GPU Programming:
Environment Mapping
Bump Mapping
Displacement Mapping
Shadow Mapping

Spring 2022

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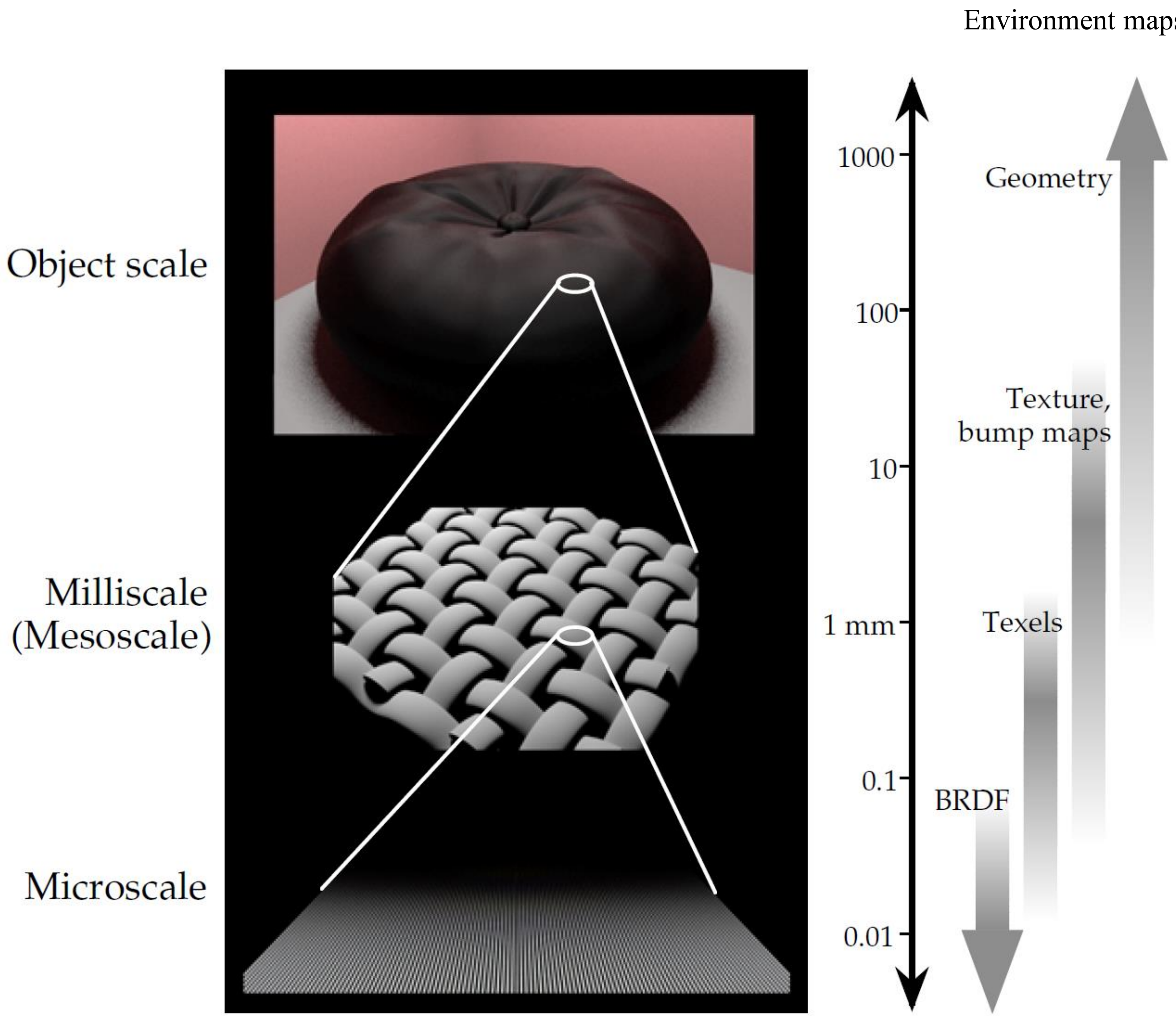


Figure 1: Applicability of Techniques

Environment Mapping (or Reflection Mapping)

- Blinn, J. F. and Newell, M. E. Texture and reflection in computer generated images. Communications of the ACM Vol. 19, No. 10 (October 1976), 542-547

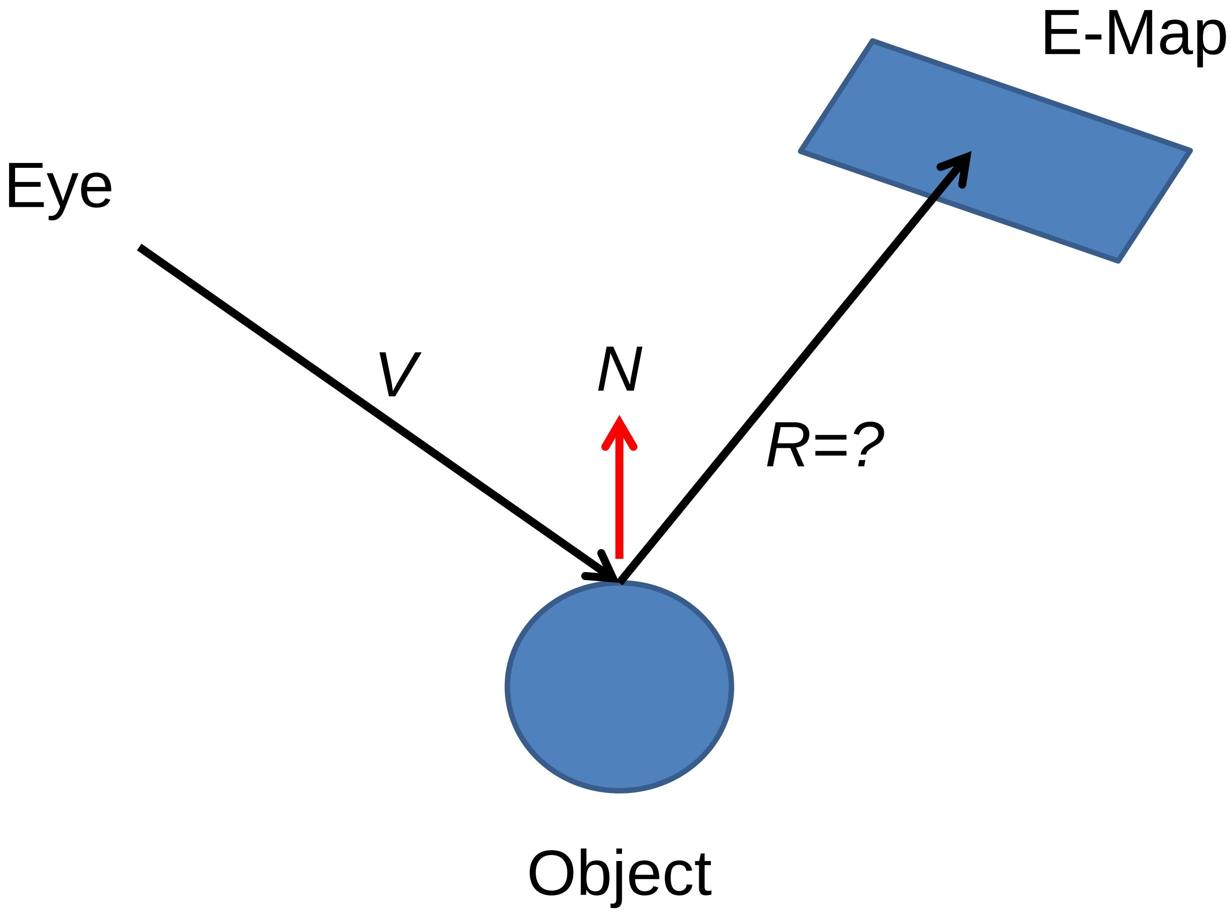
- The Abyss

- Terminator II

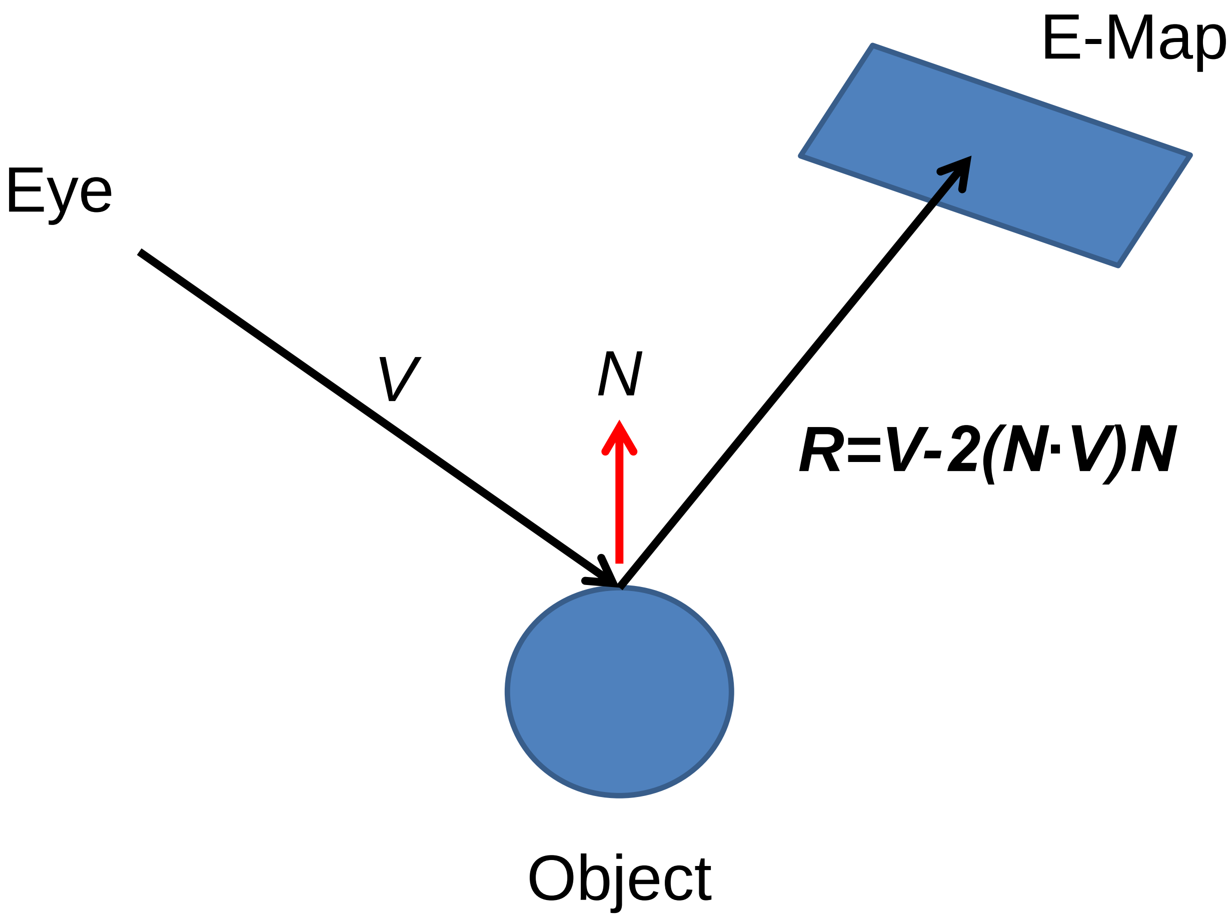
Environment Mapping

- Approximation
  - if the object is small compared to the distance to the environment, the illumination on the surface only depends on the direction of the reflected ray, *not* on the point position on the object
- Algorithm
  - pre-compute the incoming illumination and store it in a texture map

Environment Mapping



Environment Mapping



Environment Maps Forms

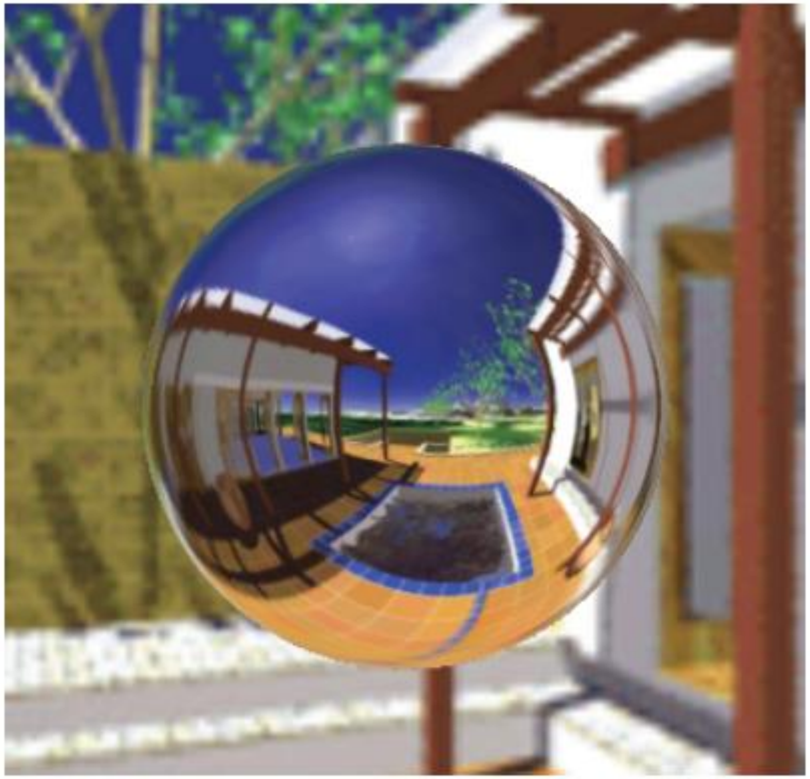
- Spherical Mapping
- Cubical Mapping (or Cube Map)
- Paraboloidal Mapping

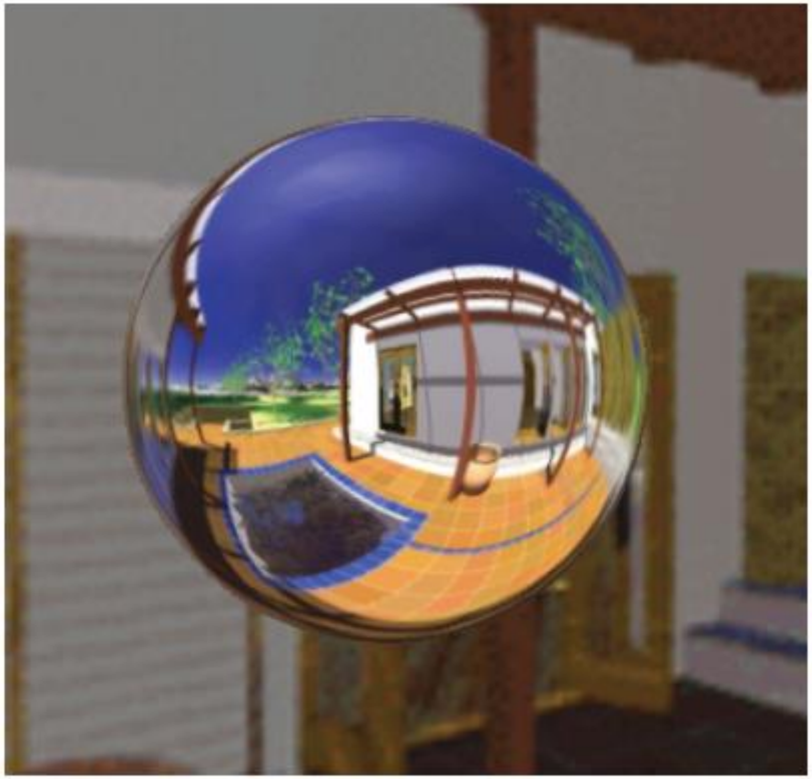
Spherical Mapping

Spherical Mapping

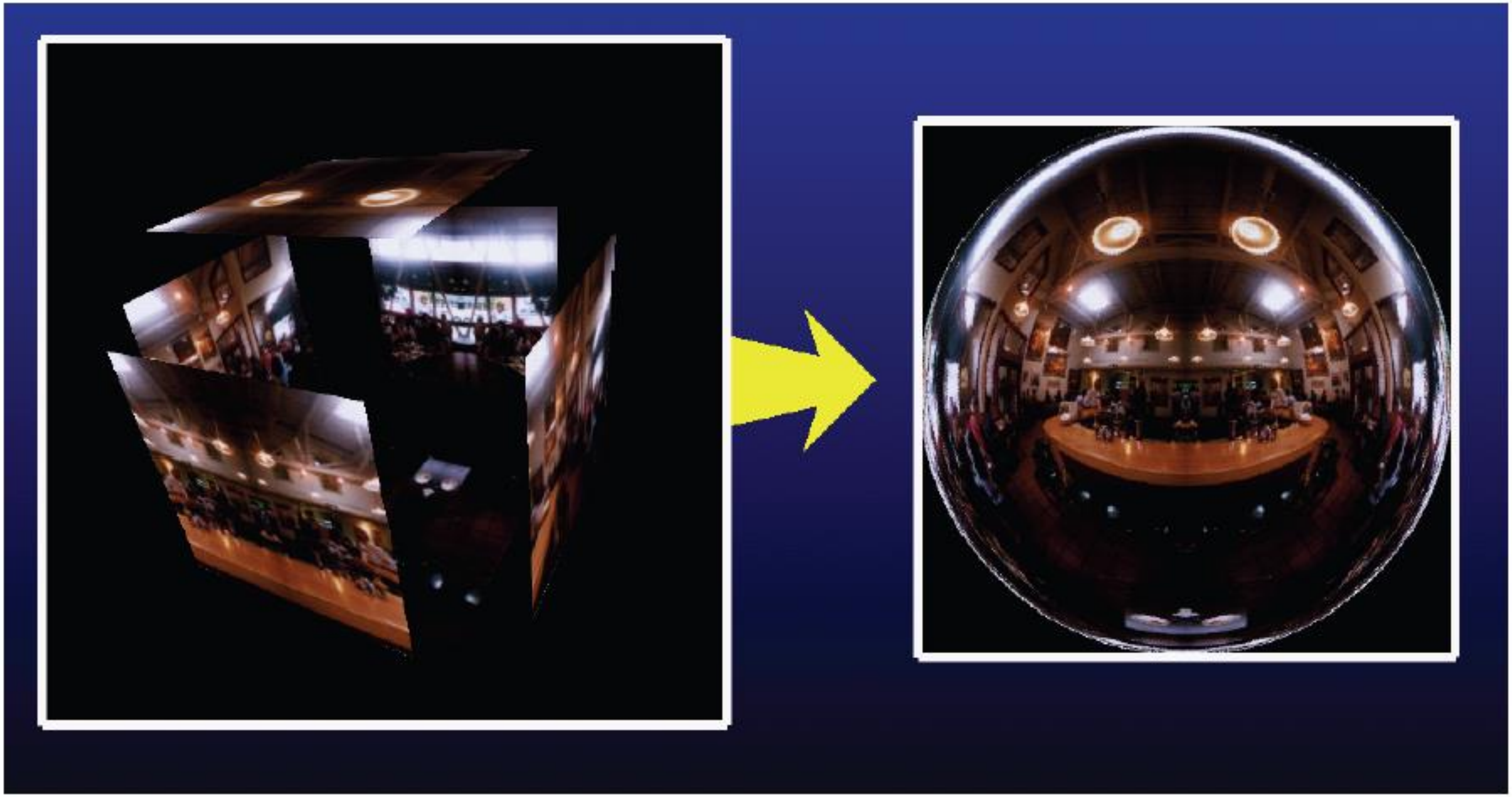
Spherical Mapping

Spherical Mapping: Renderings

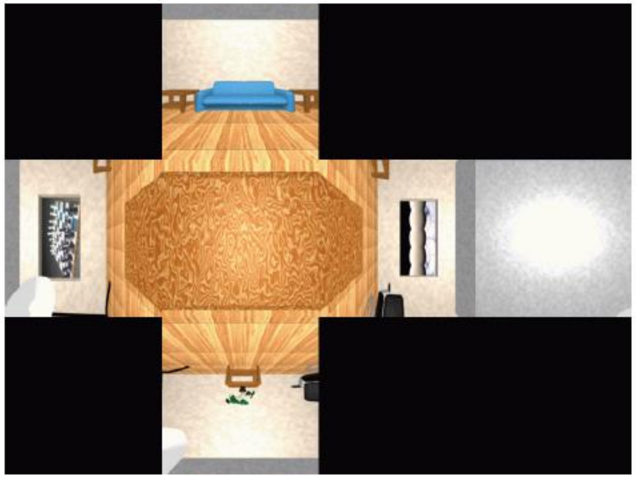




Cubical Mapping

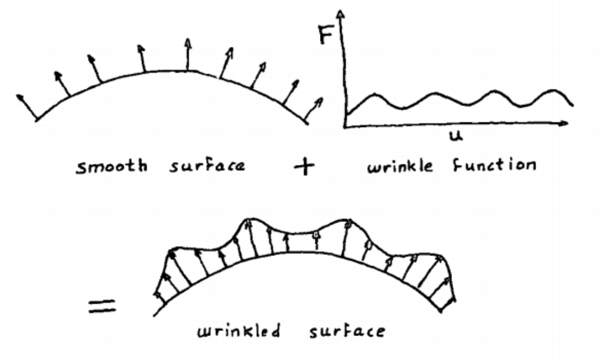


Cubical Mapping: Renderings

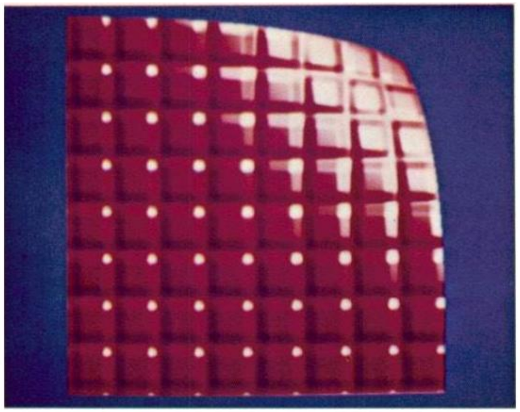


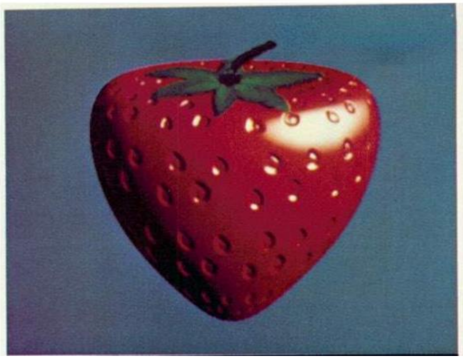
Bump Mapping

- Blinn, "Simulation of Wrinkled Surfaces", *Computer Graphics*, (Proc. Siggraph), Vol. 12, No. 3, August 1978, pp. 286-292. [PDF]



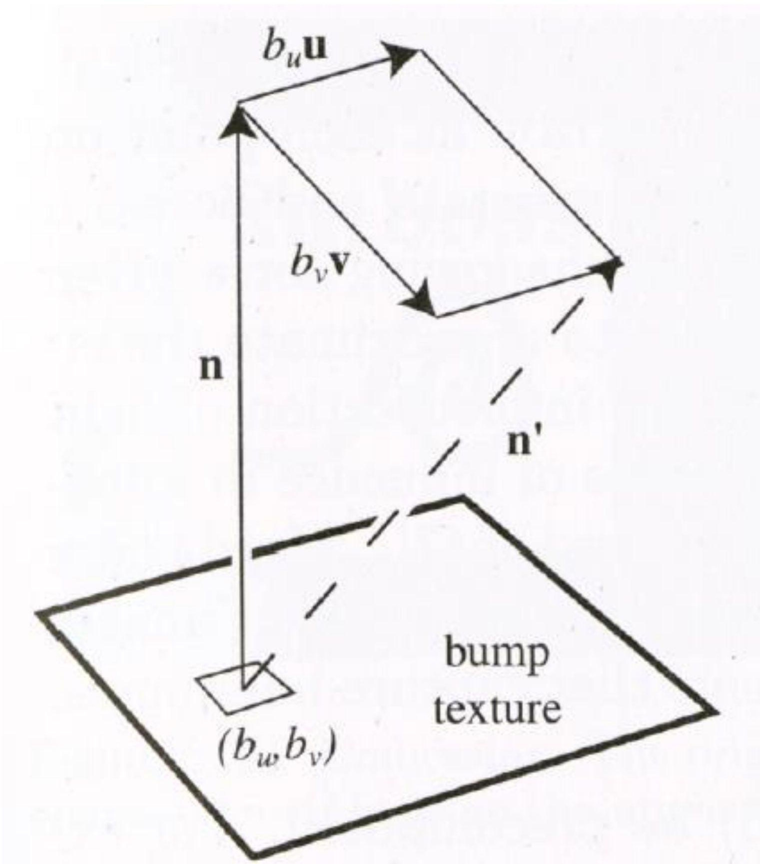
- Simulates small surface variations
- Key idea: tweak normals used for lighting (geometry stays the asme)
- Benefit: much more efficient, geometry-wise, than creating an approximation using very small triangles

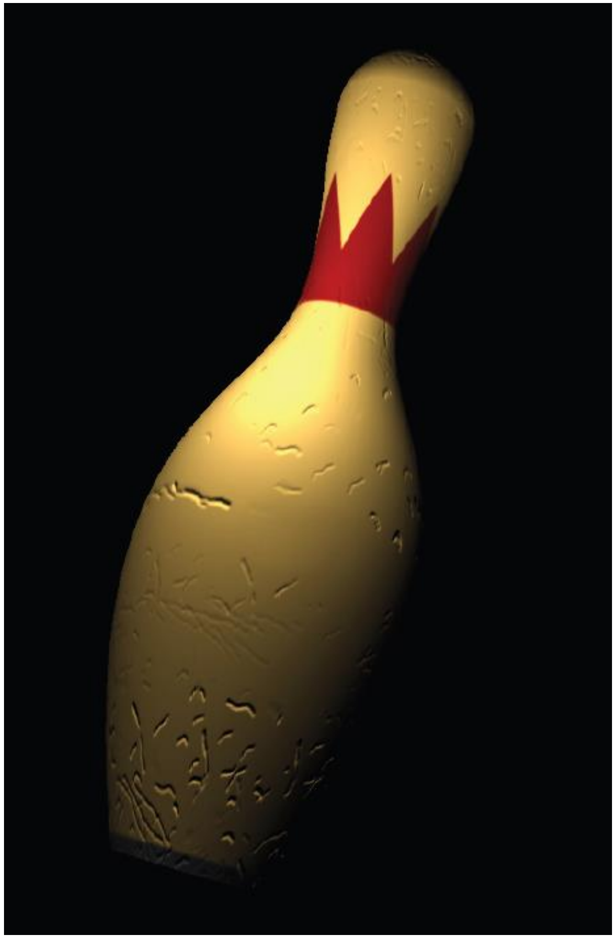




Bump Mapping

- Each texel stores two offsets (in u and in v)



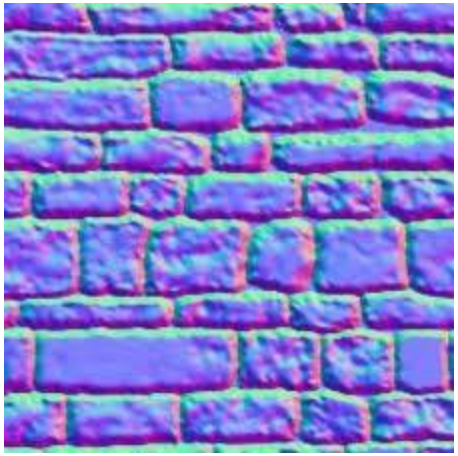


Bump Mapping Demo

- https://apoorvaj.io/exploring-bump-mapping-with-webgl/

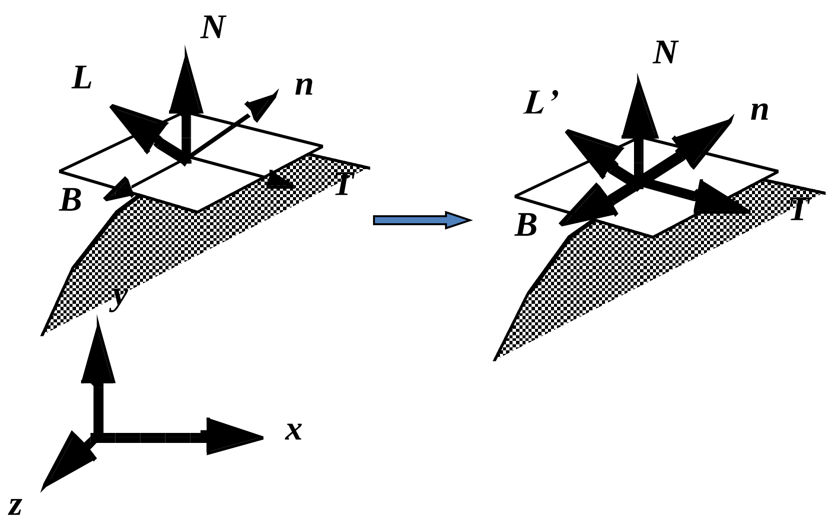
Normal Map (used for Bump Mapping)

- Use texel values to modify vertex/pixel normals of polygon
- Texel values correspond to normals (or heights) modifying the current normals
- RGB = (**n**+1)/2
- **n** = 2*RGB – 1



Bump Mapping

- The light source direction ***L*** and pixel normal ***N*** are represented in the global coord ***x, y, z***
- The bump map normal ***n*** is in its local coordinates, which is called *tangent space* or *texture space*
  - *T: tangent vector*
  - *N: surface normal*
  - *B: bitangent*
  - *How to compute TNB?*



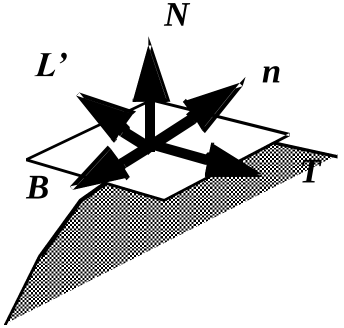
Bump Mapping

- Given triangle $\{v_1, v_2, v_3\}$:

$T = (v_2 - v_1) / | v_2 - v_1 |$

$N = T' / | T' |$ (or $(v_2 - v_1) \times (v_3 - v_1)$)

$B = T \times N$

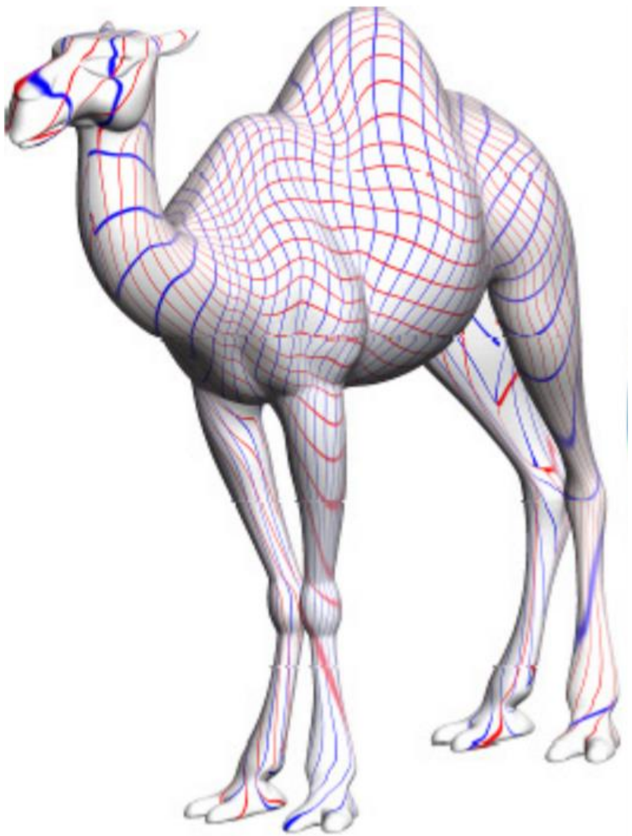


Bump Mapping

- Issue: adjacent triangles do not necessarily have similarly aligned T and B vectors which causes bump discontinuity
- Solutions:
  - 1: Compute TNB per triangle, and flip when it seems necessary
    - Might not work in all cases…

Bump Mapping

- Solutions:
  - 2: Assume a nicely organized mesh of triangles
    - Works, but assume a nicely organized mesh of triangles



Bump Mapping

- Solutions:
  - 3: Use a 2D parameterization of the object surface
    - Works, but assumes a 2D parameterization
    - **How to compute such a 2D parameterization?**

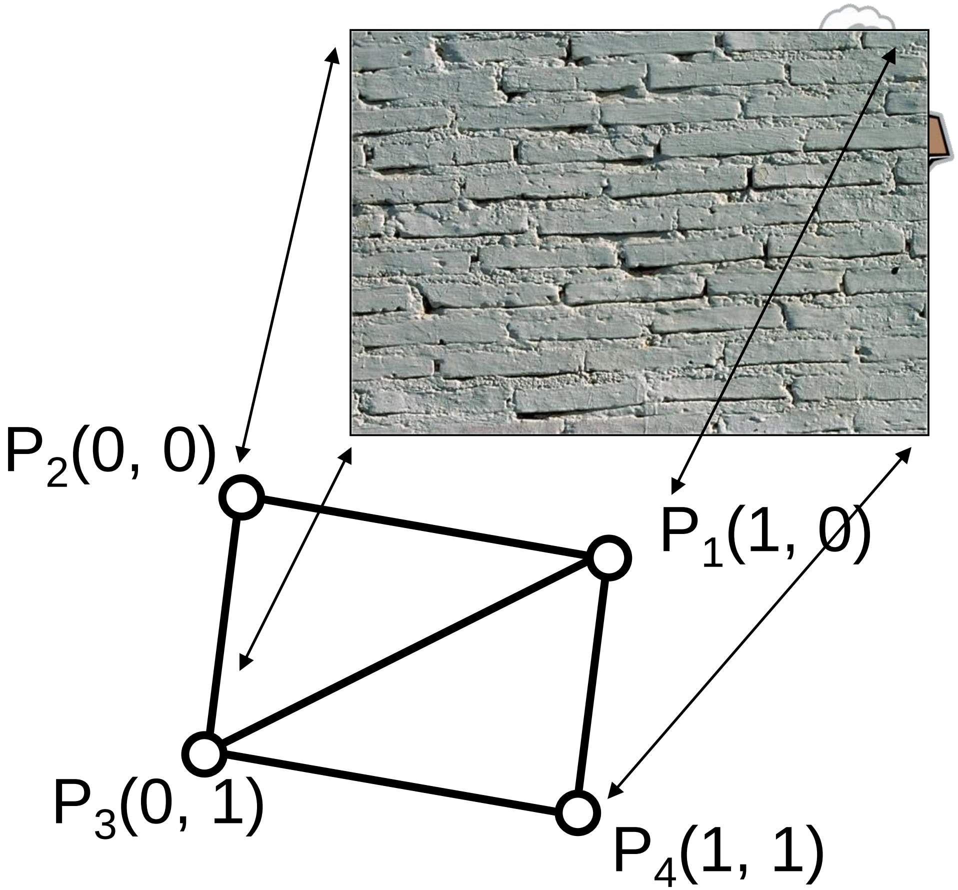
Texture Coordinate Generation (or 2D/UV Parameterization)

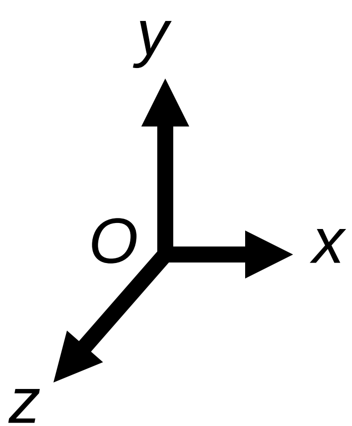
- Recall texture mapping…

Texture Mapping

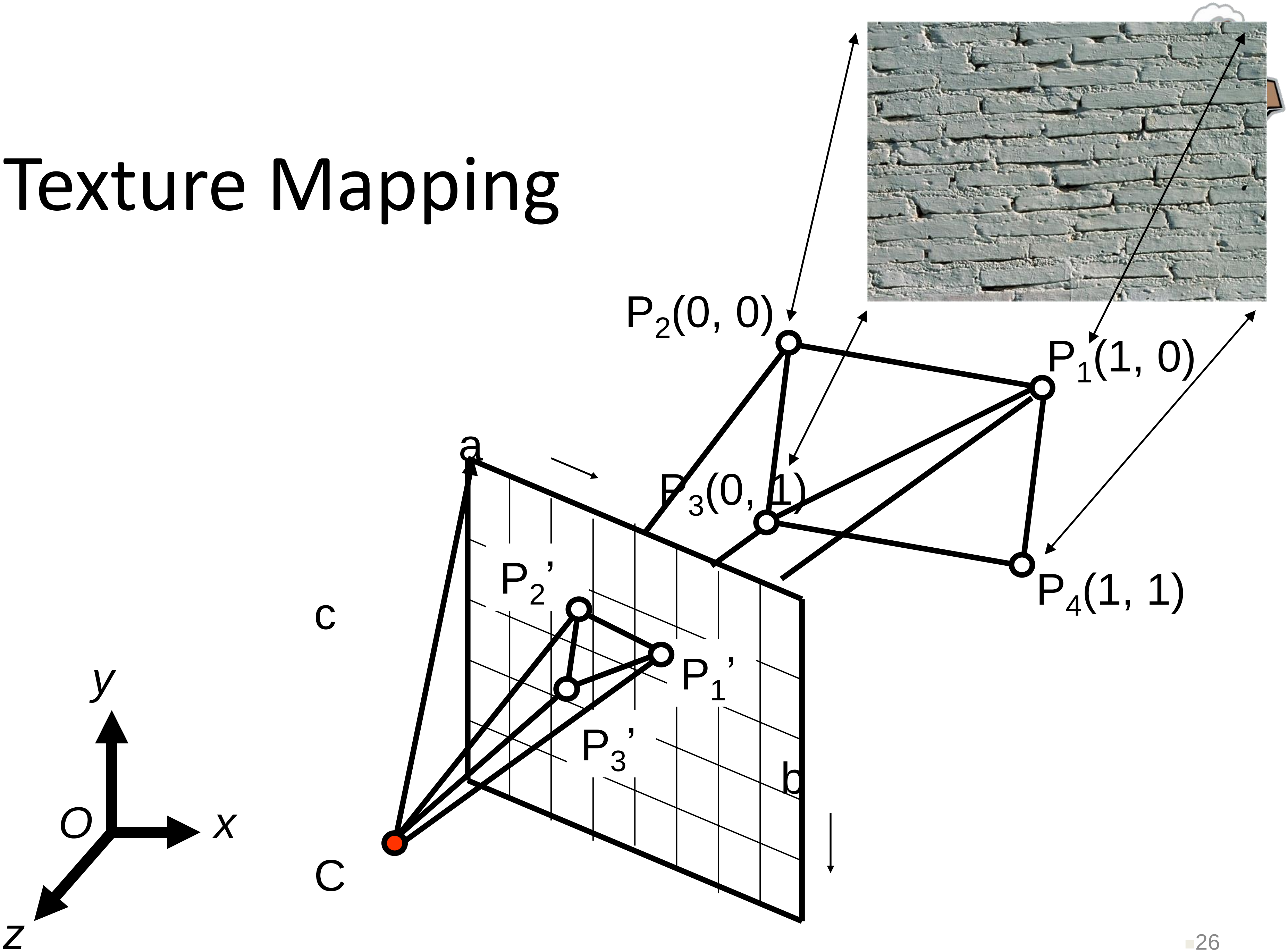
- Mechanism for attaching a texture (or image) to the modeled surface
  - *texels* – color samples in texture maps
  - corners of the image are (0, 0), (0, 1), (1, 1), and (1, 0)
  - tiling indicated with tex. coords. > 1
  - a pair of floats (s, t) for each (triangle) vertex

Texture



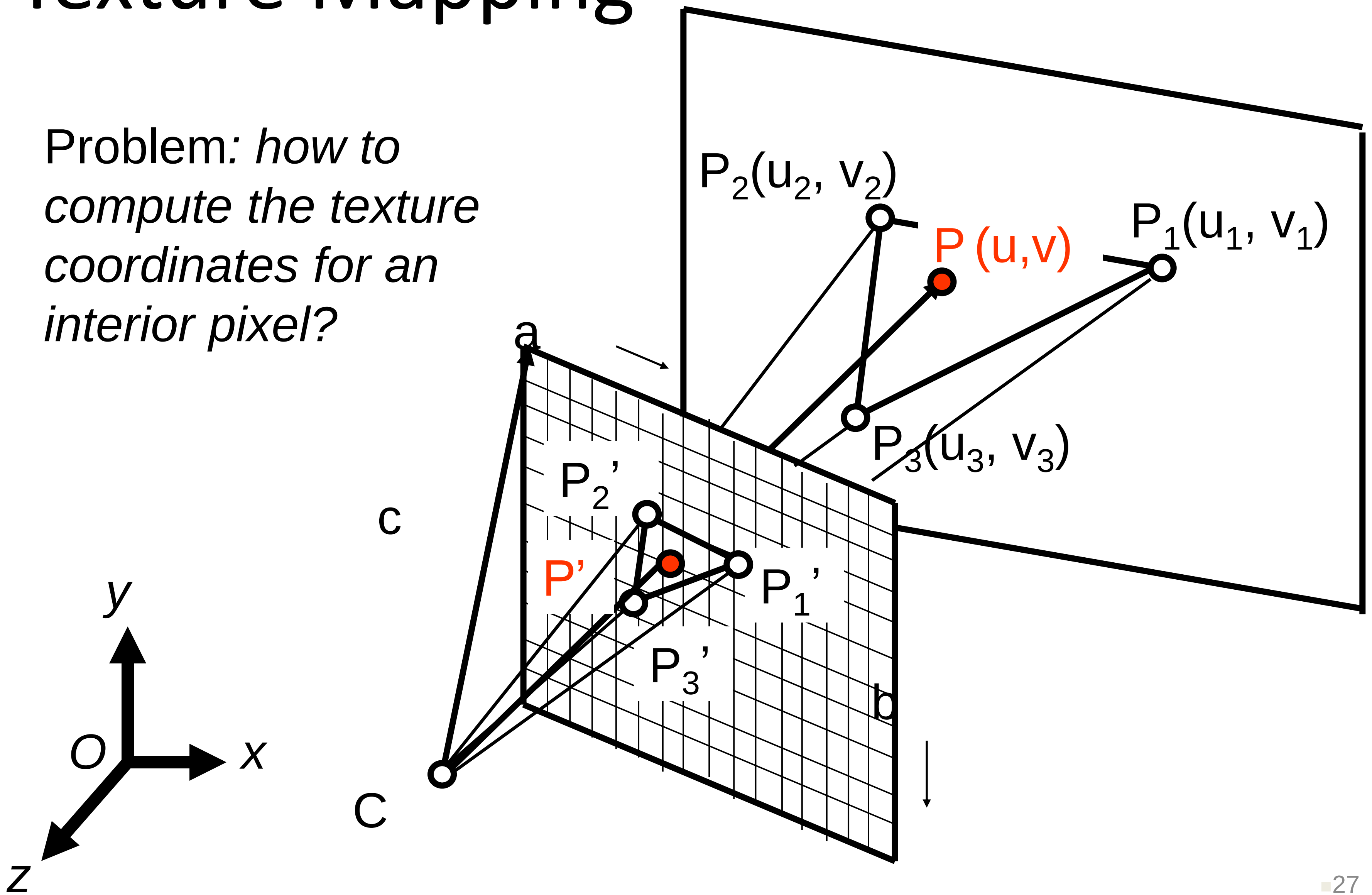


Texture Mapping



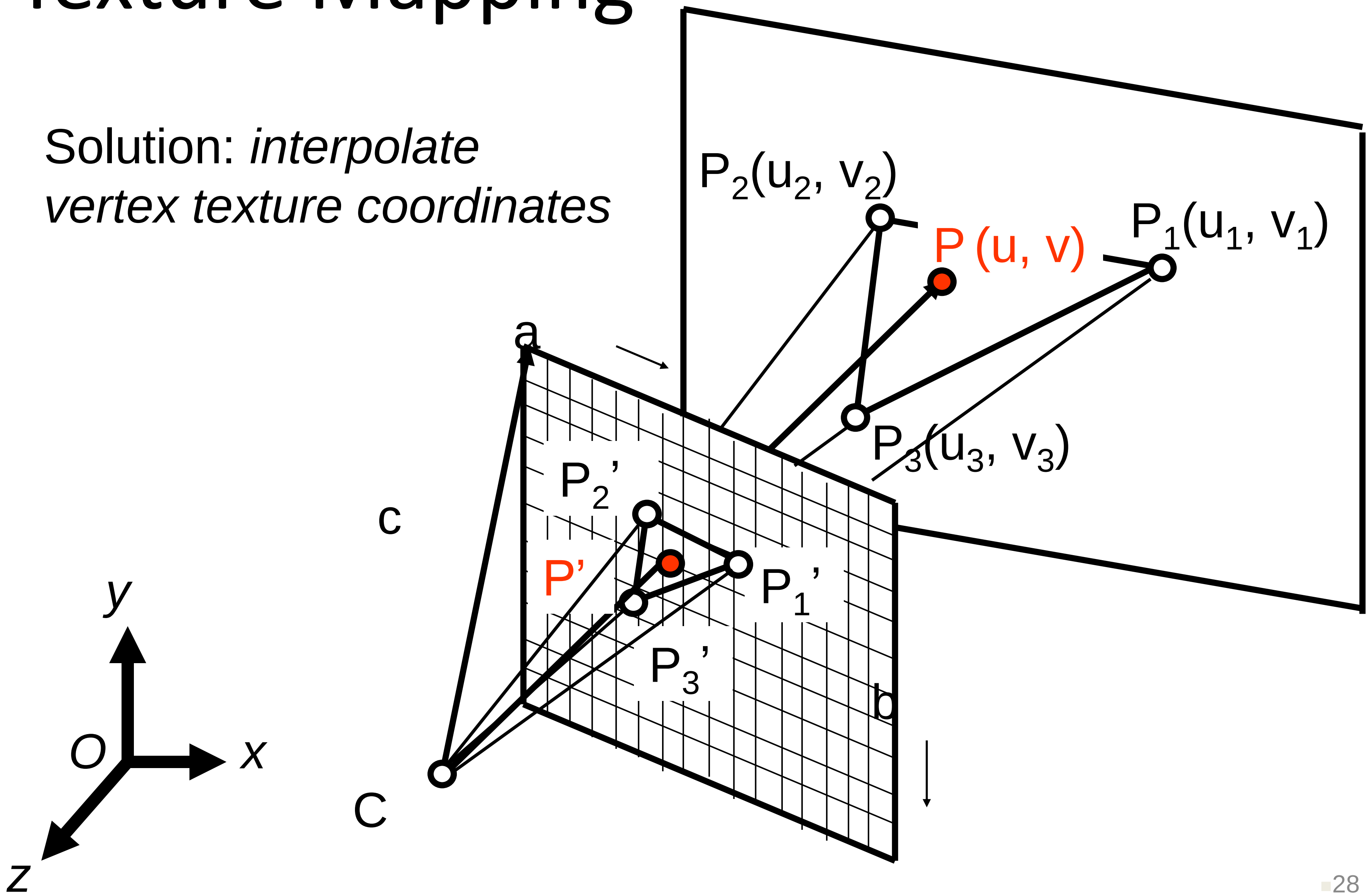
Texture Mapping

Problem: *how to compute the texture coordinates for an interior pixel?*



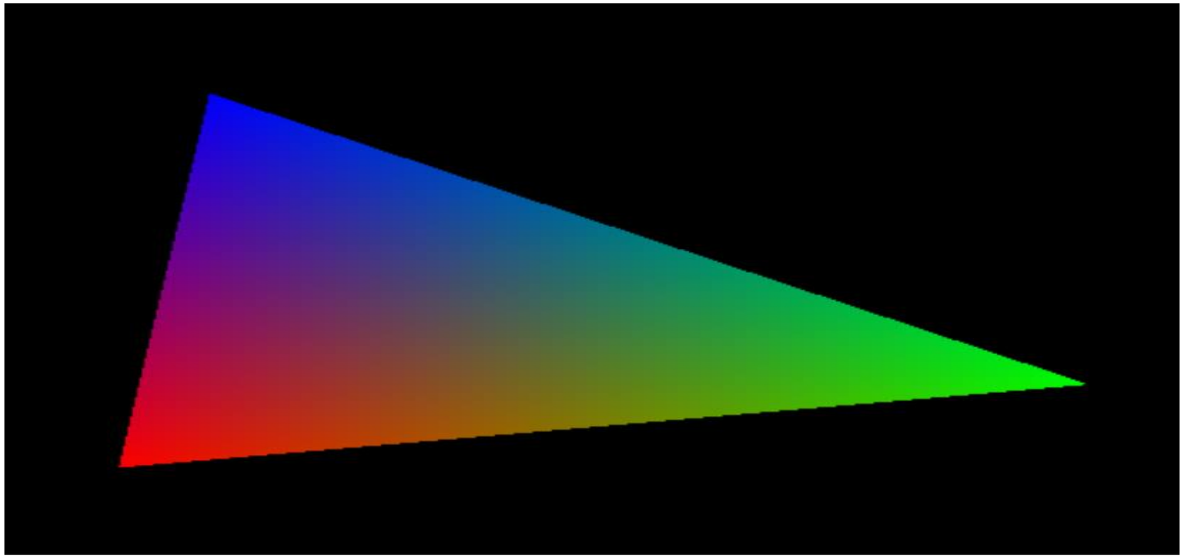
Texture Mapping

Solution: *interpolate vertex texture coordinates*



Parameter Interpolation

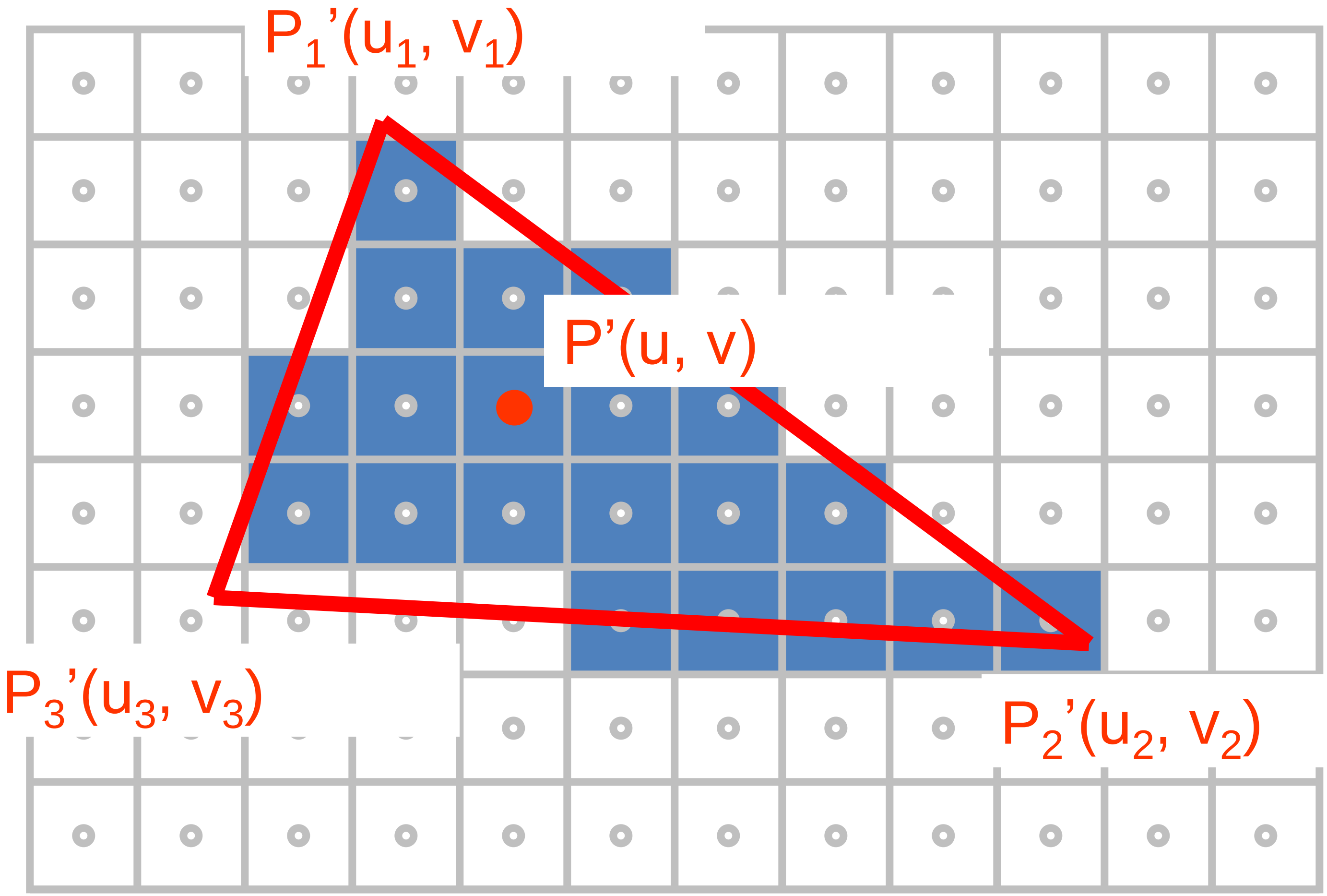
- Texture coordinates, colors, normals, etc.



- How?
  - Use barycentric coordinates…
  - **Or, this is actually done by the GPU as "varying" parameters in the fragment shader**

Interpolation on the GPU

From the vertex values, the GPU interpolates texture coordinates for the intermediate pixels (as well as other values if so desired)



Fragment Shader

```
// Fragment shader
uniform sampler2D tex;
varying vec2 v_texCoord;

void main(void)
{
   gl_FragColor = texture2D(tex, v_texCoord);
}
```

Texture Coordinate Generation (or 2D/UV Parameterization)

- How to generate/compute texture coordinates?

Texture Coordinate Generation (or 2D/UV Parameterization)

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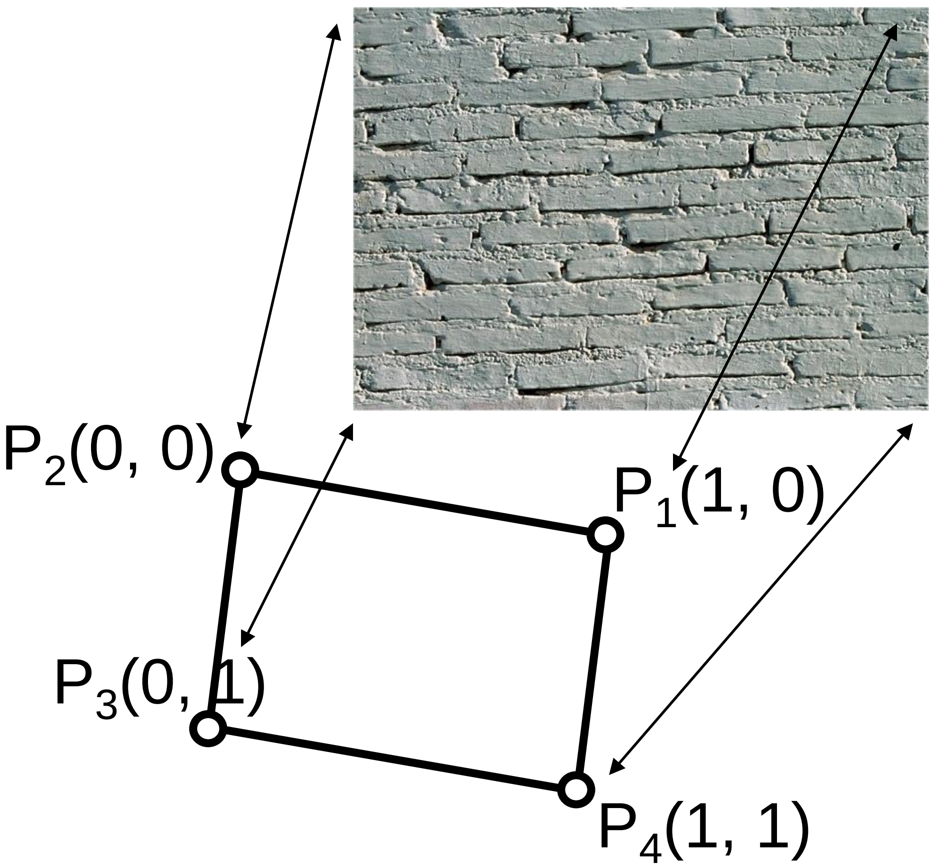
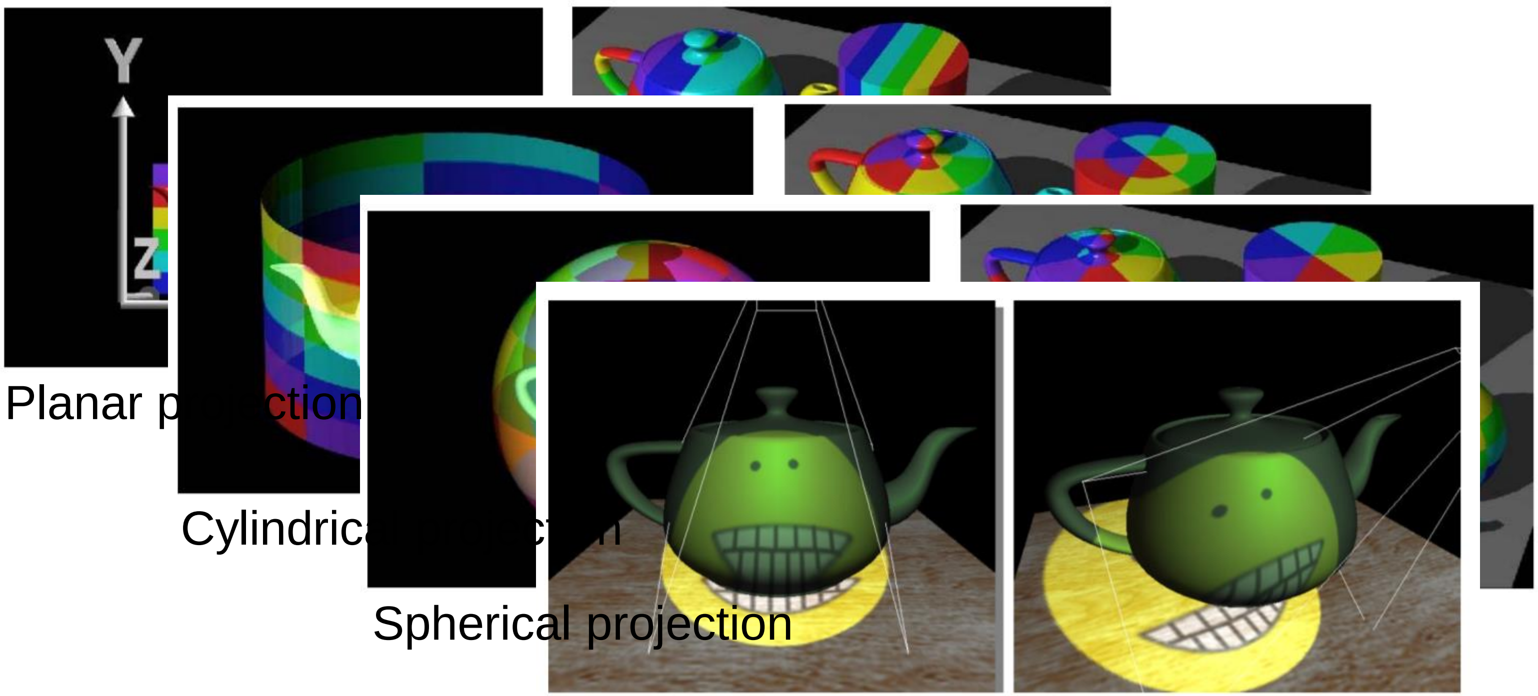


Texture Coordinate Generation (or 2D/UV Parameterization)

- How to generate/compute texture coordinates?



Planar projection

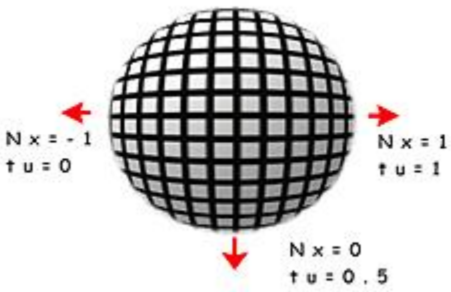
Cylindrical projection

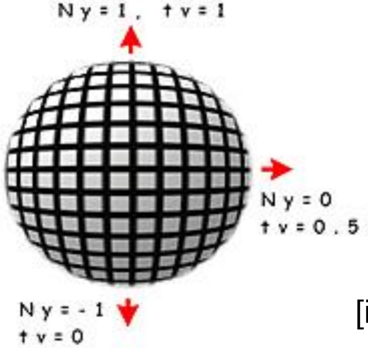
Spherical projection

Projective texture mapping

How to compute spherical projection texture coords?

- Option A:





[images by Robert Dunlop]

$$u = \frac{\operatorname{asin}(N_x)}{\pi} + 0.5$$

$$v = \frac{\operatorname{asin}(N_y)}{\pi} + 0.5$$

How to compute spherical projection texture coords?

- Option B:
  - Compute normal as vector from center thru point

$$N = (p - c)/\|p - c\|$$

Then, option A:

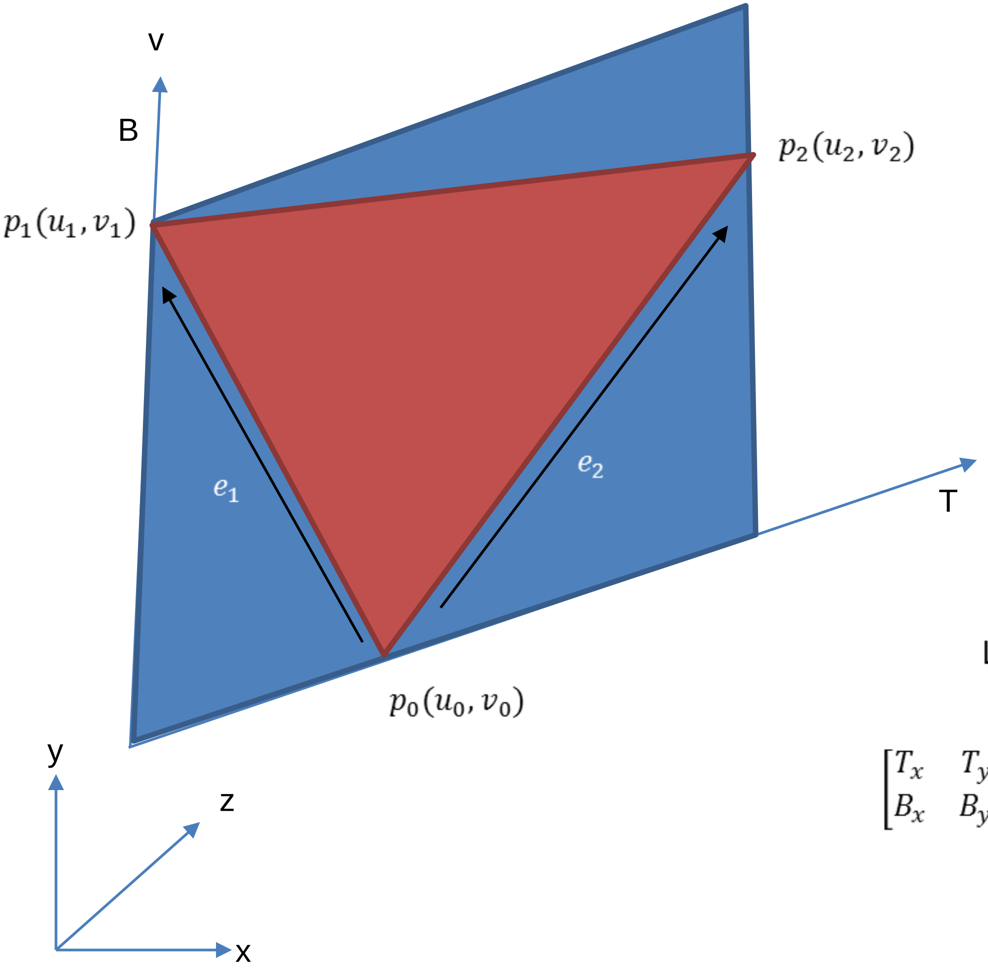
$$u = \frac{\operatorname{asin}(N_x)}{\pi} + 0.5$$

$$v = \frac{\operatorname{asin}(N_y)}{\pi} + 0.5$$

TNB Frame

- You have texture coordinates and surface normal
- How to compute TNB frames aligned between pixels/triangles?

TNB Frame



$$e_1 = (u_1 - u_0)T + (v_1 - v_0)B$$
$$e_2 = (u_2 - u_0)T + (v_2 - v_0)B$$

$$[e_{1x} \quad e_{1y} \quad e_{1z}] = \Delta u_1 [T_x \quad T_y \quad T_z] + \Delta v_1 [B_x \quad B_y \quad B_z]$$
$$[e_{2x} \quad e_{2y} \quad e_{2z}] = \Delta u_2 [T_x \quad T_y \quad T_z] + \Delta v_2 [B_x \quad B_y \quad B_z]$$

$$\begin{bmatrix} e_{1x} & e_{1y} & e_{1z} \\ e_{2x} & e_{2y} & e_{2z} \end{bmatrix} = \begin{bmatrix} \Delta u_1 & \Delta v_1 \\ \Delta u_2 & \Delta v_2 \end{bmatrix} \begin{bmatrix} T_x & T_y & T_z \\ B_x & B_y & B_z \end{bmatrix}$$

Left multiply by inverse of $\begin{bmatrix} \Delta u_1 & \Delta v_1 \\ \Delta u_2 & \Delta v_2 \end{bmatrix}$ and obtain T and B:

$$\begin{bmatrix} T_x & T_y & T_z \\ B_x & B_y & B_z \end{bmatrix} = \frac{1}{\Delta u_1 \Delta v_2 - \Delta u_2 \Delta v_1} \begin{bmatrix} \Delta v_2 & -\Delta v_1 \\ -\Delta u_2 & \Delta u_1 \end{bmatrix} \begin{bmatrix} e_{1x} & e_{1y} & e_{1z} \\ e_{2x} & e_{2y} & e_{2z} \end{bmatrix}$$

Adjacent TNB Frames

- For neighboring triangles with slightly different normals and tangent values, the TNB frames differ a small amount

- One option is to average the neighboring "tangent" vectors

- However, this might make the TNB frame no longer orthogonal

- Solution?
  - We can re-orthogonalize using a simplied version of Gram-Schmidt orthogonalization:
  - Given T and N
  - $T = normalize(T - (T \cdot N)N)$
  - $B = N \times T$

Fragment Shader Simple

```
vec3 CalcBumpedNormal()
{
   // grab a copy of the TNB computed as described in previous slides
   vec3 Normal = normalize(Normal0);
   vec3 Tangent = normalize(Tangent0);
   vec3 Bitangent = normalize(Bitangent0);

   vec3 BumpMapNormal = texture(gNormalMap, TexCoord0).xyz;
   BumpMapNormal = 2.0 * BumpMapNormal - vec3(1.0, 1.0, 1.0);
   vec3 NewNormal;
   mat3 TBN = mat3(Tangent, Bitangent, Normal);
   NewNormal = TBN * BumpMapNormal;
   NewNormal = normalize(NewNormal);
   return NewNormal;
}

void main()
{
   vec3 Normal = CalcBumpedNormal();
   ...
```

Fragment Shader

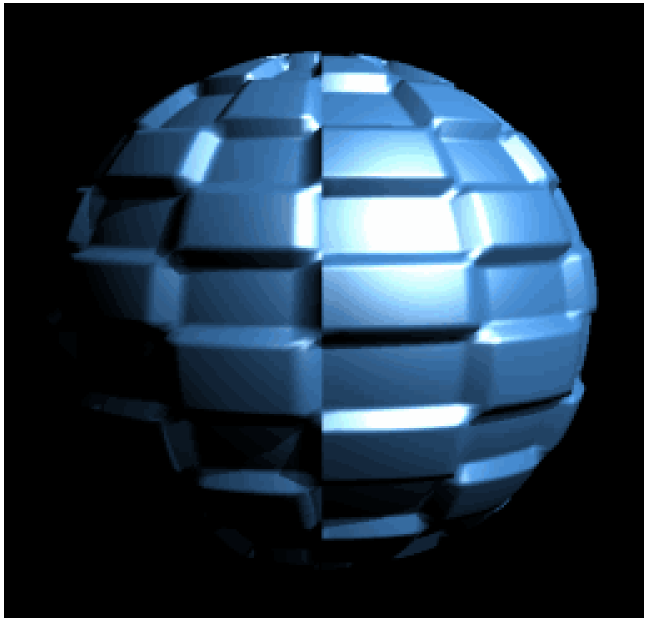
```
vec3 CalcBumpedNormal()
{
    // grab a copy of the TN computed as described in previous slides
   vec3 Normal = normalize(Normal0);
   vec3 Tangent = normalize(Tangent0);
   Tangent = normalize(Tangent - dot(Tangent, Normal) * Normal);   // re-orthogonalize
   vec3 Bitangent = cross(Tangent, Normal); // we don't actually need to use the precomputed Bitangent0

   vec3 BumpMapNormal = texture(gNormalMap, TexCoord0).xyz;
   BumpMapNormal = 2.0 * BumpMapNormal - vec3(1.0, 1.0, 1.0);
   vec3 NewNormal;
   mat3 TBN = mat3(Tangent, Bitangent, Normal);
   NewNormal = TBN * BumpMapNormal;
   NewNormal = normalize(NewNormal);
   return NewNormal;
}

void main()
{
   vec3 Normal = CalcBumpedNormal();
   ...
```

Displacement Mapping

- Bump mapping
  - can be at pixel level
  - has no geometry/shape change
- Displacement Mapping
  - Actually modify the surface geometry (vertices)
  - re-calculate the normals
  - Can include bump mapping

Displacement Mapping

- Bump mapped normals are inconsistent with actual geometry. No shadow.
- Displacement mapping affects the surface geometry
  - Texture stores "offset along the normal"



Short Video with Cool Music

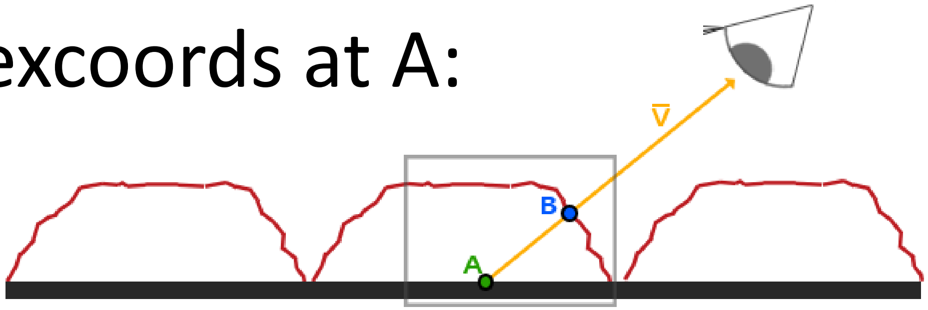
- https://www.youtube.com/watch?v=1mdR2imNeZI

Even More…

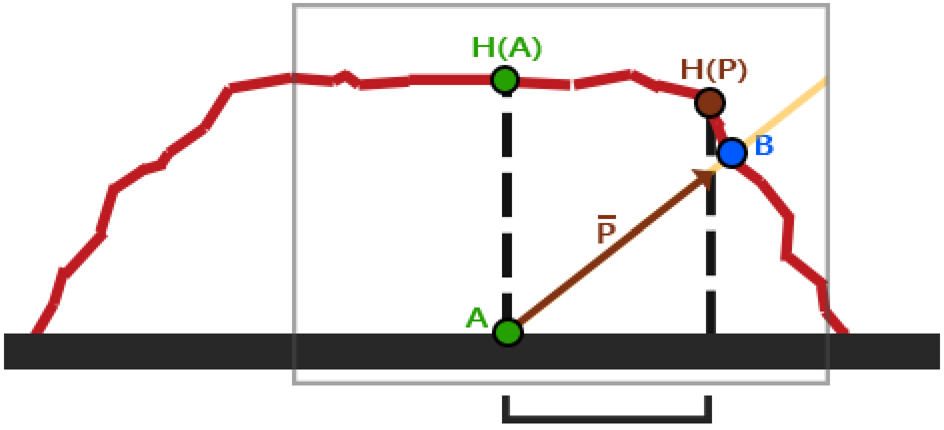
- Parallax Mapping
  - Offsets texture coordinates
  - https://www.youtube.com/watch?v=6PpWqUqeqeQ
  - Improvements: Steep Parallax Mapping, Parallax Occlusion Mapping
- Relief Mapping
  - Offsets heights to recompute normals
  - https://www.youtube.com/watch?v=_erYebogWUw
  - https://www.youtube.com/watch?v=5gorm90TXJM

Parallax Mapping (briefly)

- Normally, you use texcoords at A:



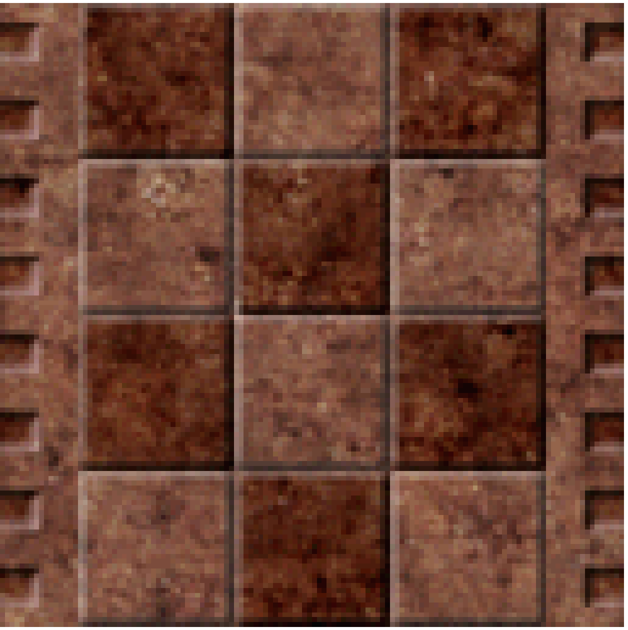
- Instead, we want to walk-back by P to find B texcoords:



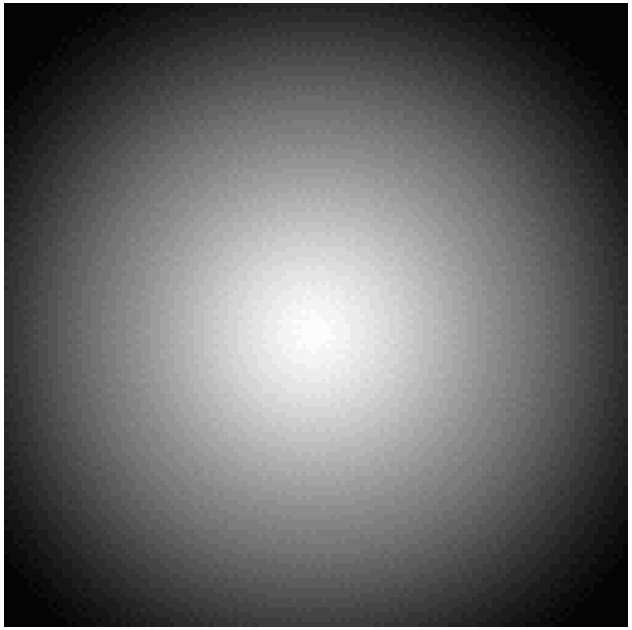
[see https://learnopengl.com/Advanced-Lighting/Parallax-Mapping]

Light Mapping

- Pre-render special lighting effects
- Multi-texturing idea: arbitrary texel-by-texel shading calc'd from multiple texture maps



Reflectance Texture

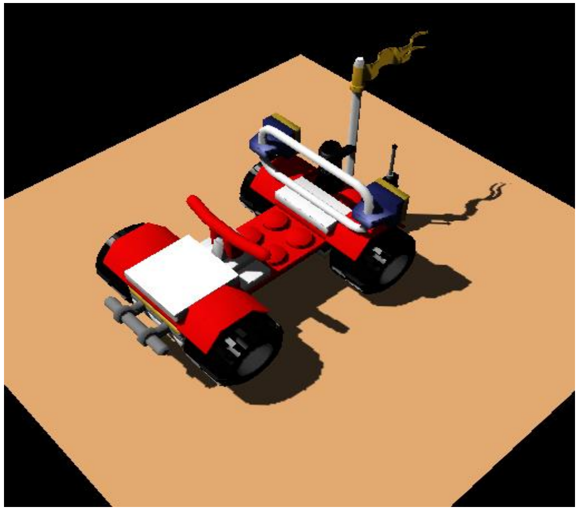


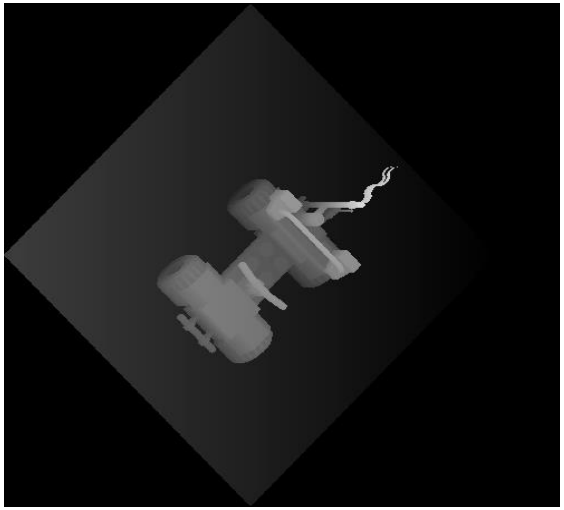
× **Light Map** (Illumination Texture)

= Display texture

Shadow Mapping

- Render scene from light's point of view
  - Store depth of each pixel



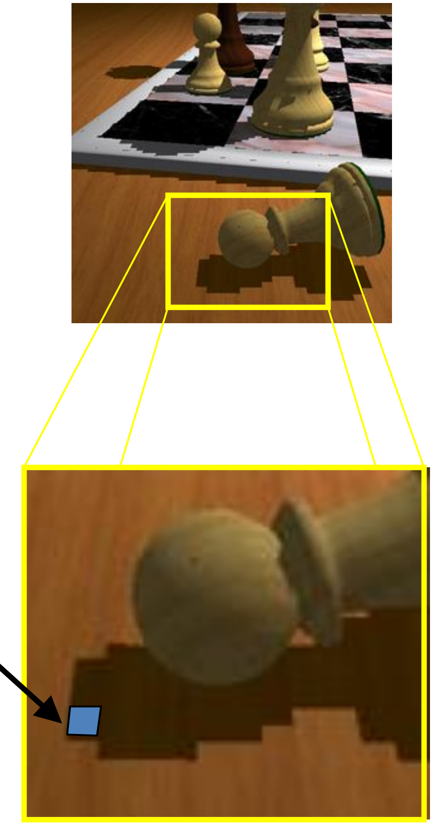


Shadow Mapping

- Render scene from light's point of view
  - Store depth of each pixel
  - From light's point of view, any pixel blocked is in the shadow.
- When shading a surface:
  - Transform surface pixel into light coordinates
  - Compare current surface depth to stored depth. If depth > stored depth, the pixel is in shadow; otherwise pixel is lit
  - Note: can be very expensive timewise…

Resolution Problem:

single shadow map pixel



What can be done?

Higher resolution helps but does not solve…