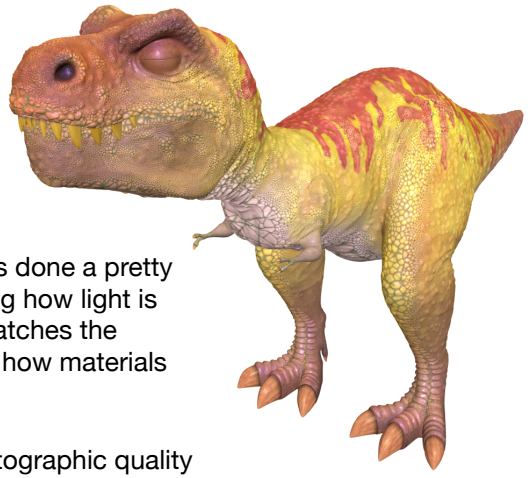
CSC 433/533
Computer Graphics

Alon Efrat
Credit: Joshua Levine

Textures

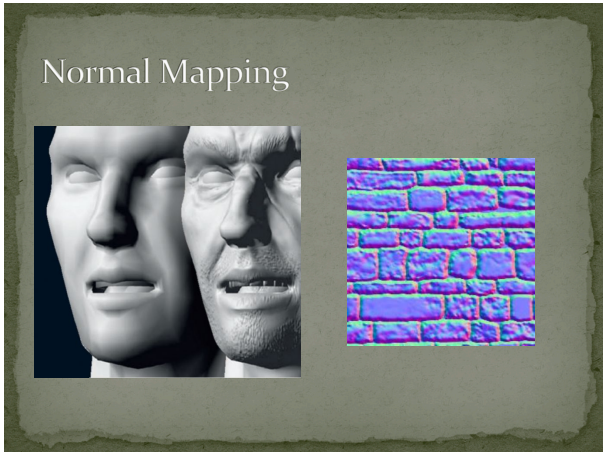
Challenge: Real World Surfaces Have Complex Materials



- While ray tracing has done a pretty good job of capturing how light is modeled, it only scratches the surface at modeling how materials look
- Goal: Replicate photographic quality by varying shading parameters?

http://ptex.us/ptexpaper.html

Texture Mapping



Texture Mapping

- Models attributes of surfaces that **vary as position changes**, but do not affect the shape of the surface.
- Examples: wood grain, wrinkles in skin, woven structures in cloth, defects in metal surfaces, patterns (in general), …

Texture Maps

- Idea: model this variation using an image, called a **texture map** (or, sometimes “texture image” or just “texture”)
- The texture map stores the surface details
  - Typically, shading parameters like k_d and k_s
- Can be used in lots of interesting ways to achieve complex effects

Texture Lookups

- Since the texture is an image, we need a way to index into it given a surface position
  - Or, where on the surface does the image go?
- Given a position, we lookup the **texture coordinates**, given as (u,v) values that refer to positions in the image
  - Easy to define for some shapes, can be very hard for others

Computing Texture Coordinates

- Idea: We will model this problem using a **texture coordinate function**,

$$\phi: S \rightarrow T, \text{ for all (x,y,z)} \in S \text{ and (u,v)} \in T$$

- When shading a point (x,y,z), we compute ϕ(x,y,z) to get the appropriate pixel (u,v) in the texture.
- u and v normally values in [0,1] (and then are scaled to the size of the texture)

Computing Texture Coordinates - Example

```
function texture_lookup(tex, u, v) {
  let i = Math.round(u * tex.width() - 0.5);
  let j = Math.round(v * tex.height() - 0.5);
  return tex.get_pixel(i,j);
}

function shade_surface_point(surf, pt, tex) {
  let normal = surf.get_normal(pt);
  [u,v] = surf.get_texcoord(pt);
  let diffuse_color = texture_lookup(tex,u,v);
  //compute shading using diffuse_color and normal
  //return shading result
}
```

Three Spaces

- Just like we have mappings from world space to image, we use ϕ as another mapping

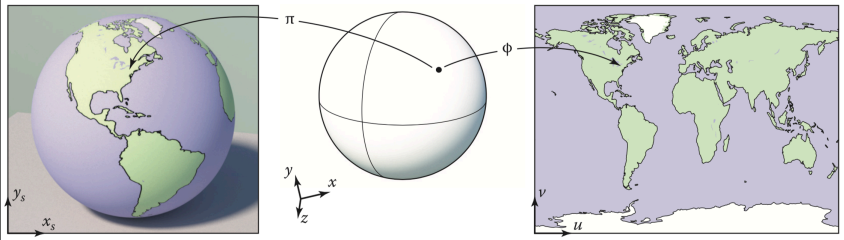


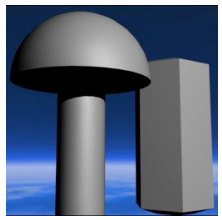
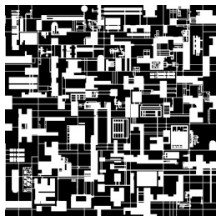
Image space | Surface S in world space | Texture space, T

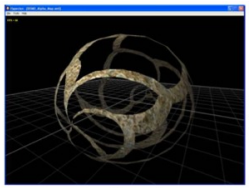
Examples of Texture Coordinate Functions

Problem #1: Defining Texture Coordinate Functions

- Defining ϕ can be very difficult for complex shapes
- Similar to the problem of taking a surface and flattening it
  - e.g. Cartographers problem
- Inevitably will have distortion of areas, angles, or distances

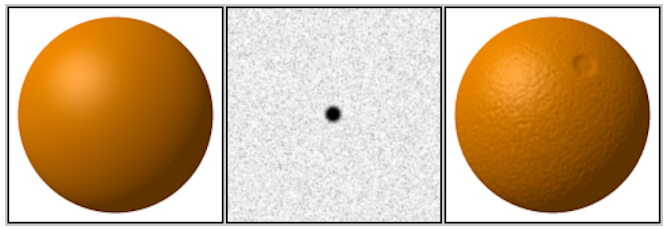
Opacity mapping

http://lectrablog.lectralizard.com/page/2

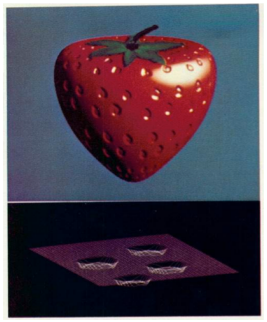
Bump mapping

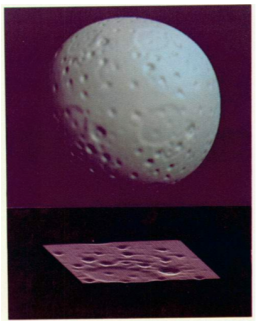


- Simulates roughness ("bumpiness") of a surface without adding geometry
- Uses a two-dimensional height field (bump map) to perturb the normal during per-fragment shading calculations
- Limitations: the mapping of texture onto the surface is unaffected; silhouette is also unaffected.

GDallimore (Wikimedia Commons)

Bump mapping





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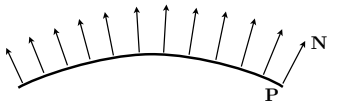
Blinn, SIGGRAPH 1978

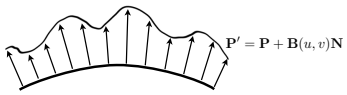
Important

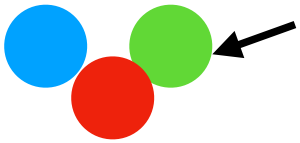
When we perform ray-tracing/z-buffering to find the first object hits by a ray, the texture does not change the answer.

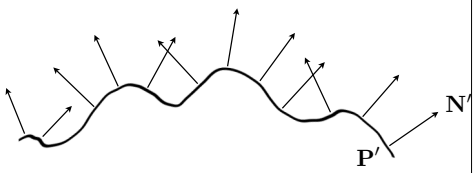
For example, we still treat a sphere as. a smooth normal sphere.

We use the bumps map only after computing
1) The first sphere hit, and
2) The hitting point (with some exceptions here)









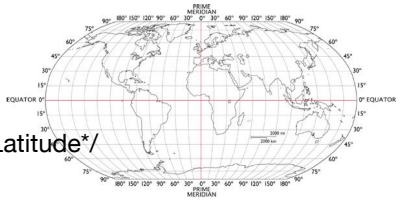
Spherical Projection

- Convert (x,y,z) to spherical coordinates, discard radius

  r = sqrt($x^2+y^2+z^2$)

  u = (π + atan2(y,x)) / (2π)

  v = (π + acos(z/r)) / (π) /*Latitude*/



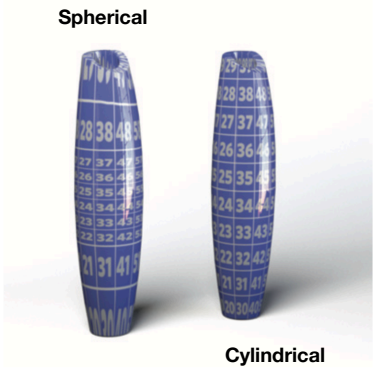
- Similar to casting a ray outward from center

Cylindrical Projection

- Convert (x,y,z) to cylindrical coordinates, discard radius

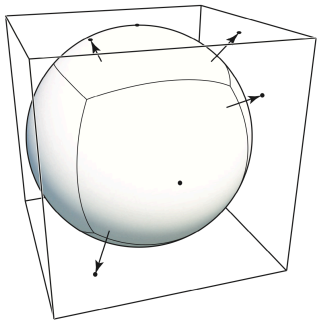
  u = (π + atan2(y,x)) / (2π)

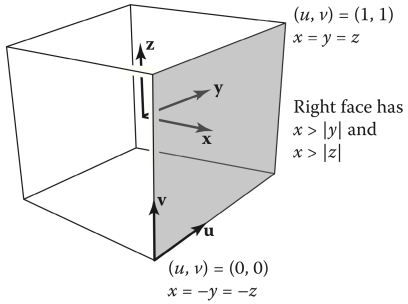
  v = 0.5 + z/2



Cubemaps

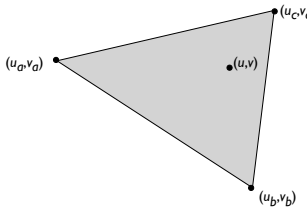
- Project onto faces of a cube, 6 planar projections
- Seams can be tricky to handle.

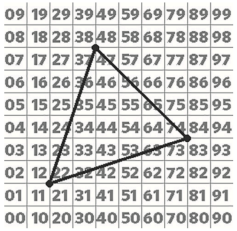


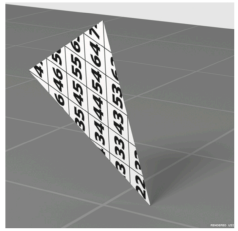


Interpolated Texture Coordinates

- Explicitly store (u,v) coordinates on the vertices of a triangle mesh, interpolate in the center using barycentric coordinates
- Texture coordinates just another per-vertex data. How to compute them? Can be difficult!





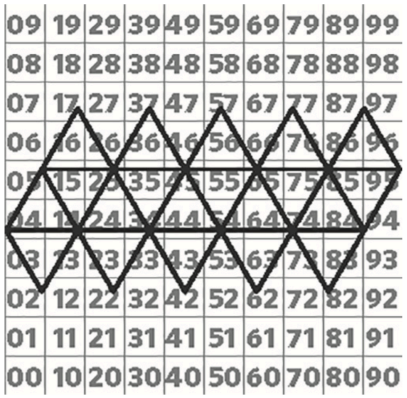


Properties of Texture Coordinate Functions

Goals for Texture Functions

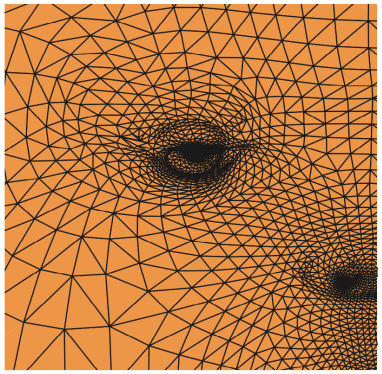
1. One-to-one vs one-to-many:
   - Each point on the surface should map to a different point on the texture, unless you want repetition
2. Size distortion:
   - Scale of texture kept constant across the surface
3. Shape distortion:
   - Shapes/Angles in the texture should state similarly shaped
4. Continuity:
   - Are there visible seams? ϕ should have as few discontinuities as possible

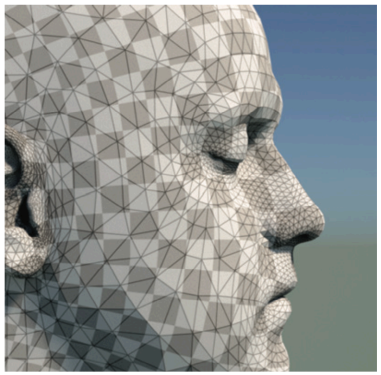
Distortions vs. Discontinuities



No distortion to area,
Many discontinuities

Shape vs. Area Distortions

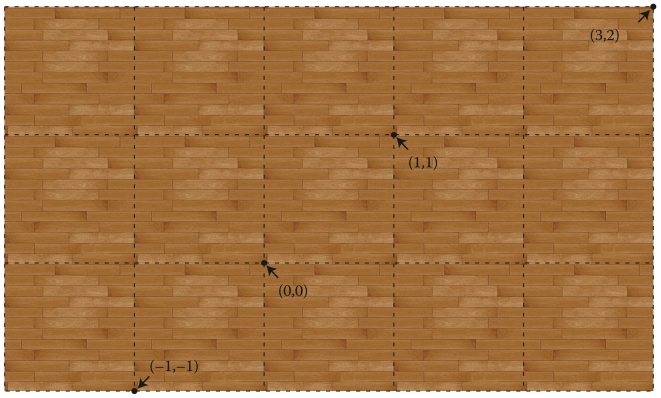




Low shape distortion,
Moderate area distortion

Tiling and Wrapping

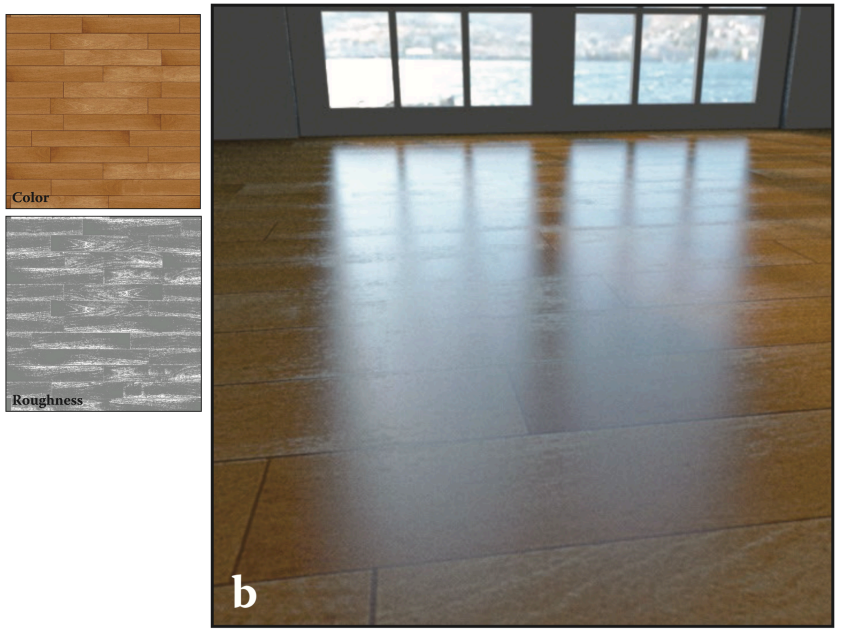
- Can be achieved by modifying the mapping to cycle around in various ways (similar to boundary conditions for image processing)
- Could also just clamp values



Applications of Textures

Controlling Shading Parameters

- Can look up k_d and k_s, or both

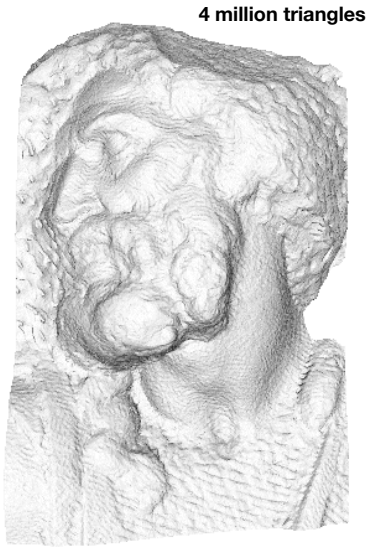


Normal Maps

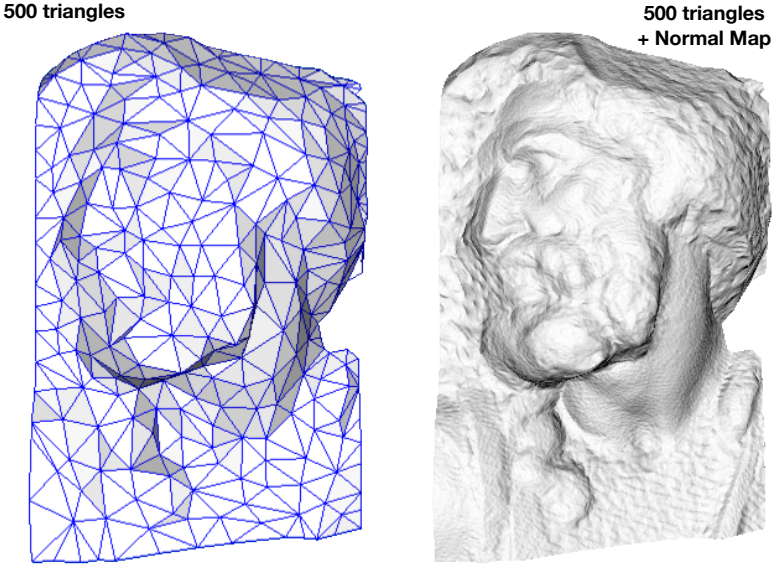
- Can also use textures to look up normal information for the surface
- Typically, store the normal vector (n_x,n_y,n_z) as (r,g,b) values for the pixel
- Problem: orientation of the surface could change — normals are usually defined relative to a local coordinate space

Normal Map Example

- Transfer details from high resolution mesh to normal map image



https://en.wikipedia.org/wiki/Normal_mapping



https://en.wikipedia.org/wiki/Normal_mapping

Bump Maps

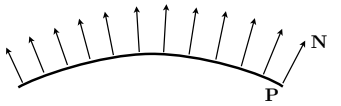
- Normals specified indirectly using a height field
  - The bump map encodes a local offset of the detailed surface above the original smooth surfaces
- Normal map is derived by taking the derivative of the bump map

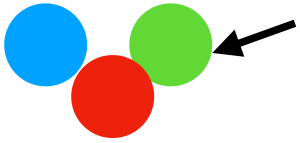
Important

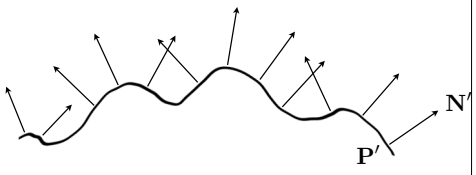
When we perform ray-tracing/z-buffering to find the first object hits by a ray, the texture does not change the answer.

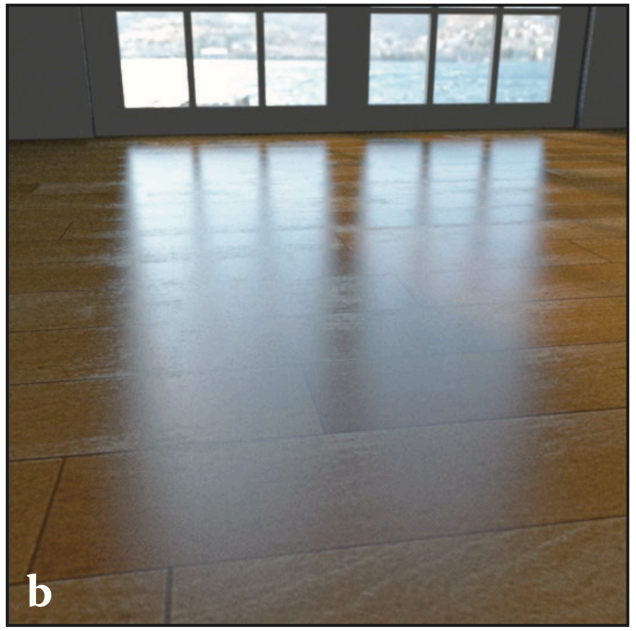
For example, we still treat a sphere as. a smooth normal sphere.

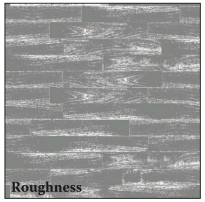
We use the bumps map only after computing
1) The first sphere hit, and
2) The hitting point (with some exceptions here)

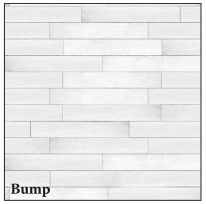










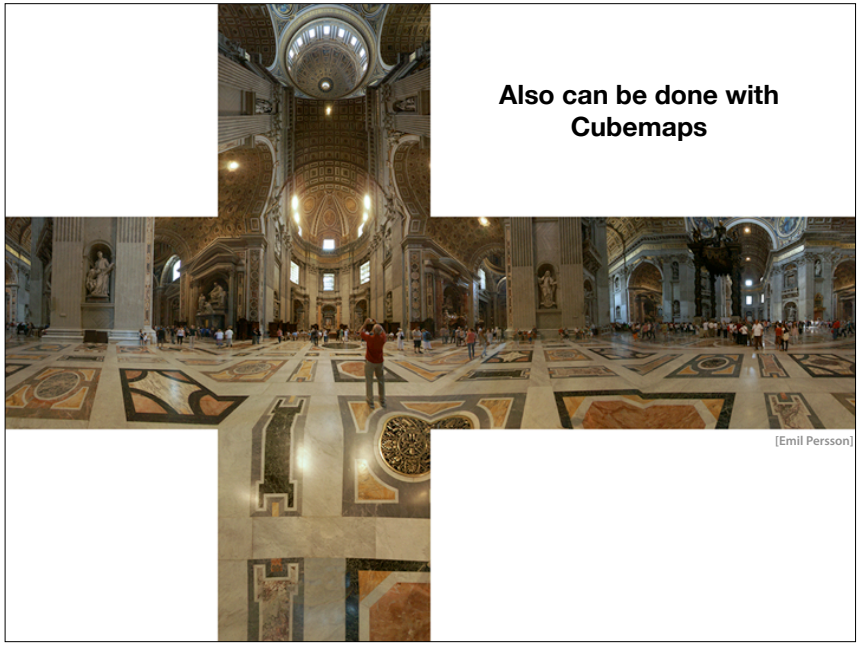


Environment Maps

- Use a texture to lookup values for rays that don't hit any objects

```
function trace_ray(ray, scene) {
  if (surface = scene.intersect(ray)) {
    return surface.shade(ray);
  } else {
    u,v = spheremap_coords(ray.direction);
    return texture_lookup(scene.env_map, u, v);
}
```

[Paul Debevec]



Also can be done with Cubemaps

[Emil Persson]

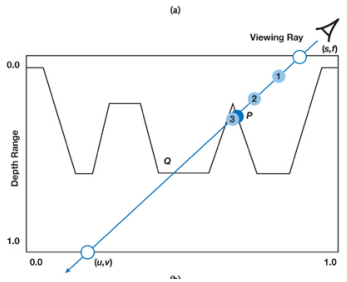
Relief mapping

normal mapping

relief mapping

Image from Natalya Tatarchuk

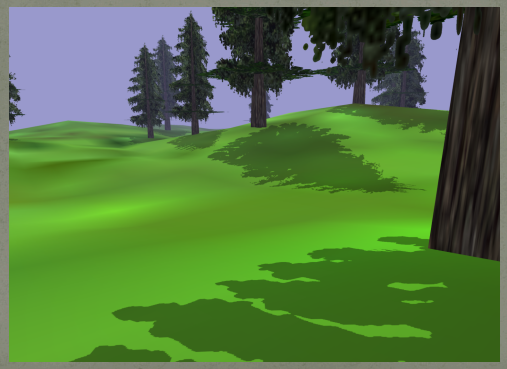
Relief mapping



- Trace the eye ray into the bump map. A simple implementation can rasterize the projection of the ray onto the tangent plane, stepping along (e_t, e_b) and adjusting the height by a factor proportional to e_h.

Image from Policarpo and Oliveira (2008)

Shadow Mapping



Shadow Mapping (Concept)

- Render image from POV of light to create shadow map
- (ie. what would the scene look like if rendered from the POV of the light?) Light's view matrix = gluLookAt? glOrtho?
- When rendering a pixel, deciding if it is in shadow?
  - Project into light clip space
  - Compare z values (ie. distance from light source)
    - Distance from light > Z value of rendered texel in shadow map => occluding object => shadow!

Rendering Large Environments

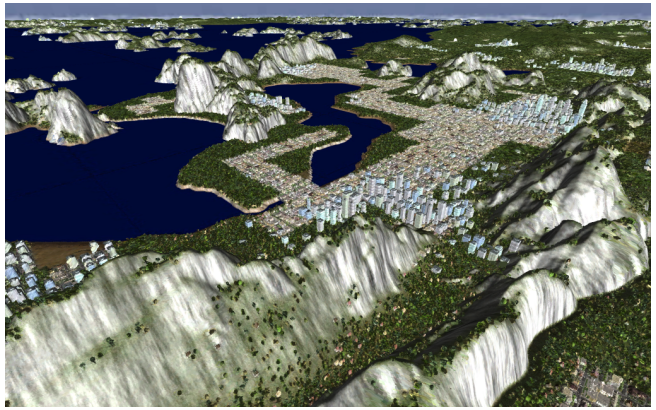
(in real time)

Siddhartha Chaudhuri

~500,000 polygons

~3,000,000 polygons

~25,000,000,000 polygons



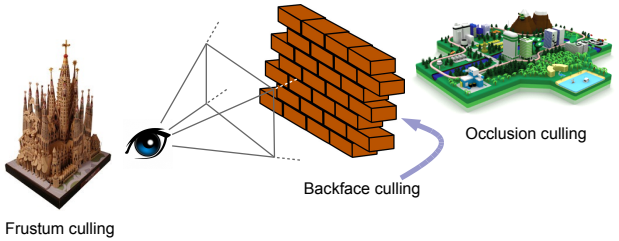
Nvidia 2070
$500
24M shaded polygons in 40 fps
Approximately. Depends on various parameters

Largescale Rendering Cheat Sheet

- Don't render what you can't see
- Don't render what the display can't resolve
- People won't notice small errors, especially in background objects
- If all else fails, fog is your best friend :)

Don't render what you can't see

- Rasterizing invisible objects is wasteful
- Detect such objects early and ignore (***cull***) them



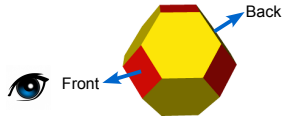
Difficulty

Backface < Frustum <<< Occlusion

Backface Culling

- Drop faces on the far side of object meshes
  - Assume face normals consistently point **inside-out**
  - Back faces have **normals pointing away** from the camera
- OpenGL:

```
glEnable(GL_CULL_FACE);
glCullFace(GL_BACK);
```

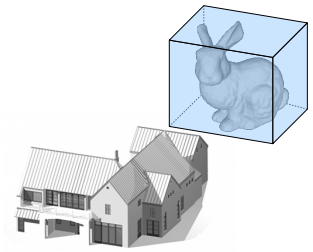


Frustum Culling

- Test each object against the view frustum
  - Much faster: **test the bounding box** instead
    - If object is visible, no frustum plane can have all 8 corners on invisible side
- Optimization:
  - **Group objects hierarchically**
    - ***Octree*** (or ***quadtree*** for 2.5D scenes)
    - ***Binary Space Partitioning (BSP) tree*** (or a restricted version called a ***kd-tree***)
    - ***Bounding box/sphere hierarchy***
  - Traverse tree top-down and ignore subtrees whose roots fail the bounding box test

Hardware Occlusion Queries

- Part of OpenGL/D3D API
- At any time, pretend to draw a dummy shape (say the bounding box of a complex object) and check if any pixels are affected
- Accelerated by hierarchical z-buffer
- Works for dynamic scenes



Unoccluded pixels of bounding box, so object is potentially visible

From-Region Visibility

- Preprocessing:
  - Break scene up into regions
  - For each region, compute a ***potentially visible set (PVS)*** of objects
- Runtime:
  - Detect the region containing the observer
  - Render the objects in the corresponding PVS
- PVS is usually quite conservative, so further culling is needed

Portal-Based Rendering

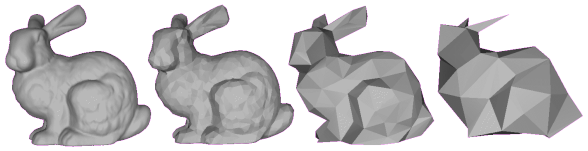
- Suitable for indoor environments
- Divide environment into ***cells***, connected by simple polygonal ***portals*** (doors/windows/...)
- Render:
  - Neighboring cells with visible portals (check if projected polygon is within screen limits)
  - Neighbors-of-neighbors with portals visible through the first set of portals
  - ... and so on
- Further culling possible with frusta through portals

Guiding Principle

For every object, choose the **simplest possible representation** that will look nearly the same as the original *when rendered at the current distance*

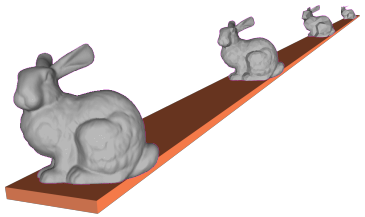
Levels of Detail (LOD)

- **Coarser representations for distant objects**
  - Hierarchy of representations of the same object at different resolutions
- The same idea can also be used for textures (***mipmapping***)



69,451 polys 2,502 polys 251 polys 76 polys

Levels of Detail (LOD)



Environment Maps

- Very distant stuff looks the same from anywhere within reasonable limits
- Pre-render distant objects (including the sky) out to a 360° image
- Texture-map it onto a bounding cube at runtime

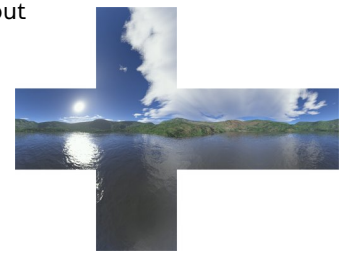
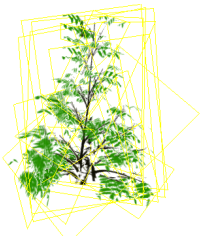


Image-Based Rendering

- Render complex objects to images and texture-map them to simple proxy shapes (***impostors***)
  - Environment mapping is a specific example
- ***Billboards/sprites***: Textured quads always facing the viewer
  - Single image is valid if viewer doesn't move much

Problem: If the place the image of the wolf onto a rectangular billboard, how could we see the grass below the wolf ?

Image-Based Rendering



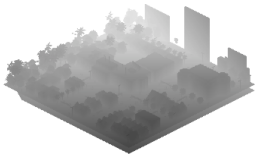
Tree decomposed into a cloud of texture-mapped planar slices

Impostors Original

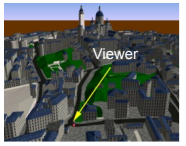
Décoret, Sillion, Durand and Dorsey 2002

Adding Depth to Images

- Store the **depth map** as well as the color
- Impostor is **heightfield** defined by the depth map
- Fixes parallax errors (impostor is still valid when viewing position changes significantly)
- What are the drawbacks?



Images + Geometry



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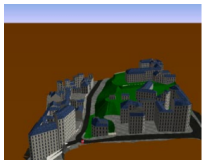

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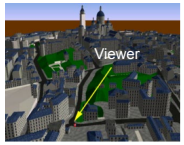
Foreground Background

Images + Geometry



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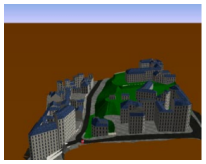

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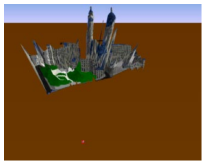
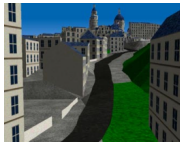


Foreground Background Impostor

Images + Geometry (Rendered View)



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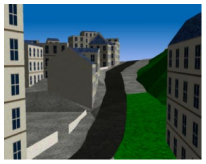

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Foreground Background Impostor

Case Study: Quake

- Preprocessing:
  - Level map preprocessed into BSP-tree
  - Each leaf node stores potentially visible polygons from that region
- Runtime:
  - Leaf node containing player detected by searching the tree (very fast)
  - PVS of polygons for this node are rendered
  - (BSP-tree is NOT used for back-to-front rendering!)

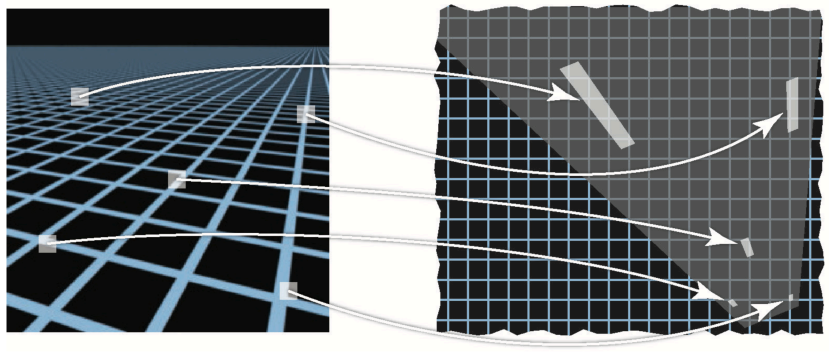
Antialiasing and Mipmaps

Problem: Sampling Textures Can Lead to Aliasing

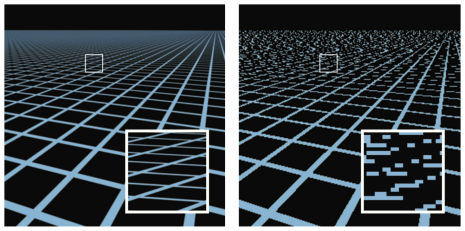
- Just as we've seen with image processing and raytracing applications, if details are not captured with sufficient samples we can see noticeable artifacts
- Solution: use a better sampling/reconstruction

Pixel Footprints

- Can vary in size, shape, and orientation relative to the texture
- Problem: Which of the texture pixels show we pick for each image pixel ? (blue or black)



Answer: neither blue nor black is correct. We need to average them.

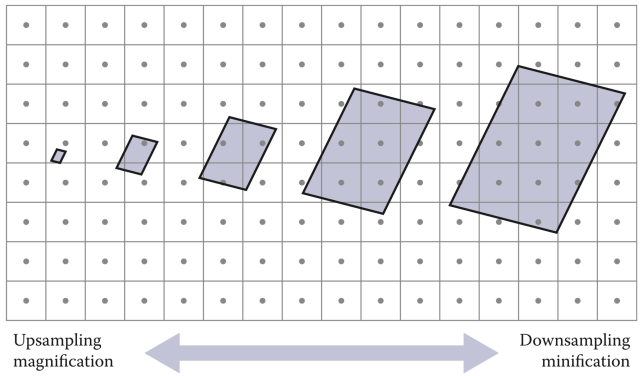


High-resolution image Point sampling

To resolve the aliasing problem: For each rendered image pixel, we need to average multiple texture pixels. Their number might be large.

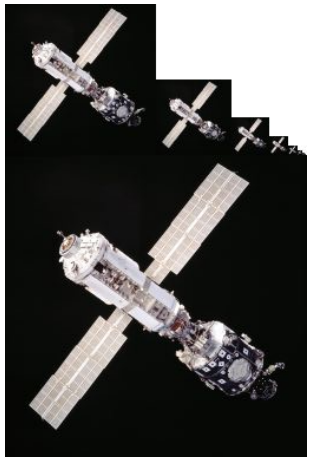
Sampling and Reconstruction

- If footprint is small, need better reconstruction (e.g. bilinear instead of nearest neighbor)
- If the footprint is large, need to average many samples



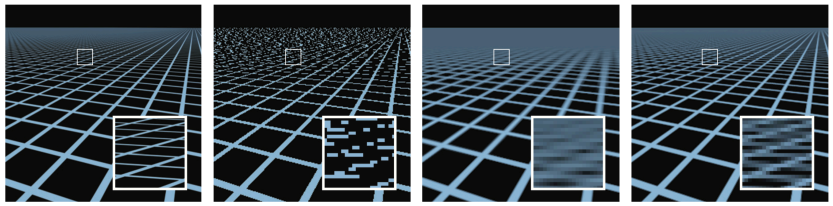
Mipmaps

- More or less the same idea as “level of details”
- Antialiasing is only one of the applications of mipmaps
- To quickly compute averages, store the texture at multiple resolutions
- For each lookup, estimate the size of the footprint and index into the mipmap accordingly



https://en.wikipedia.org/wiki/Mipmap

Correcting Aliasing



High-resolution image Point sampling

Demo (Amir)