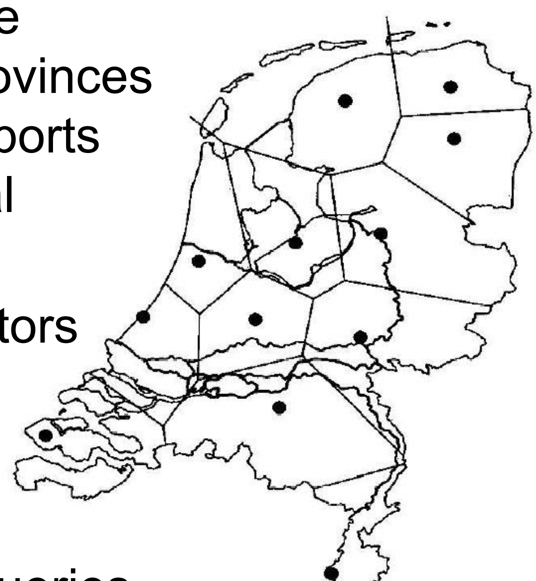


- Grey: Delauney Triangulation
  - “Best” triangulation of the red dots (most equilateral)
  - A specific triangle is in the Delauney Triangle *if and only if* the circle defined by those 3 points *does not* contain any other red dot
  - Note: Well defined when points are random. If points are on a uniform grid, we have ties…
- **Black: Voronoi Diagram**
  - Each cell is the set of all points in the plane that claim that cell’s red dot as the closest
- Note: The black edges perpendicularly bisect the grey edges



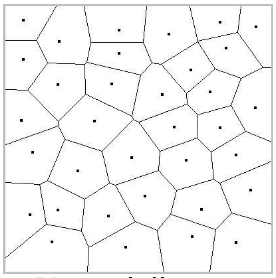
Voronoi Diagram/Cells/Regions

- How to re-district the Netherlands into provinces so that everyone reports to the closest capital
- Cell edges are the perpendicular bisectors of nearby points
- 2D or 3D
- Supports efficient *Nearest Neighbor* queries

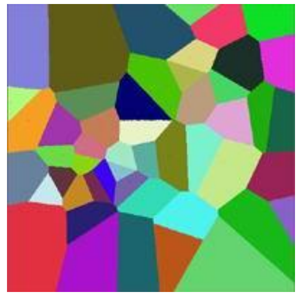


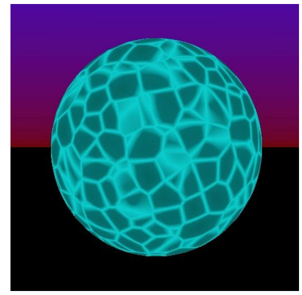
http://ccc.inaoep.mx/~rodrigo/robotica/Trigui.pdf

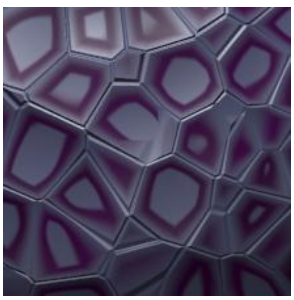
Cellular Textures



Voronoi diagram







"A Cellular Texture Basis Function", Worley, SIGGRAPH 1996

www.worley.com

Questions?

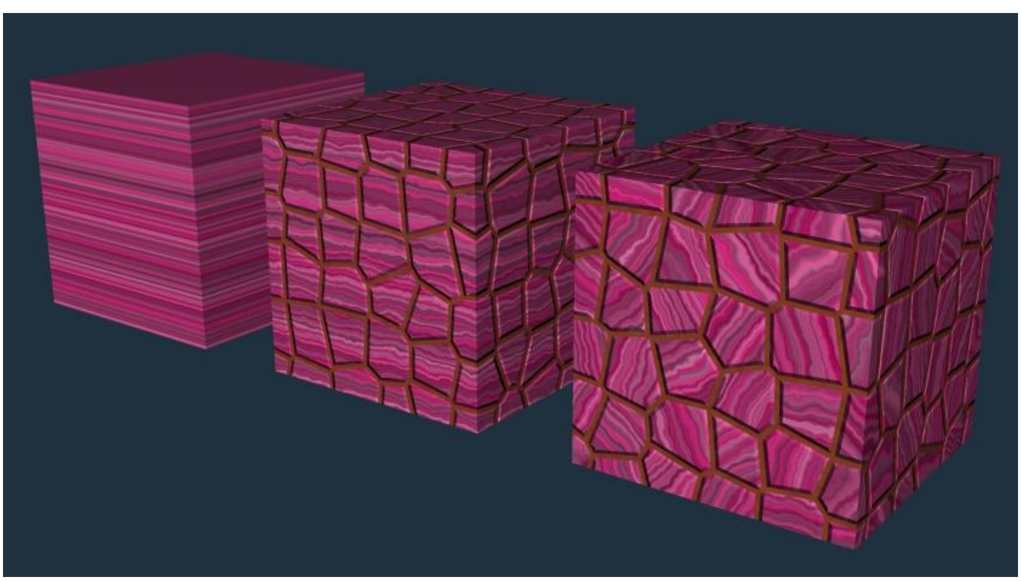


Image by Justin Legakis

Optional Reading for Today

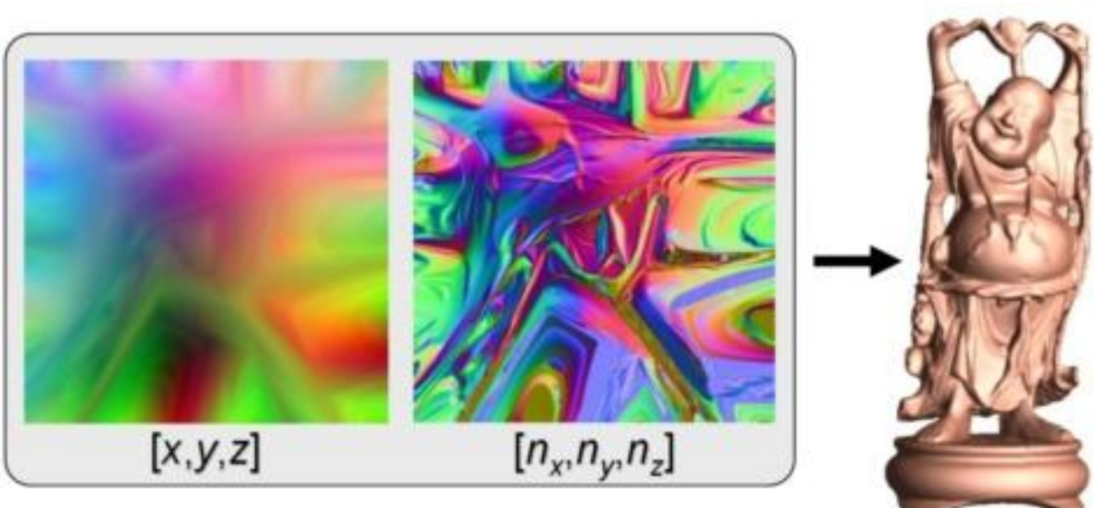
“Hardware-Accelerated Global Illumination by Image Space Photon Mapping” McGuire & Luebke, HPG 2009

Direct Illumination Only | Direct + Constant Ambient | Image Space Photon Mapping

Figure 1: Image-space photon mapping can compute global illumination at interactive rates for scenes with multiple lights, caustics, shadows, and complex BSDFs. This scene renders at 26 Hz at 1920 × 1080. (Indirect and ambient intensity are amplified for comparison in this image.)

Optional Reading for Today

"Geometry Images", Gu, Gortler, & Hoppe, SIGGRAPH 2002



3D shape is unrolled/flattened/stretched into a square image.
Stored using existing image formats and compression methods.

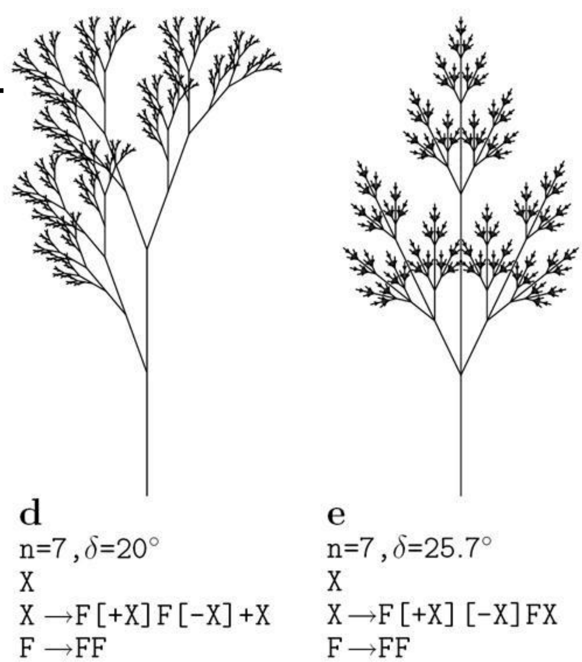
Today

- Worksheet on Real-Time Shadows
- Texture Mapping & Other "Mapping" Techniques
  - Bump Mapping
  - Displacement Mapping
  - Environment Mapping
  - Light Mapping
  - Normal Mapping
  - Parallax Mapping
  - Parallax Occlusion Mapping
- Programmable Shader Examples
  - Modern Graphics Hardware
  - Per-Pixel Shading
- Procedural Textures & Modeling
- Papers for Today
- Papers for Next Time

L-Systems

alphabet: {a,b}
initiator: a
production rules:
    a -> b
    b -> ba

generations:
    a
    b
    ba
    bab
    babba
    babbabab
    babbababbabba
    babbababbabbababbabab



Prusinkiewicz & Lindenmayer,
The Algorithmic Beauty of Plants, 1990
http://algorithmicbotany.org/

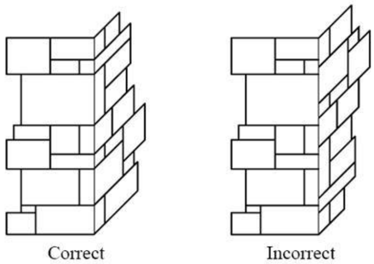
L-Systems

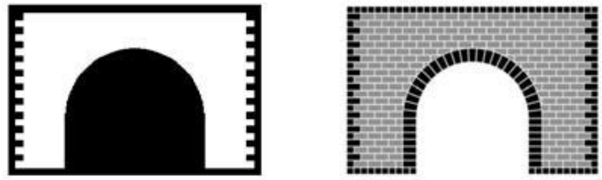
Animation of Plant Development
Prusinkiewicz et al., SIGGRAPH 1993

Prusinkiewicz & Lindenmayer, *The Algorithmic Beauty of Plants,* 1990
http://algorithmicbotany.org/

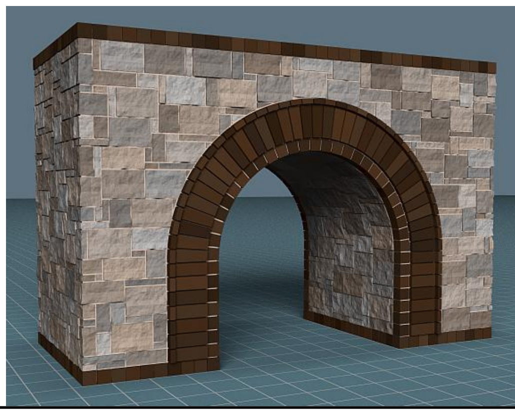
“Synthetic Topiary”, Prusinkiewicz, James, and Mech, SIGGRAPH 1994

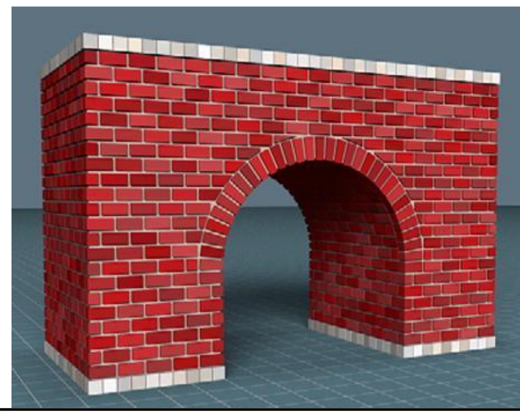
Cellular Texturing for Architecture





"Feature-Based Cellular Texturing for Architectural Models", Legakis, Dorsey, & Gortler, SIGGRAPH 2001

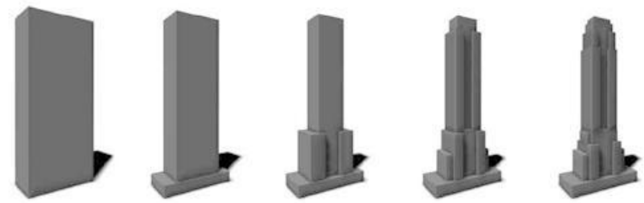




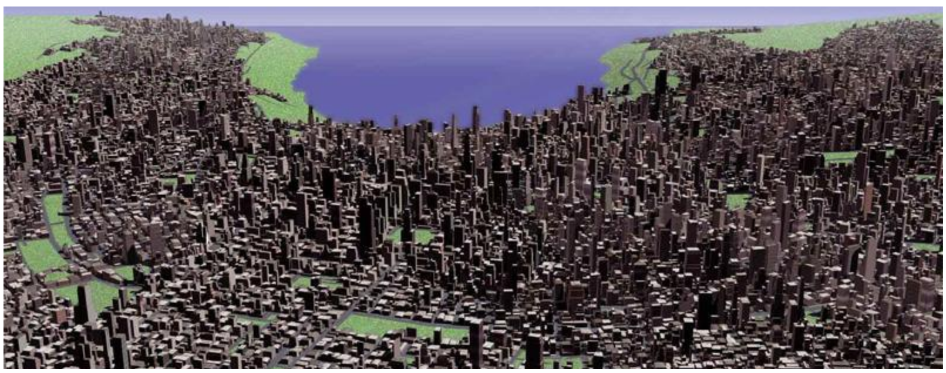
Procedural Modeling Advantages

- Small representation
- Generate detail as needed ("infinite"? resolution)
- Great for natural mathematical patterns and man-made engineering and design
- Trivial to make many duplicate objects with small variations

L-Systems for Cities



"Procedural Modeling of Cities",
Parish & Müller, SIGGRAPH 2001



Procedural Modeling of Buildings

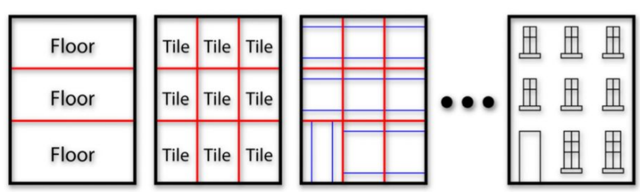
- "Procedural Modeling of Buildings", Mueller, Wonka, Haegler, Ulmer & Van Gool, SIGGRAPH 2006

Applications

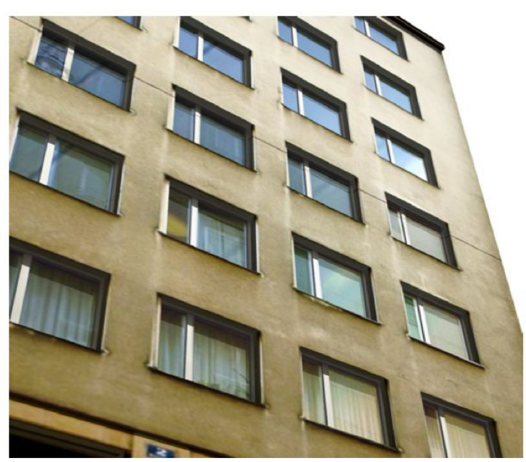
- Entertainment – Gaming
- Education – Studying botanical variation
- Archeological reconstruction
- Realism for Training
- Predicting the future (how will things grow over time)
- Urban planning (preparing for traffic)
- Accommodate for that growth/change

Image-based Procedural Modeling of Facades

- Mueller, Zeng, Wonka, & Van Goo SIGGRAPH 2007



Input Photograph



Reconstructed 3D Geometry

Questions about Procedural Modeling

- Number of rules necessary?
- Cost in human designer time of creating procedural model?
- Re-useability of procedural model?
- Validation
- Can you build a procedural model that produces a specific target?
  - *From a photo of a specific rare wood grain, can you create a procedural model that creates texture that looks like it came from a different location of the same/similar tree?*