Texture Mapping

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(601.457/657)

Textures

[J. Birn]

We know how to render geometry.

How do we get:

- Detailed geometry?
- Detailed colors?
- Shadows?

Textures

How should we draw surfaces with complex detail?

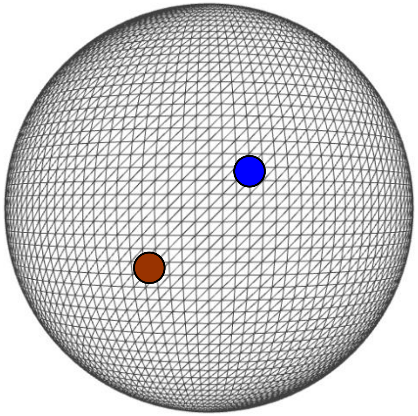
Target Model

Textures

How should we draw surfaces with complex detail?

Direct:
- Tessellate finely and assign material properties to each vertex

Target Model



Complex Surface

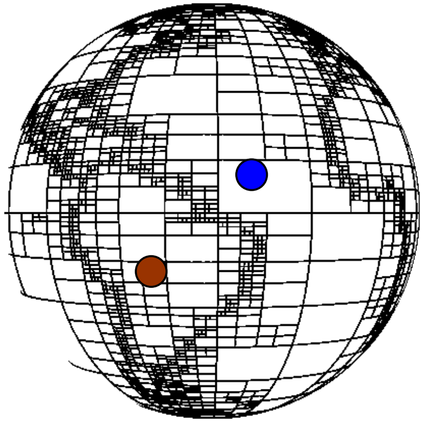
Textures

How should we draw surfaces with complex detail?

Target Model

Direct:

- Tessellate adaptively and assign material properties to each vertex



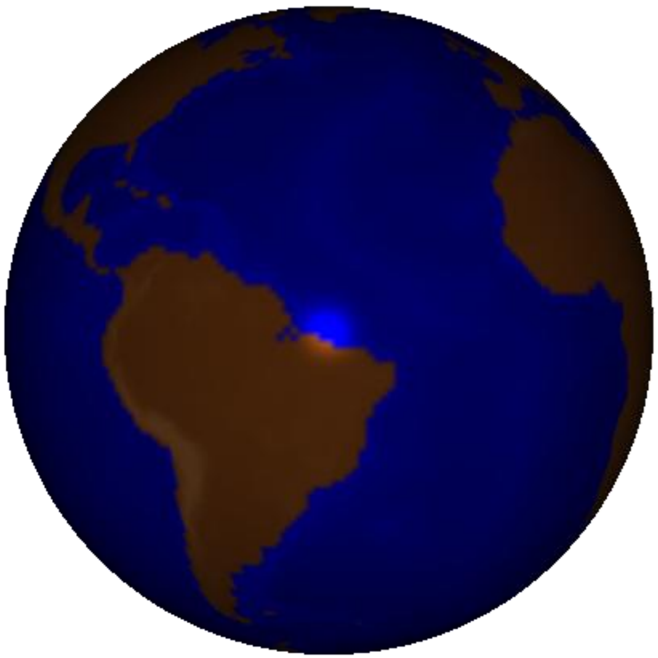
Complex Surface

Textures

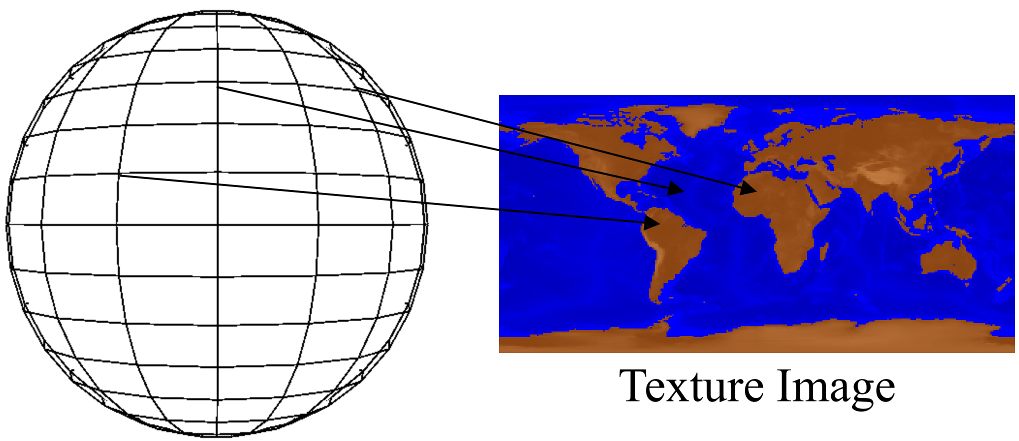
How should we draw surfaces with complex detail?

<u>Indirect</u>:

- Use a simple tessellation with an auxiliary *texture image*.
- Use *texture coordinates* stored at surface points to look up color values from the texture.



Target Model



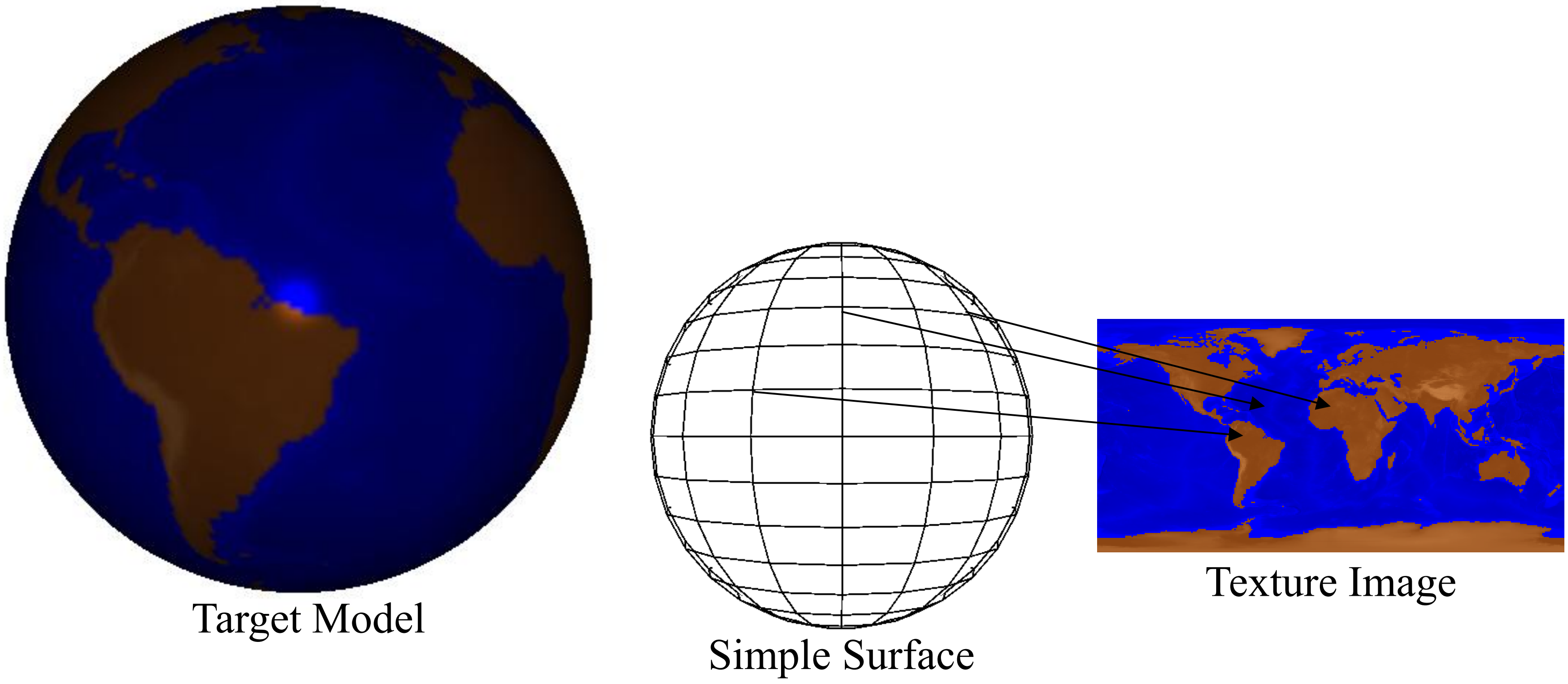
Simple Surface

Texture Image

Textures

Advantages:

- The 3D model remains simple
- It is easier to design/modify a texture image than it is to design/modify a signal on a surface.



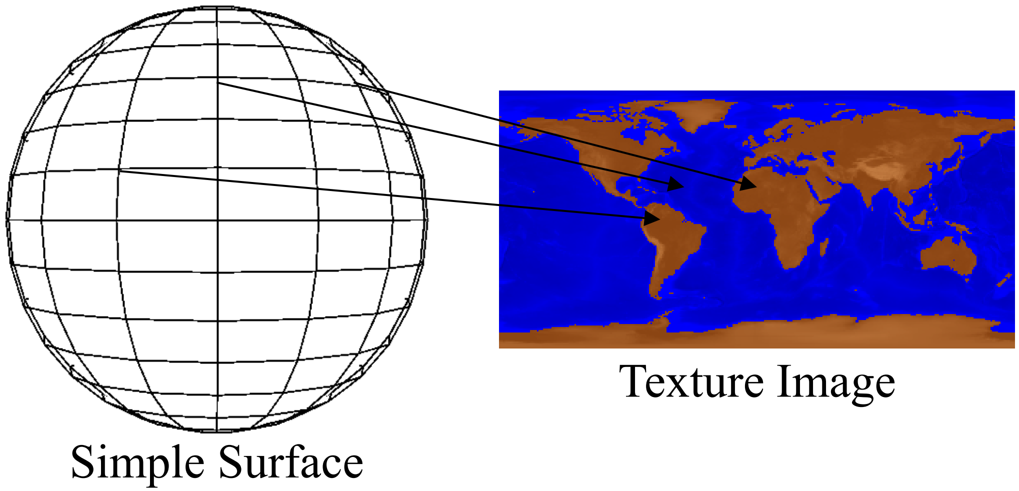
Textures (2 dimensions)

Implementation:

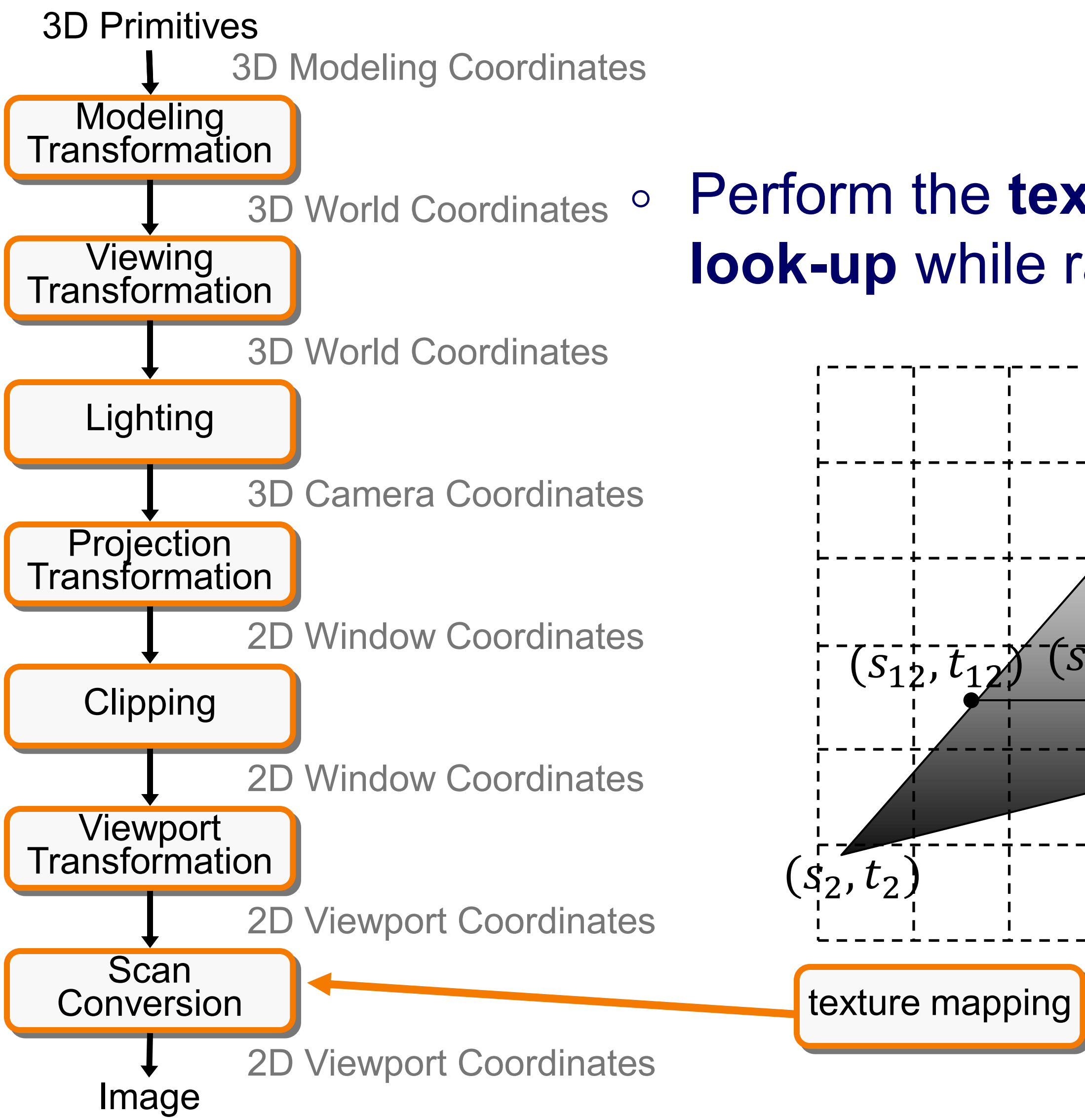
- Associate a *texture coordinate* to each vertex v:
$$(s_v, t_v) \text{ with } (0 \leq s_v, t_v \leq 1)$$
- When rasterizing, *interpolate* to get the texture coordinate at pixel p:
$$(s_p, t_p)$$
- *Sample* the texture at (s_p, t_p) to get the color at p.

Terminology:

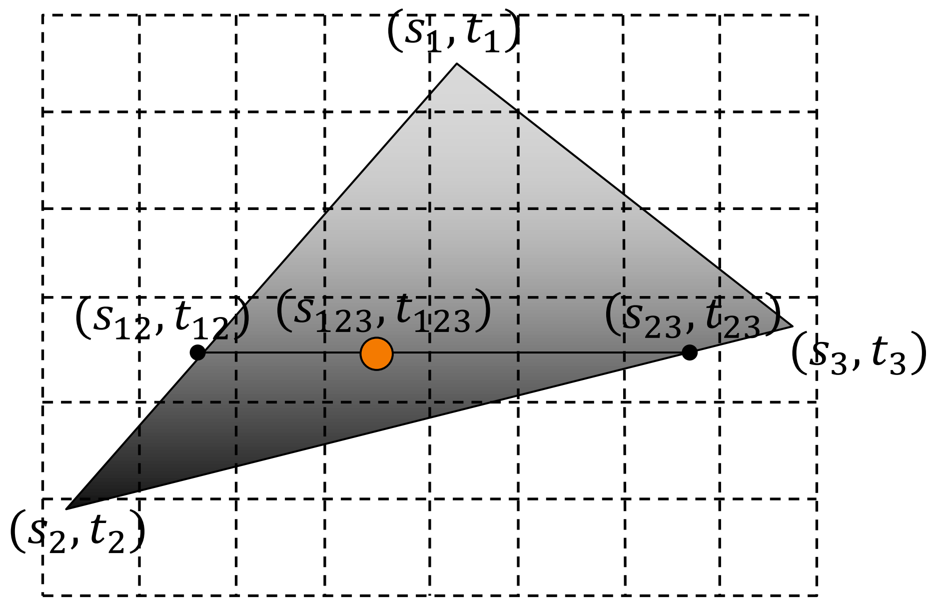
Texture elements are called *texels*



3D Rendering Pipeline



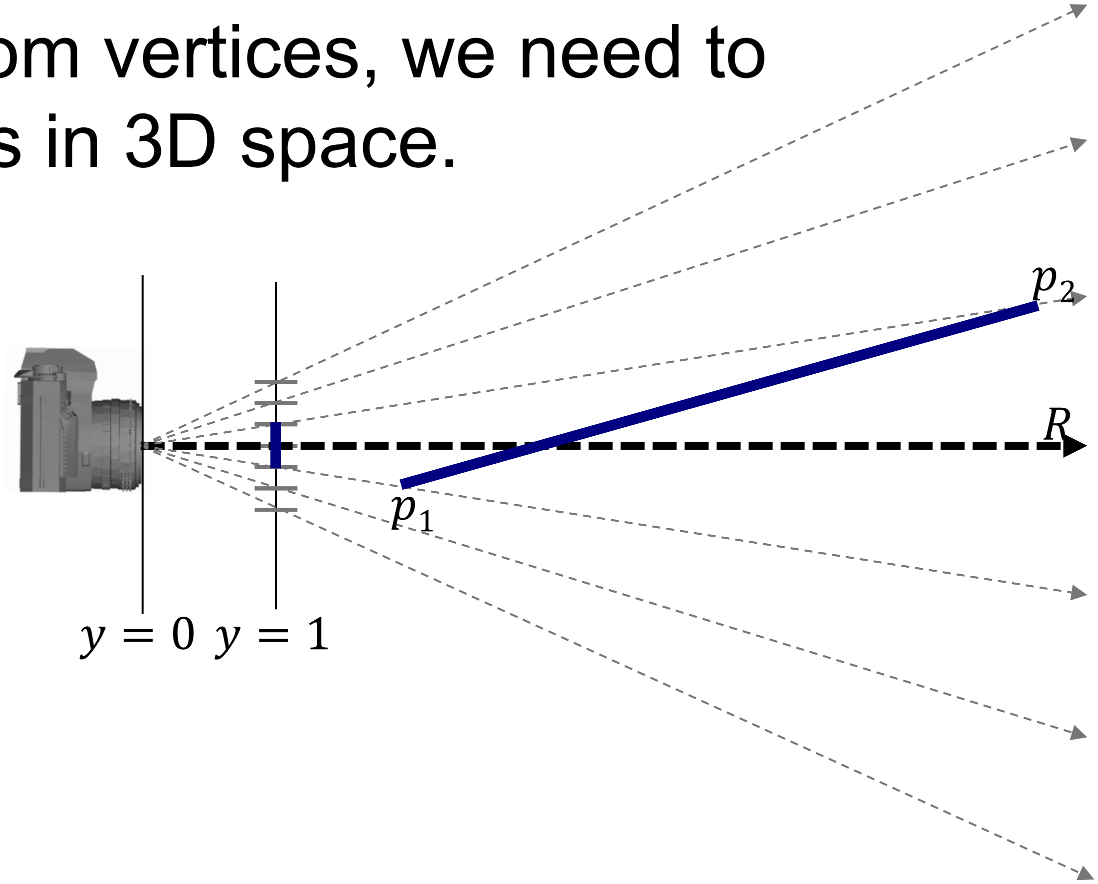
- Perform the **texture interpolation** and **look-up** while rasterizing the pixels.



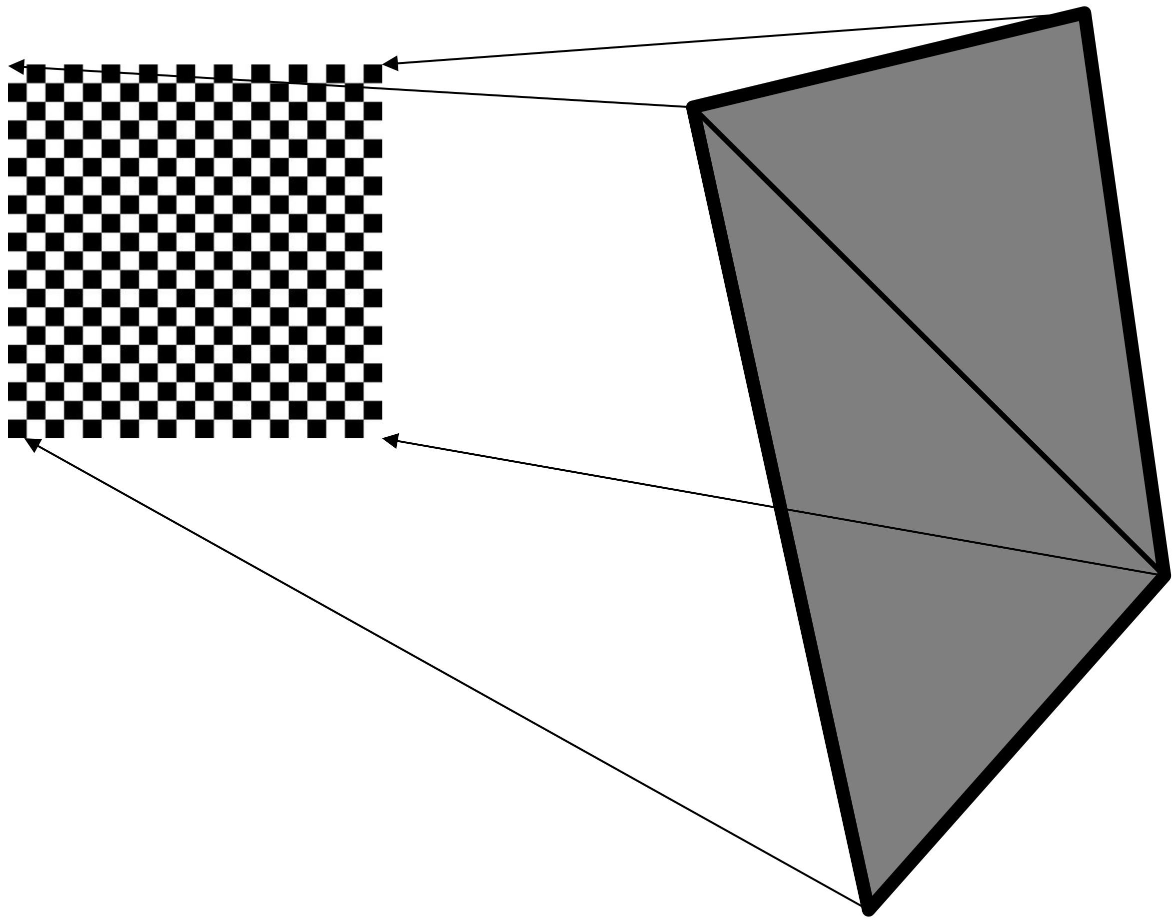
Texture Mapping

Recall (Perspective Divide):

When performing scan-line rasterization and interpolating data from vertices, we need to compute the weights in 3D space.

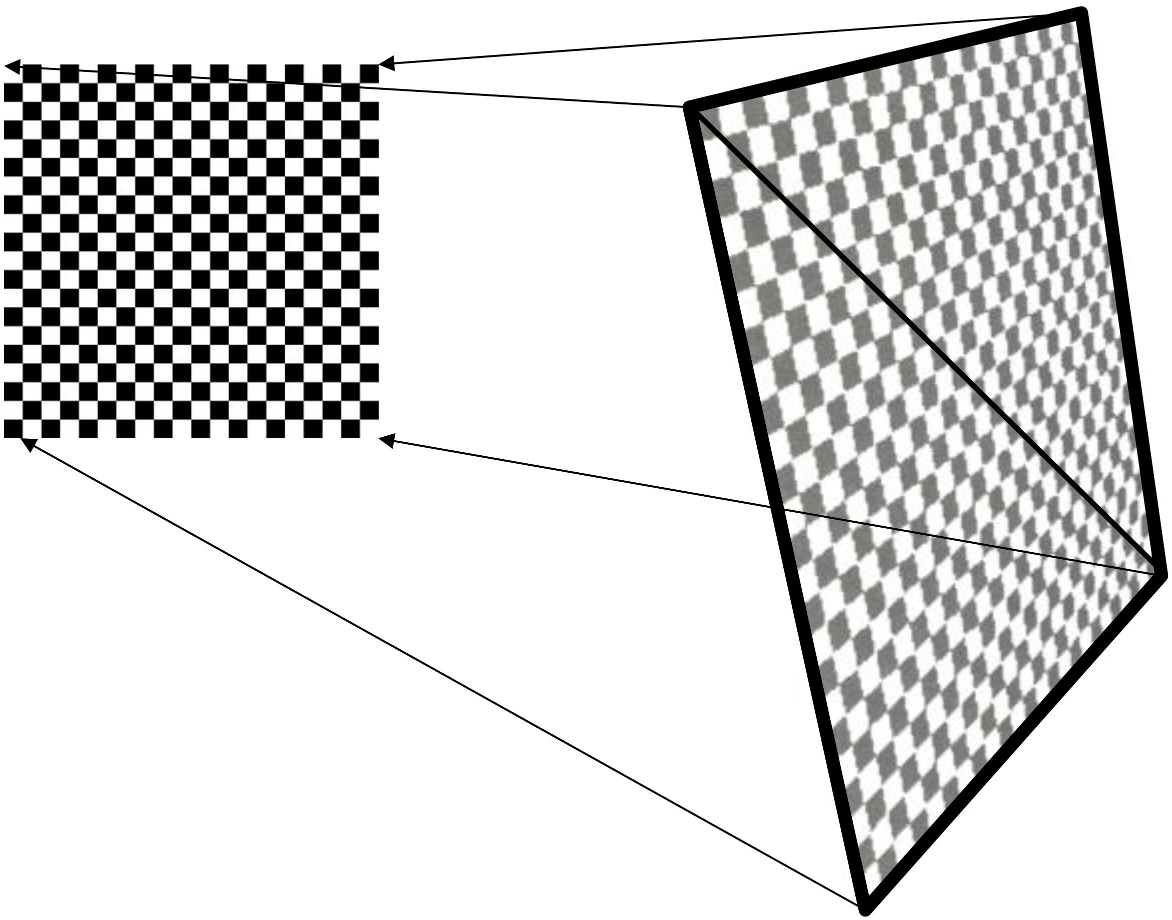


Texture Mapping



Hill Figure 8.42

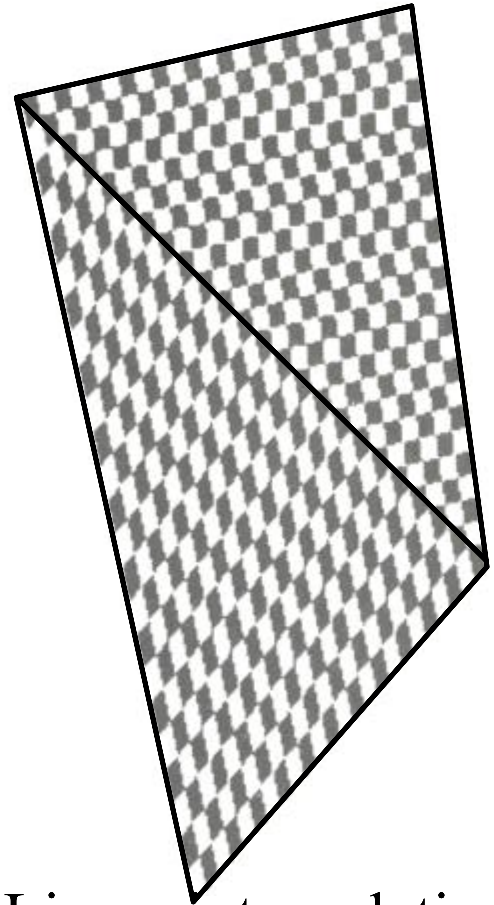
Texture Mapping



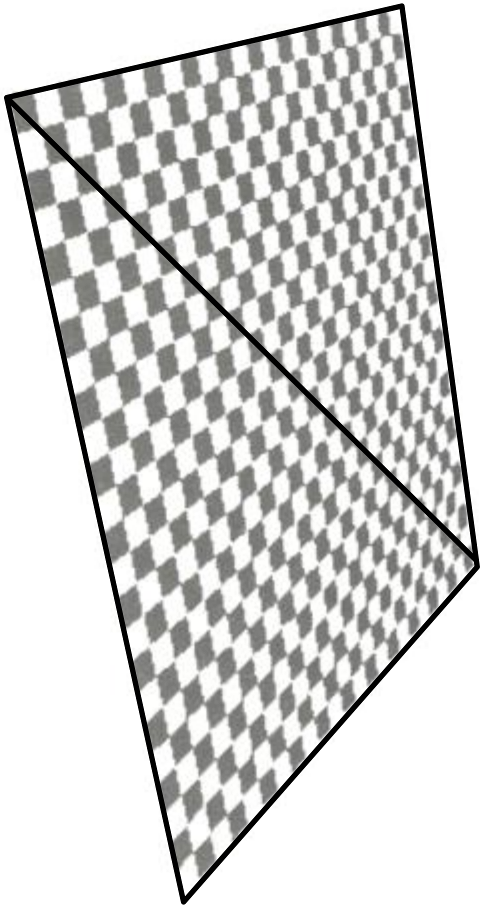
Correct interpolation
of texture coordinates
with perspective divide

Hill Figure 8.42

Texture Mapping



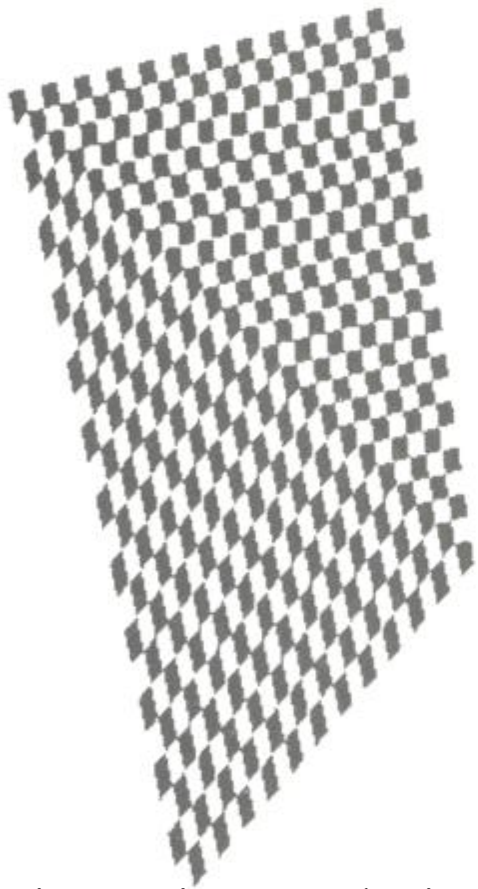
Linear interpolation of texture coordinates **w/o perspective divide**



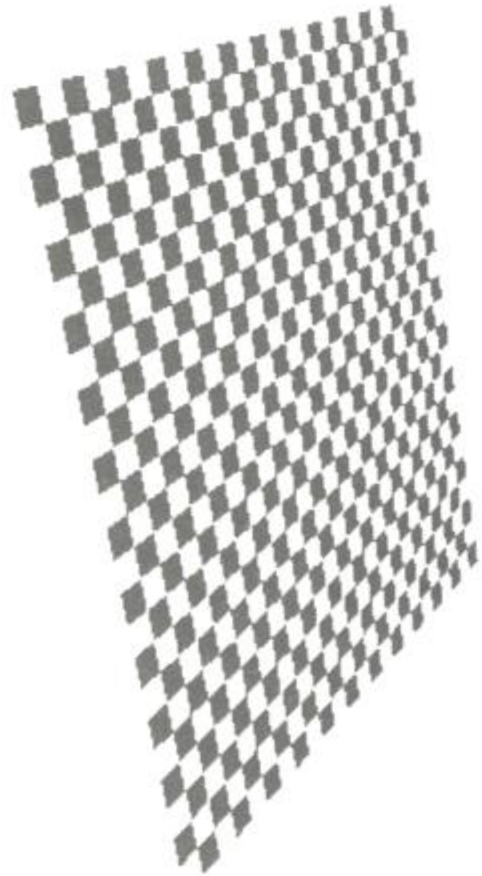
Correct interpolation of texture coordinates **w/ perspective divide**

Hill Figure 8.42

Texture Mapping



Linear interpolation
of texture coordinates
w/o perspective divide



Correct interpolation
of texture coordinates
w/ perspective divide

Hill Figure 8.42

Overview

Texture mapping methods

- Parameterization
- Sampling

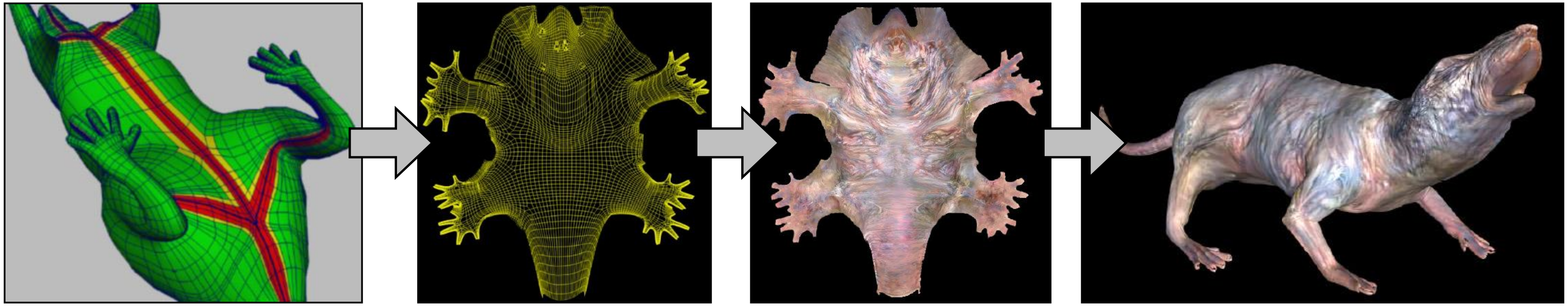
Texture mapping applications

- Modulation textures
- Illumination mapping
- Bump mapping
- Environment mapping
- Shadow maps

Map to a 2D Domain (w/ Added Cuts)

- Introduce cuts to give the surface a disk topology
- Map the cut surface to the 2D plane
- Assign texture coordinates in the plane

✓ Good cut placement can reduce distortion
✗ Need to ensure cross-seam continuity
✗ Have to contend with distortion

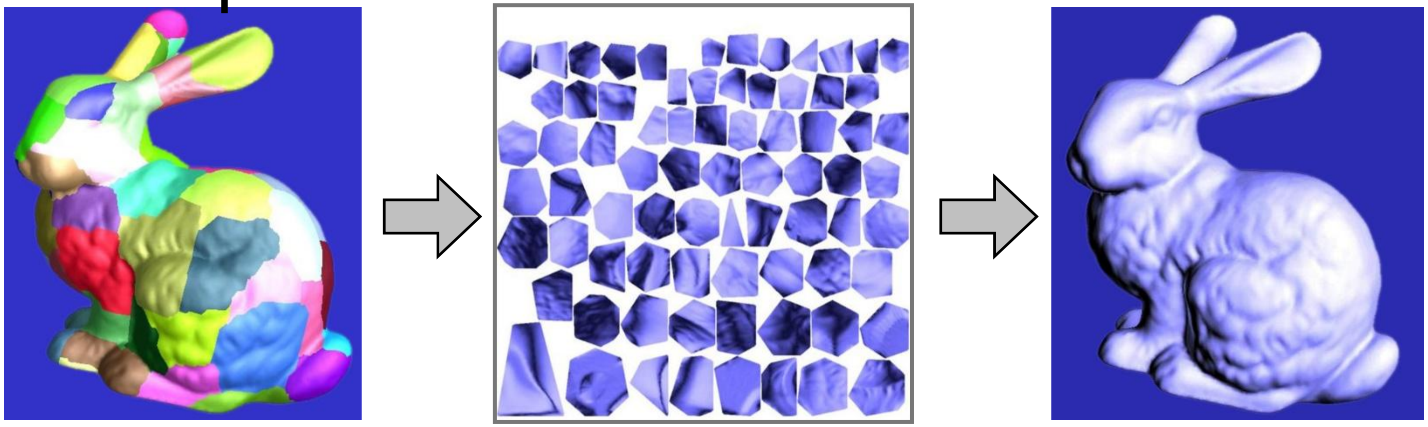


[Piponi, 2000]

Texture Atlases

- Decompose the surface into multiple charts
- Map each chart to the 2D plane
- Assign texture coordinates in the plane

✓ Less distortion in the mapping
✗ Harder to ensure cross-seam continuity
✗ Need to pack the atlases into 2D



[Sander, 2001]

Overview

Texture mapping methods

- Parameterization
- Sampling

Texture mapping applications

- Modulation textures
- Illumination mapping
- Bump mapping
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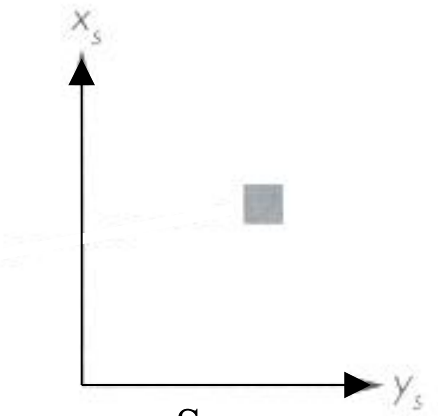
- Shadow maps

Texture Filtering

Given pixel on a screen:

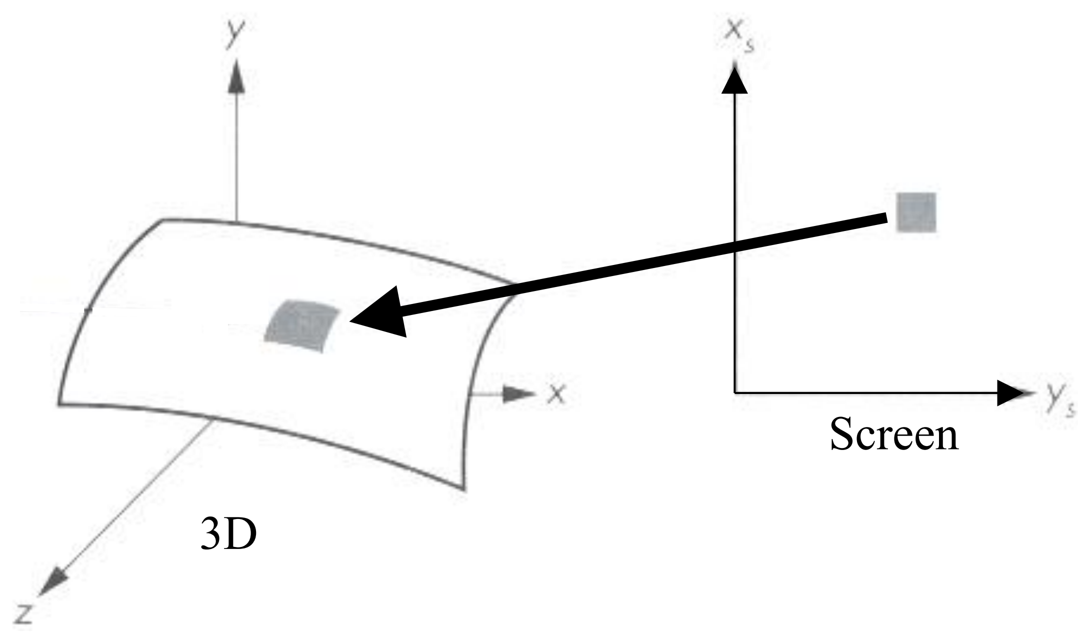


Angel Figure 9.4

Texture Filtering

Given pixel on a screen:

1. Determine the corresponding surface patch

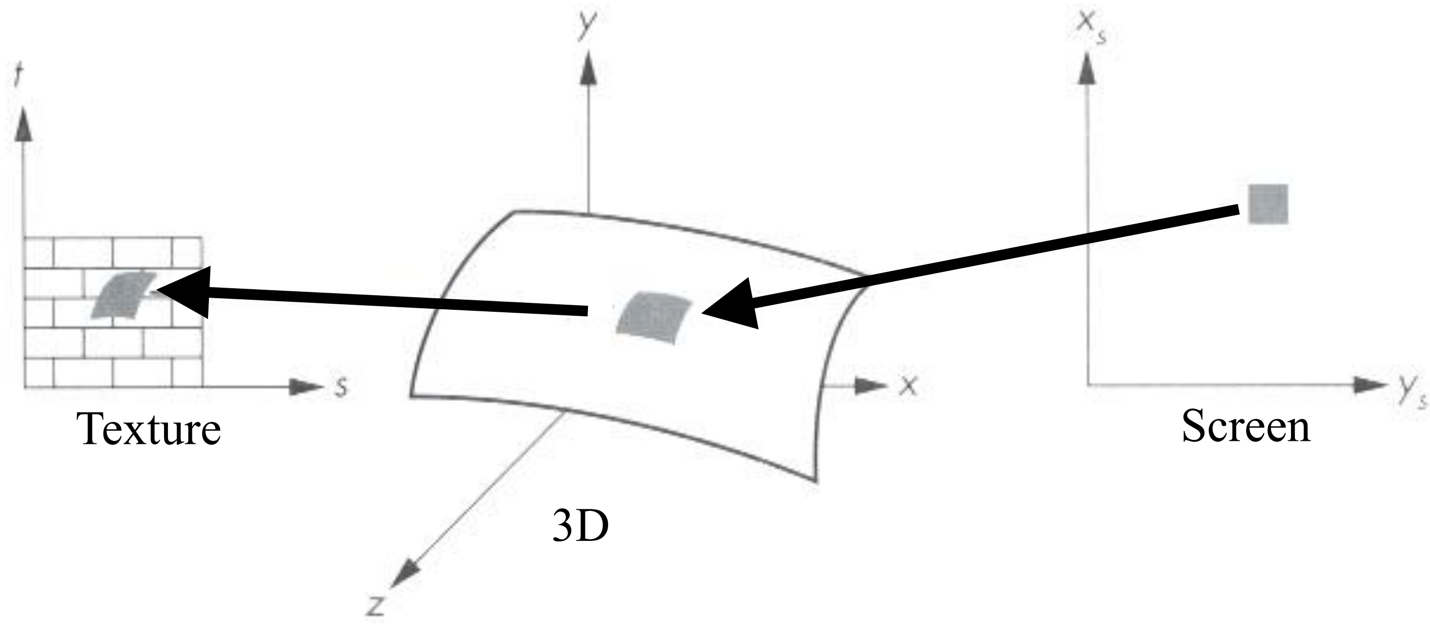


Angel Figure 9.4

Texture Filtering

Given pixel on a screen:

1. Determine the corresponding surface patch
2. Determine the corresponding texture patch

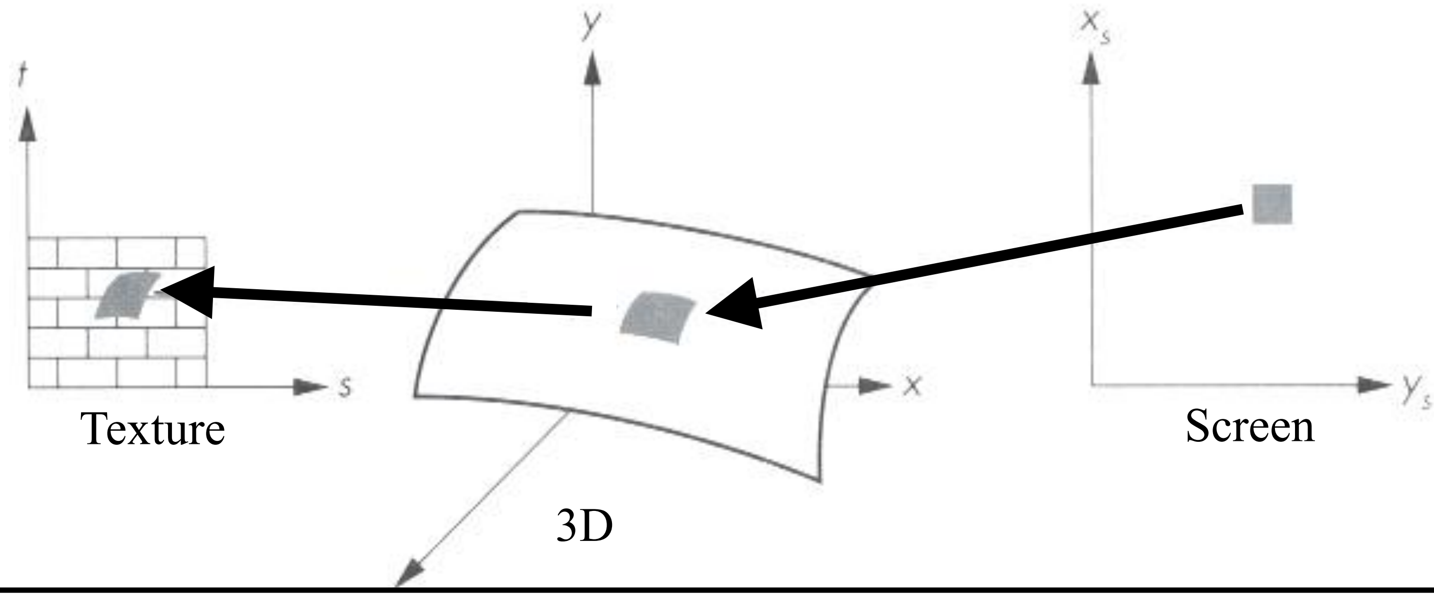


Angel Figure 9.4

Texture Filtering

Given pixel on a screen:

1. Determine the corresponding surface patch
2. Determine the corresponding texture patch

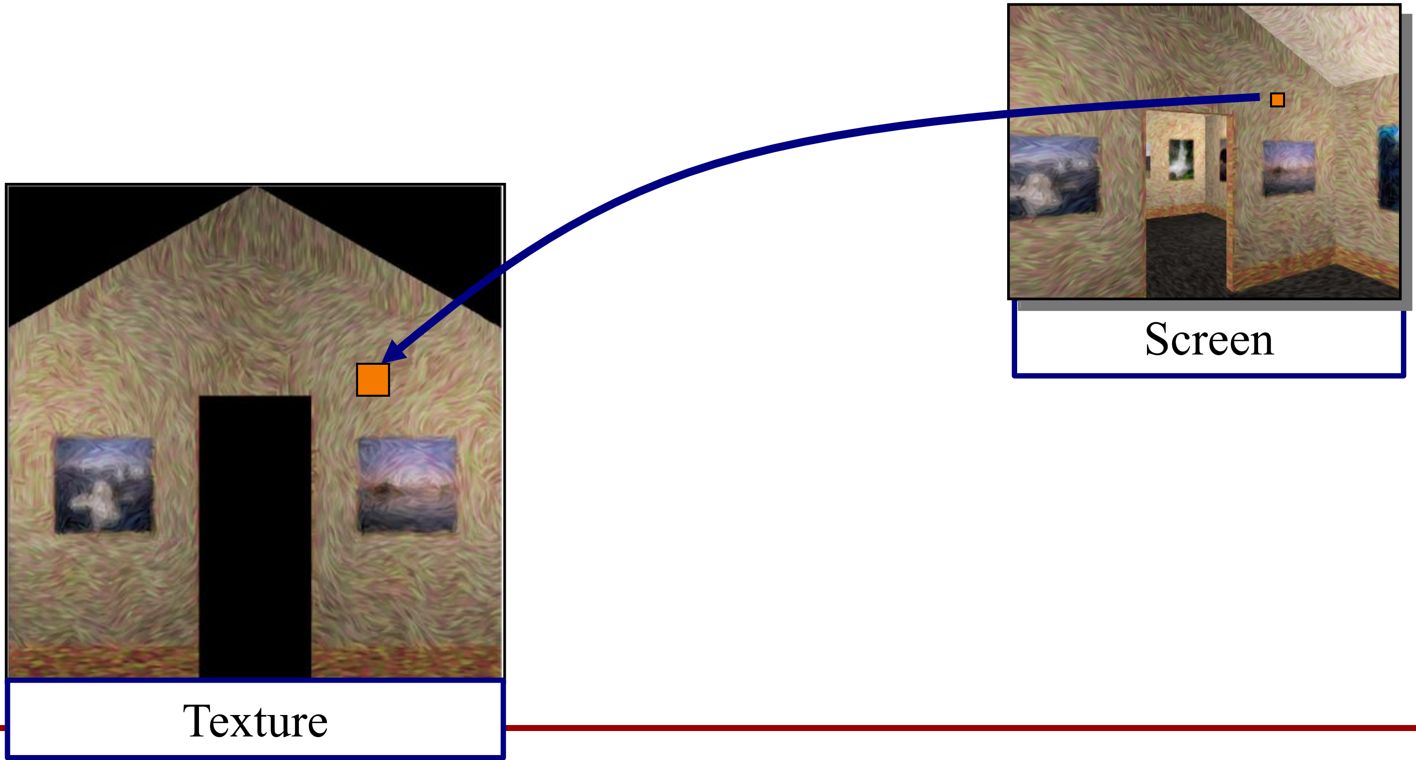


While the true shape of the texture patch mapping to a screen pixel may be hard to compute, we can approximate it using the Jacobian.

Texture Filtering

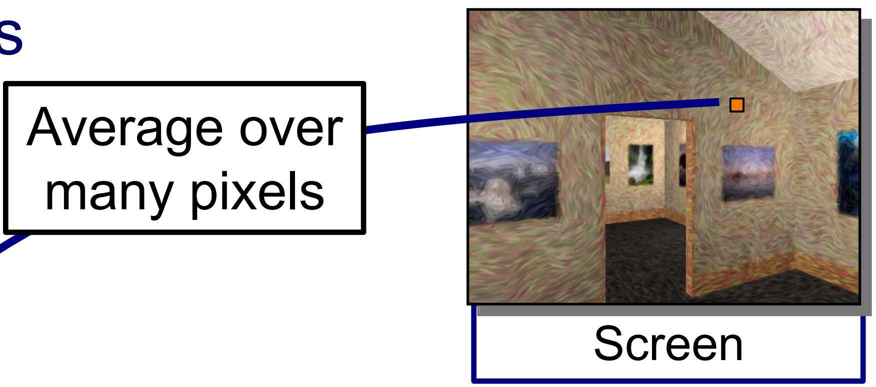
Given pixel on a screen:

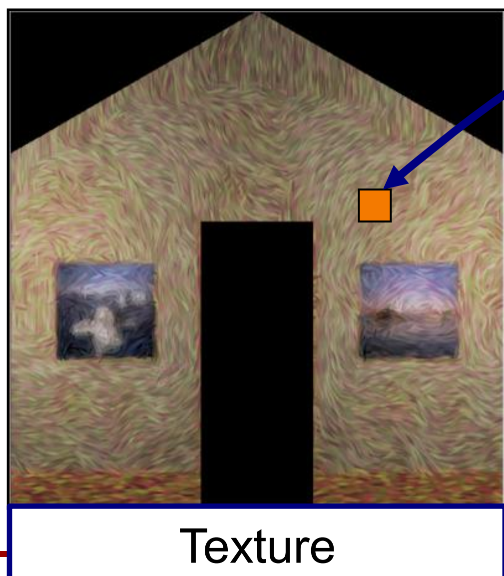
1. Determine the corresponding surface patch
2. Determine the corresponding texture patch
3. Average texel values over the texture patch



Texture Filtering

- Size of texture patch depends on the deformation
  - Computation is proportional to the pixel footprint
- Can pre-filter images for better performance
  - MIP (Multum In Parvo*) maps
  - Summed area tables

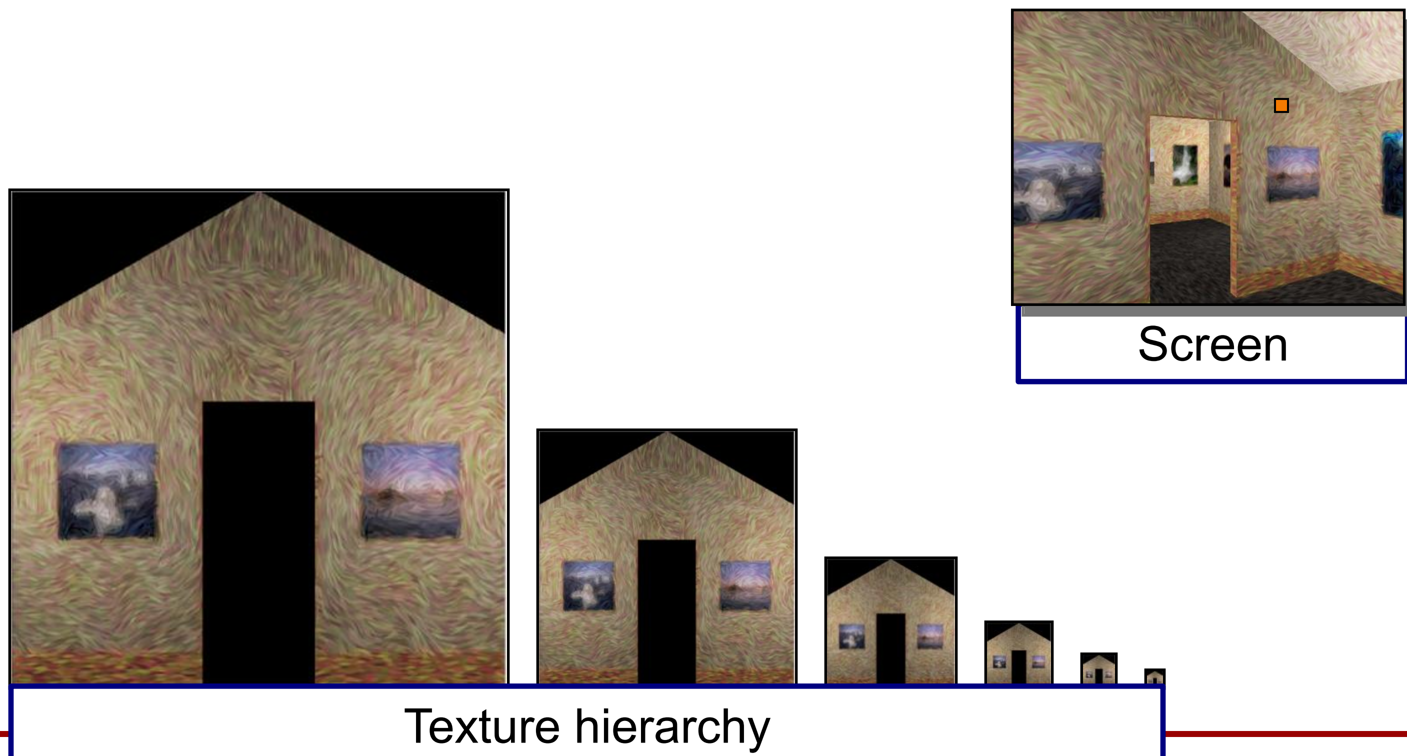




*multum in parvo = much in little

MIP Maps

Pre Processing: Compute a hierarchy of successively down-sampled texture images

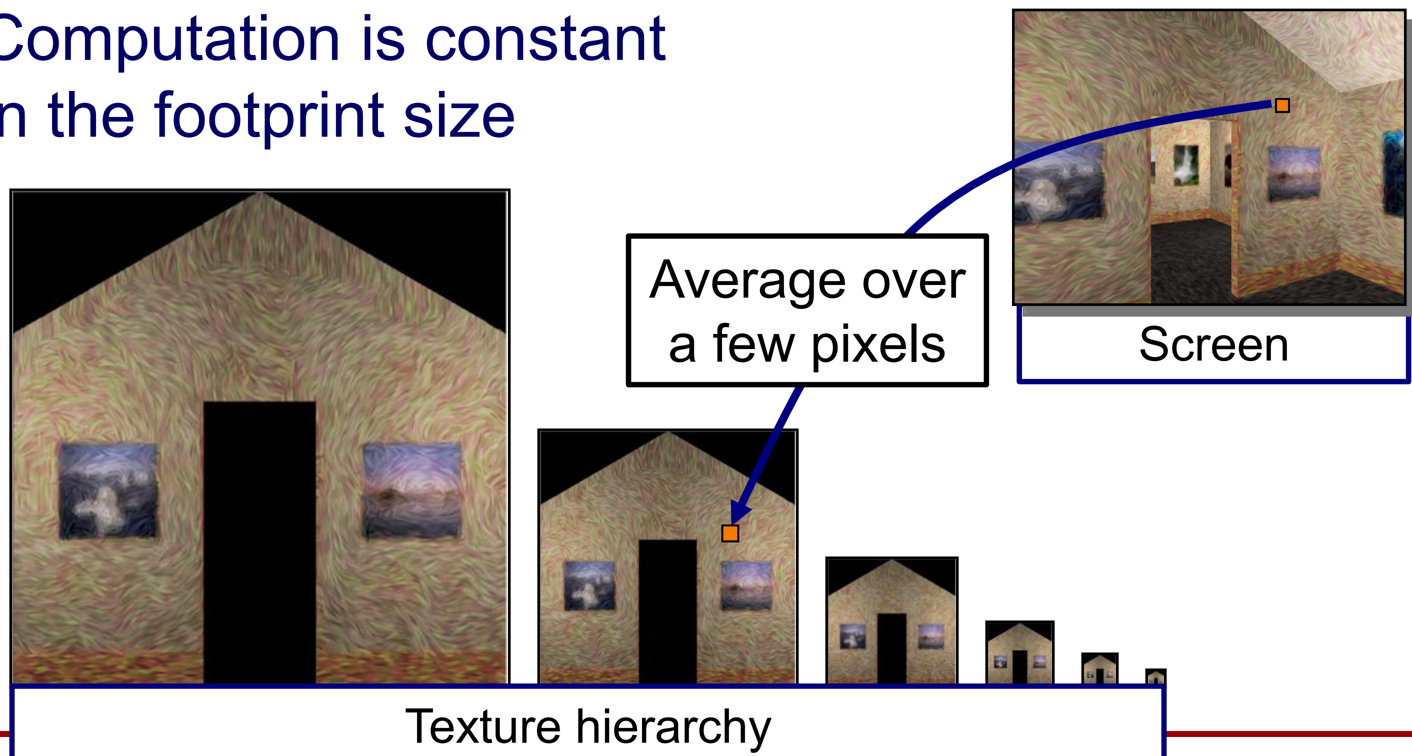


MIP Maps

Pre Processing: Compute a hierarchy of successively down-sampled texture images

Run-time: Sample the closest MIP map level(s)

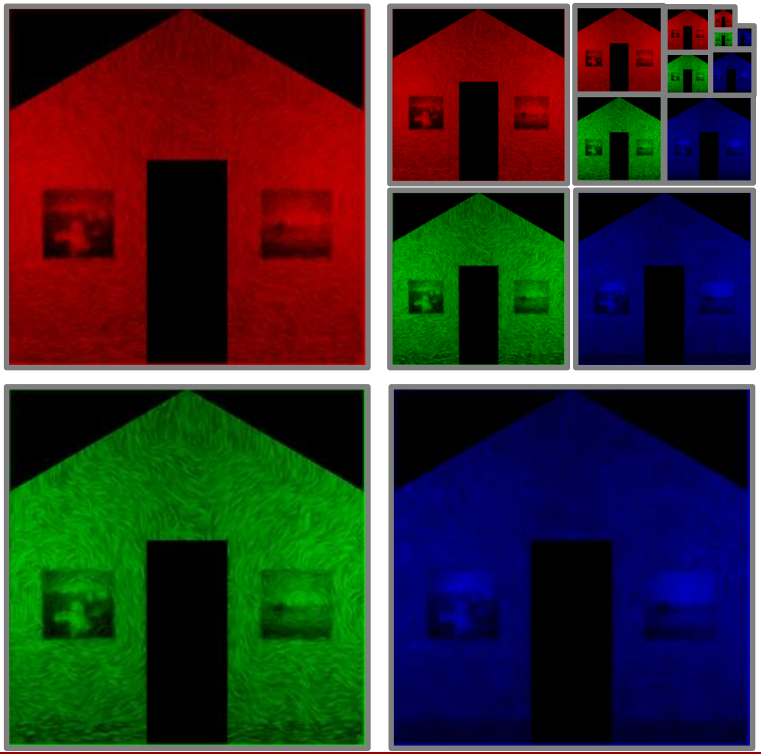
- Easy for hardware
- Computation is constant in the footprint size



MIP Maps

Pre Processing: Compute a hierarchy of successively down-sampled texture images

- ✓ Storage is 4/3× the size of the input image



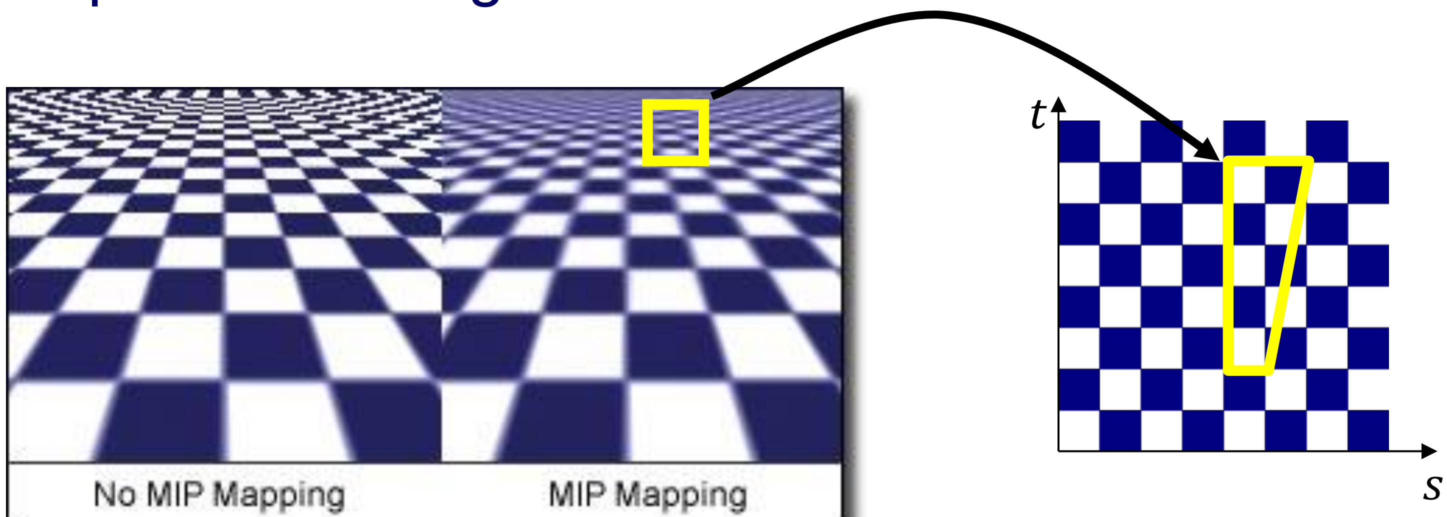
MIP Maps

Pre Processing: Compute a hierarchy of successively down-sampled texture images

- ✓ Storage is 4/3× the size of the input image

Run-time: Sample the closest MIP map level(s)

- ✗ The filtering is isotropic – assumes identical compression along vertical and horizontal directions



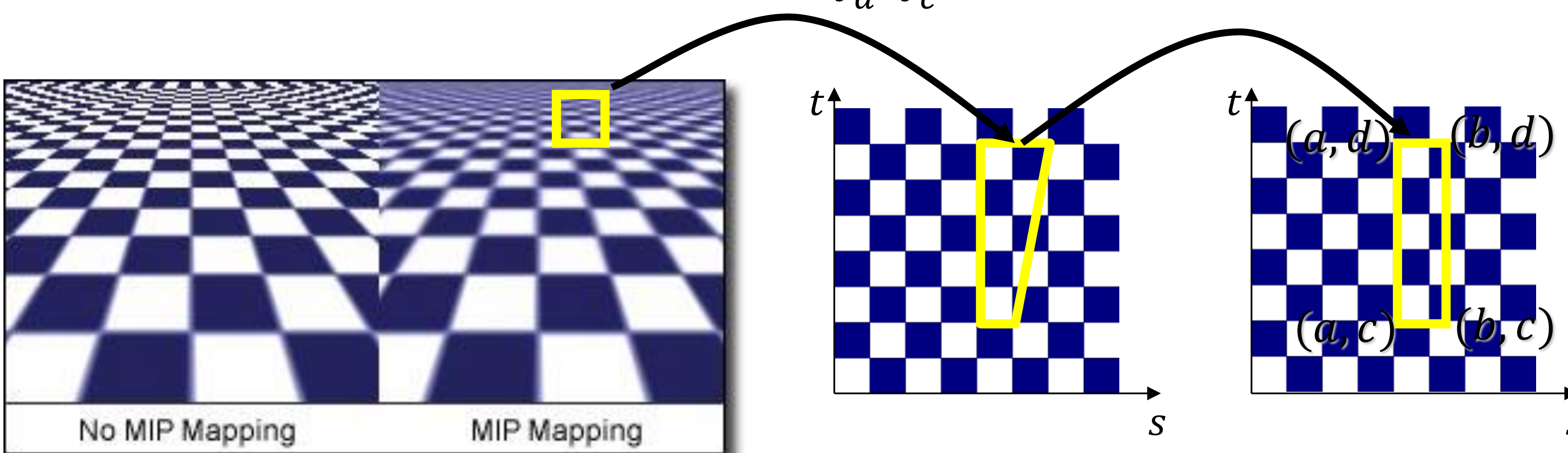
[Trading aliasing for blurring!]

Summed-Area Tables

Key Idea:

Approximate the summation/integration over an arbitrary region by a summation/integration over an axis-aligned rectangle:

$$\text{Sum}([a,b]\times[c,d]) = \int_a^b \int_c^d f(x,y)\,dy\,dx$$

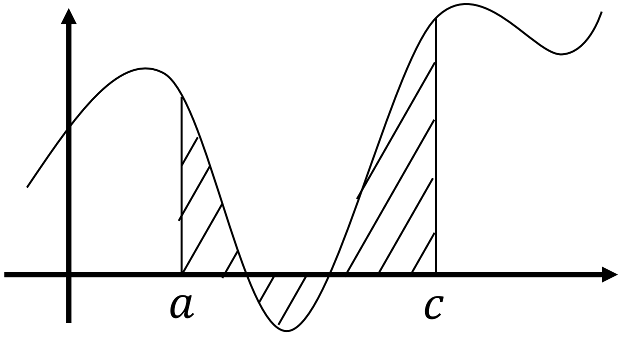


Summed-Area Tables (1D)

Integration:

Given a function $f(x)$ and interval $[a, c]$, the integral of f over the interval is:

$$\int_a^c f(x)dx$$



Naïve Approach:

Pre-compute $S(a, b) \equiv \int_a^b f(x)\,dx$ in a look-up table and evaluate that.

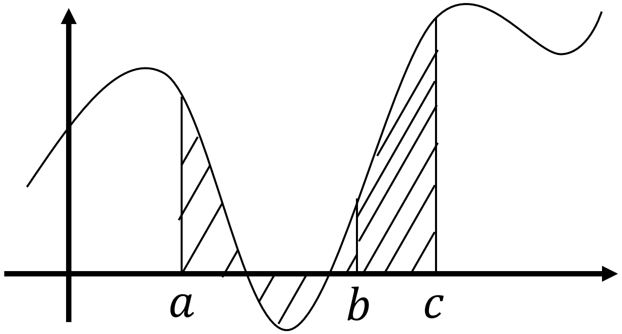
- ✓ Fast (constant time) look up
- × Replaces 1D function f with 2D function S.

Summed-Area Tables (1D)

Integration:

Given a function $f(x)$ and interval $[a, c]$, the integral of f over the interval is:

$$\int_a^c f(x) dx$$



Recall:

For any point $b \in [a, c]$ in the interval, we have:

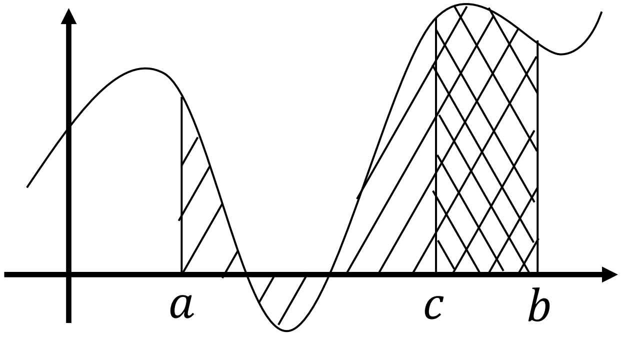
$$\int_a^c f(x)\, dx = \int_a^b f(x)\, dx + \int_b^c f(x)\, dx$$

Summed-Area Tables (1D)

Integration:

Given a function $f(x)$ and interval $[a, c]$, the integral of f over the interval is:

$$\int_a^c f(x)dx$$



Recall:

For any point $b \in [a, c]$ in the interval, we have:

$$\int_a^c f(x)\,dx = \int_a^b f(x)\,dx + \int_b^c f(x)\,dx$$

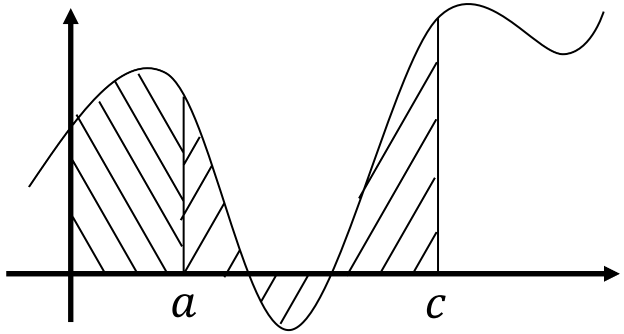
This is true even if b is outside the interval since:

$$\int_a^b f(x)\,dx = -\int_b^a f(x)\,dx$$

Summed-Area Tables (1D)

Approach:

Replace the integral over an interval, with two variable end-points with the difference between integrals with one variable end-point:



$$\int_a^c f(x)dx = \int_0^c f(x)dx - \int_0^a f(x)dx$$

$\Rightarrow$ Replace a look-up in the 2D function $S(a,c) = \int_a^c f(x)\,dx$ with two look-ups in in the 1D function $S_0(b) = \int_0^b f(x)\,dx$

Summed-Area Tables (2D)

Integration:

In 2D, we can write out the integral of the function f over the rectangle $[a, b] \times [c, d]$ as:

$$\int_a^b \int_c^d f(s,t)dt\, ds$$

Summed-Area Tables (2D)

Integration:

In 2D, we can write out the integral of the function f over the rectangle $[a,b]\times[c,d]$ as:

$$\int_a^b \boxed{\int_c^d} f(s,t)\,dt\,ds = \int_a^b \left(\boxed{\int_0^d} f(s,t)\,dt - \boxed{\int_0^c} f(s,t)\,dt \right) ds$$

Summed-Area Tables (2D)

Integration:

In 2D, we can write out the integral of the function f over the rectangle $[a,b]\times[c,d]$ as:

$$\int_a^b\int_c^d f(s,t)dt\,ds = \boxed{\int_a^b}\left(\int_0^d f(s,t)dt - \int_0^c f(s,t)dt\right)ds$$

$$= \boxed{\int_0^b}\left(\int_0^d f(s,t)dt - \int_0^c f(s,t)dt\right)ds - \boxed{\int_0^a}\left(\int_0^d f(s,t)dt - \int_0^c f(s,t)dt\right)ds$$

Summed-Area Tables (2D)

Integration:

In 2D, we can write out the integral of the function f over the rectangle $[a,b] \times [c,d]$ as:

$$
\begin{aligned}
\int_a^b \int_c^d f(s,t)\,dt\,ds &= \int_a^b \left(\int_0^d f(s,t)\,dt - \int_0^c f(s,t)\,dt \right) ds \\
&= \int_0^b \left(\int_0^d f(s,t)\,dt - \int_0^c f(s,t)\,dt \right) ds - \int_0^a \left(\int_0^d f(s,t)\,dt - \int_0^c f(s,t)\,dt \right) ds \\
&= \int_0^b \int_0^d f(s,t)\,dt\,ds - \int_0^b \int_0^c f(s,t)\,dt\,ds - \int_0^a \int_0^d f(s,t)\,dt\,ds + \int_0^a \int_0^c f(s,t)\,dt\,ds
\end{aligned}
$$

Precomputing the 2D function:

$$S_{(0,0)}(x,y) \equiv \int_0^x \int_0^y f(s,t)\, dt\, ds$$

lets us evaluate integrals with four look-ups:

$$\int_a^b \int_c^d f(s,t)\, dt\, ds = S_{(0,0)}(b,d) - S_{(0,0)}(b,c) - S_{(0,0)}(a,d) + S_{(0,0)}(a,c)$$

over the rectangle $[a,b] \times [c,d]$ as:

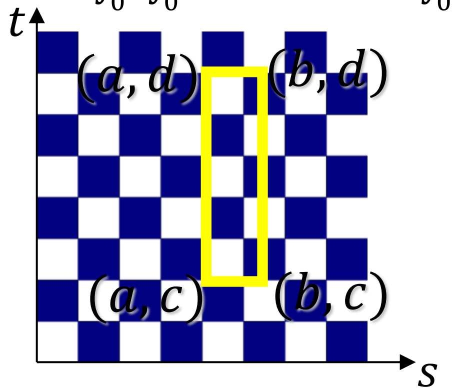
$$\begin{aligned}
\int_a^b \int_c^d f(s,t)dt\, ds &= \int_a^b \left(\int_0^d f(s,t)dt - \int_0^c f(s,t)dt \right) ds \\
&= \int_0^b \left(\int_0^d f(s,t)dt - \int_0^c f(s,t)dt \right) ds - \int_0^a \left(\int_0^d f(s,t)dt - \int_0^c f(s,t)dt \right) ds \\
&= \int_0^b \int_0^d f(s,t)dt\, ds - \int_0^b \int_0^c f(s,t)dt\, ds - \int_0^a \int_0^d f(s,t)dt\, ds + \int_0^a \int_0^c f(s,t)dt\, ds
\end{aligned}$$

Summed-Area Tables (2D)

Integration:

In 2D, we can write out the integral of the function f over the rectangle $[a, b] \times [c, d]$ as:

$$\boxed{\int_a^b \int_c^d f(s,t)dt\,ds} = \int_0^b \int_0^d f(s,t)dt\,ds - \int_0^b \int_0^c f(s,t)dt\,ds - \int_0^a \int_0^d f(s,t)dt\,ds + \int_0^a \int_0^c f(s,t)dt\,ds$$

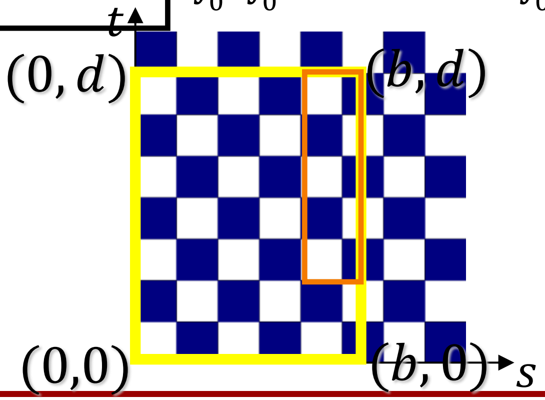


Summed-Area Tables (2D)

Integration:

In 2D, we can write out the integral of the function f over the rectangle $[a,b]\times[c,d]$ as:

$$\int_a^b\int_c^d f(s,t)dt\,ds = \boxed{\int_0^b\int_0^d f(s,t)dt\,ds} + \int_0^b\int_0^c f(s,t)dt\,ds - \int_0^a\int_0^d f(s,t)dt\,ds + \int_0^a\int_0^c f(s,t)dt\,ds$$



Summed-Area Tables (2D)

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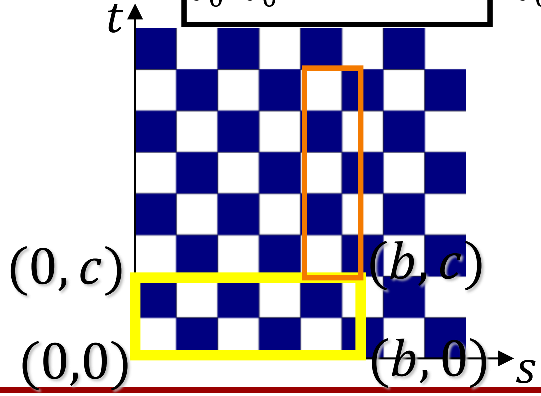

Summed-Area Tables (2D)

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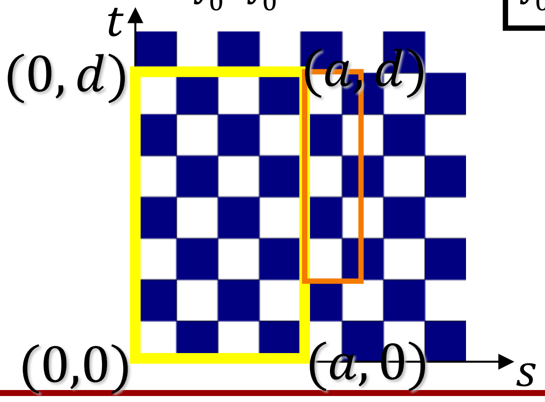
$$\int_a^b \int_c^d f(s,t)dt\,ds = \int_0^b \int_0^d f(s,t)dt\,ds - \int_0^b \int_0^c f(s,t)dt\,ds - \boxed{\int_0^a \int_0^d f(s,t)dt\,ds} + \int_0^a \int_0^c f(s,t)dt\,ds$$

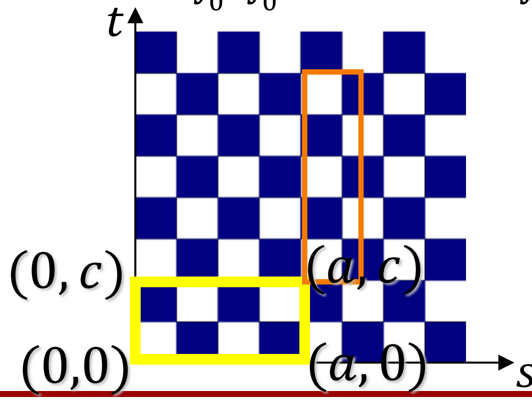


Summed-Area Tables (2D)

<u>Integration</u>:

In 2D, we can write out the integral of the function f over the rectangle $[a,b]\times[c,d]$ as:

$$\int_a^b\int_c^d f(s,t)dt\,ds = \int_0^b\int_0^d f(s,t)dt\,ds - \int_0^b\int_0^c f(s,t)dt\,ds - \int_0^a\int_0^d f(s,t)dt\,ds + \boxed{\int_0^a\int_0^c f(s,t)dt\,ds}$$



Summed-Area Tables (Pre-Process)

Precompute the values of the integral:

$$S_{(0,0)}(a,b) = \int_0^a \int_0^b f(s,t)\,dt\,ds$$

Each summed-area table texel is the sum of all input texels below and to the left

Input image

1	2	4	0
0	3	1	1
4	2	0	1
1	2	1	3

→

Summed area table

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Summed area table

1			

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Precompute the values of the integral:

$$S_{(0,0)}(a,b) = \int_0^a \int_0^b f(s,t)\,dt\,ds$$

Each summed-area table texel is the sum of all input texels below and to the left

Input image

1	2	4	0
0	3	1	1
4	2	0	1
1	2	1	3

→

Summed area table

1	3		

Summed-Area Tables (Pre-Process)

Precompute the values of the integral:

$$S_{(0,0)}(a,b) = \int_0^a \int_0^b f(s,t)\, dt\, ds$$

Each summed-area table texel is the sum of all input texels below and to the left

Input image

1	2	4	0
0	3	1	1
4	2	0	1
1	2	1	3

Summed area table

1	3	4	

Summed-Area Tables (Pre-Process)

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$$S_{(0,0)}(a,b) = \int_0^a \int_0^b f(s,t)\, dt\, ds$$

Each summed-area table texel is the sum of all input texels below and to the left

Input image

1	2	4	0
0	3	1	1
4	2	0	1
1	2	1	3

Summed area table

1	3	4	7

Summed-Area Tables (Pre-Process)

Precompute the values of the integral:

$$S_{(0,0)}(a,b) = \int_0^a \int_0^b f(s,t)\,dt\,ds$$

Each summed-area table texel is the sum of all input texels below and to the left

Input image

1	2	4	0
0	3	1	1
4	2	0	1
1	2	1	3

Summed area table

5			
1	3	4	7

Summed-Area Tables (Pre-Process)

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$$S_{(0,0)}(a,b) = \int_0^a \int_0^b f(s,t)\, dt\, ds$$

Each summed-area table texel is the sum of all input texels below and to the left

Input image

1	2	4	0
0	3	1	1
4	2	0	1
1	2	1	3

→

Summed area table

5	9		
1	3	4	7

Summed-Area Tables (Pre-Process)

Precompute the values of the integral:

$$S_{(0,0)}(a,b) = \int_0^a \int_0^b f(s,t)\,dt\,ds$$

Each summed-area table texel is the sum of all input texels below and to the left

Input image

1	2	4	0
0	3	1	1
4	2	0	1
1	2	1	3

→

Summed area table

6	15	21	26
5	12	14	19
5	9	10	14
1	3	4	7

Summed-Area Tables (Run-Time)

Example:

Compute the average in the rectangle $[1,3] \times [2,3]$.
$\Rightarrow$ Compute the sum and divide by the area

1	2	4	0
0	3	1	1
4	2	0	1
1	2	1	3

Input image

6	15	21	26
5	12	14	19
5	9	10	14
1	3	4	7

Summed-area table

Summed-Area Tables (Run-Time)

Example:

Compute the average in the rectangle $[1,3] \times [2,3]$.
⇒ Compute the sum and divide by the area

$$\text{Sum}([1,3] \times [2,3]) = S_{(0,0)}(3,3)$$

1	2	4	0
0	3	1	1
4	2	0	1
1	2	1	3

Input image

6	15	21	26
5	12	14	19
5	9	10	14
1	3	4	7

Summed-area table

Summed-Area Tables (Run-Time)

Example:

Compute the average in the rectangle $[1,3] \times [2,3]$.
$\Rightarrow$ Compute the sum and divide by the area

$$\text{Sum}([1,3] \times [2,3]) = S_{(0,0)}(3,3) - S_{(0,0)}(0,3)$$

1	2	4	0
0	3	1	1
4	2	0	1
1	2	1	3

Input image

6	15	21	26
5	12	14	19
5	9	10	14
1	3	4	7

Summed-area table

Summed-Area Tables (Run-Time)

Example:

Compute the average in the rectangle $[1,3] \times [2,3]$.

⇒ Compute the sum and divide by the area

$$\text{Sum}([1,3] \times [2,3]) = S_{(0,0)}(3,3) - S_{(0,0)}(0,3) - S_{(0,0)}(3,1)$$

1	2	4	0
0	3	1	1
4	2	0	1
1	2	1	3

Input image

6	15	21	26
5	12	14	19
5	9	10	14
1	3	4	7

Summed-area table

Summed-Area Tables (Run-Time)

Example:

Compute the average in the rectangle $[1,3] \times [2,3]$.

⇒ Compute the sum and divide by the area

$$\text{Sum}([1,3] \times [2,3]) = S_{(0,0)}(3,3) - S_{(0,0)}(0,3) - S_{(0,0)}(3,1) + S_{(0,0)}(0,1)$$

1	2	4	0
0	3	1	1
4	2	0	1
1	2	1	3

Input image

6	15	21	26
5	12	14	19
5	9	10	14
1	3	4	7

Summed-area table

Summed-Area Tables (Run-Time)

Example:

Compute the average in the rectangle $[1,3] \times [2,3]$.

$\Rightarrow$ Compute the sum and divide by the area

$$\begin{aligned}\mathrm{Sum}([1,3] \times [2,3]) &= S_{(0,0)}(3,3) - S_{(0,0)}(0,3) - S_{(0,0)}(3,1) + S_{(0,0)}(0,1) \\ &= 26 - 6 - 14 + 5 = 11\end{aligned}$$

$$\mathrm{Average}([1,3] \times [2,3]) = \frac{\mathrm{Sum}([1,3] \times [2,3])}{\mathrm{Area}([1,3] \times [2,3])} = \frac{11}{6}$$

1	2	4	0
0	3	1	1
4	2	0	1
1	2	1	3

Input image

6	15	21	26
5	12	14	19
5	9	10	14
1	3	4	7

Summed-area table

Summed-Area Tables (Run-Time)

Precompute the values of the integral

- ✓ Constant time averaging, regardless of rectangle size
- ✗ If the input image has values in the range $[0,255]$ (i.e. one byte per channel), the summed area table can have values in the range $[0,255\cdot\text{width}\cdot\text{height}]$

1	2	4	0
0	3	1	1
4	2	0	1
1	2	1	3

Input image

6	15	21	26
5	12	14	19
5	9	10	14
1	3	4	7

Summed-area table

Overview

Texture mapping methods

- Parameterization
- Sampling

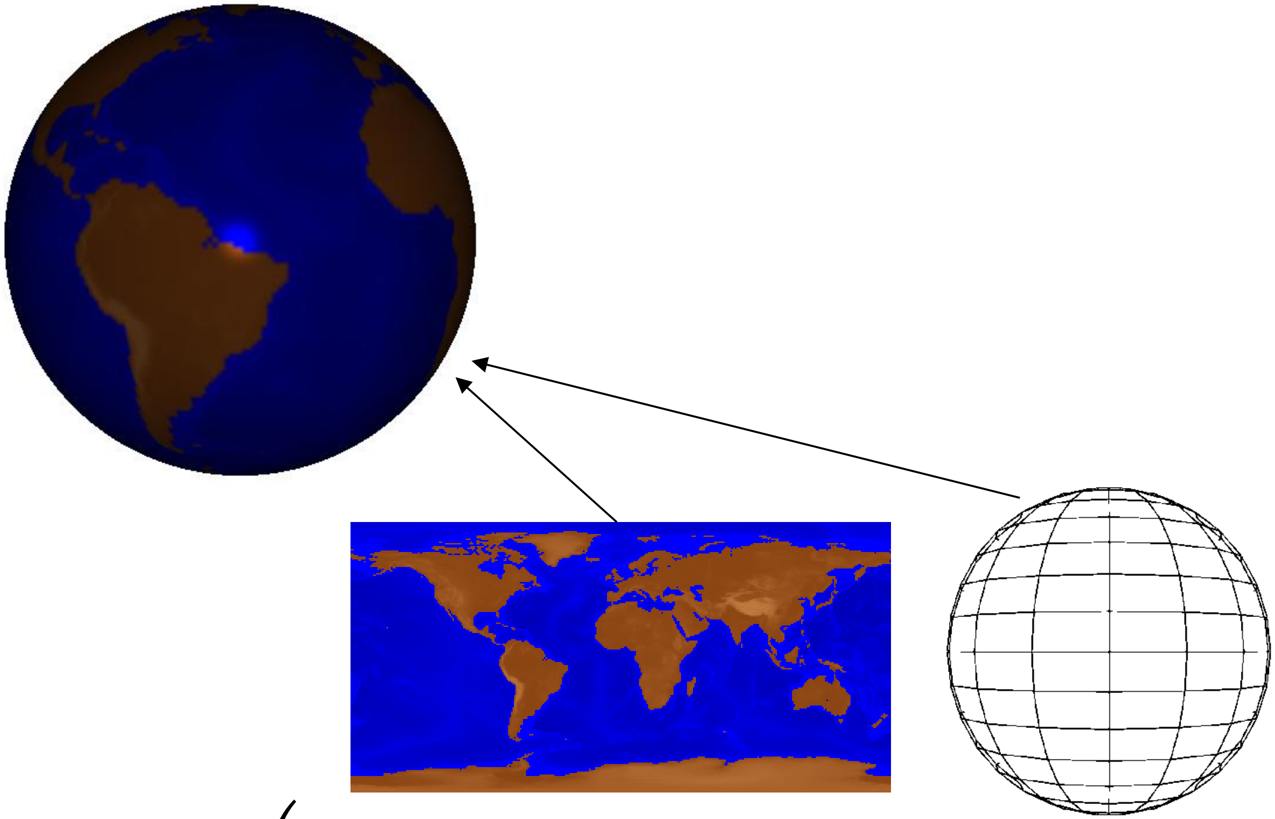
Texture mapping applications

- Modulation textures
- Illumination mapping
- Bump mapping
- Environment mapping
- Shadow mapping

Modulation textures

Map texture values to scale factor

Modulation



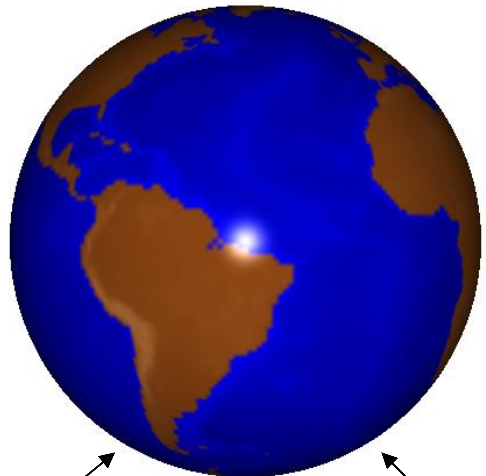
$$I = \boldsymbol{T}(\boldsymbol{s},\boldsymbol{t})\left(I_E + K_A \cdot I_L^A + \sum_L \left(K_D \cdot \langle \vec{N}, \vec{L} \rangle + K_S \cdot \langle \vec{V}, \vec{R}(\vec{L}) \rangle^{K_n}\right) \cdot I_L\right)$$

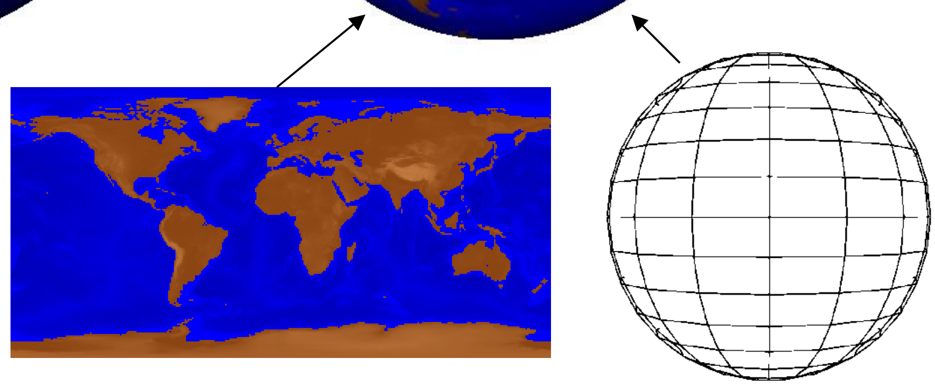
Illumination Mapping

Map texture values to a material parameter

Modulation

Diffuse



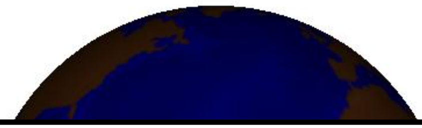


$$I = I_E + K_A \cdot I_L^A + \sum_L \left(\boldsymbol{T}(\boldsymbol{s}, \boldsymbol{t}) \langle \vec{N}, \vec{L} \rangle + K_S \cdot \langle \vec{V}, \vec{R}(\vec{L}) \rangle^{K_n} \right) \cdot I_L$$

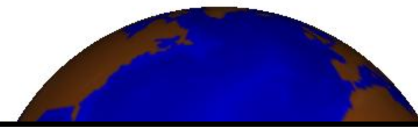
Illumination Mapping

Map texture values to a material parameter

Modulation

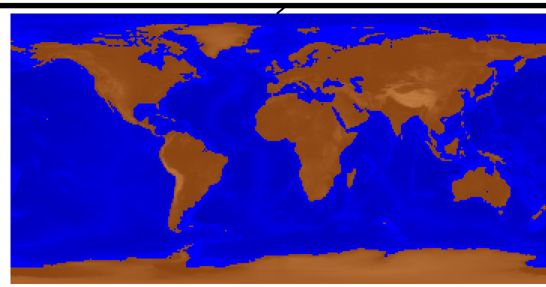


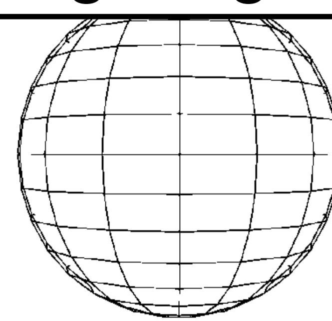
Diffuse



We need to evaluate the texture at each pixel but can the interpolated lighting values $\langle \vec{N}, \vec{L} \rangle$ from the corners

This requires the graphics card to separately store the diffuse component of the lighting at each vertex

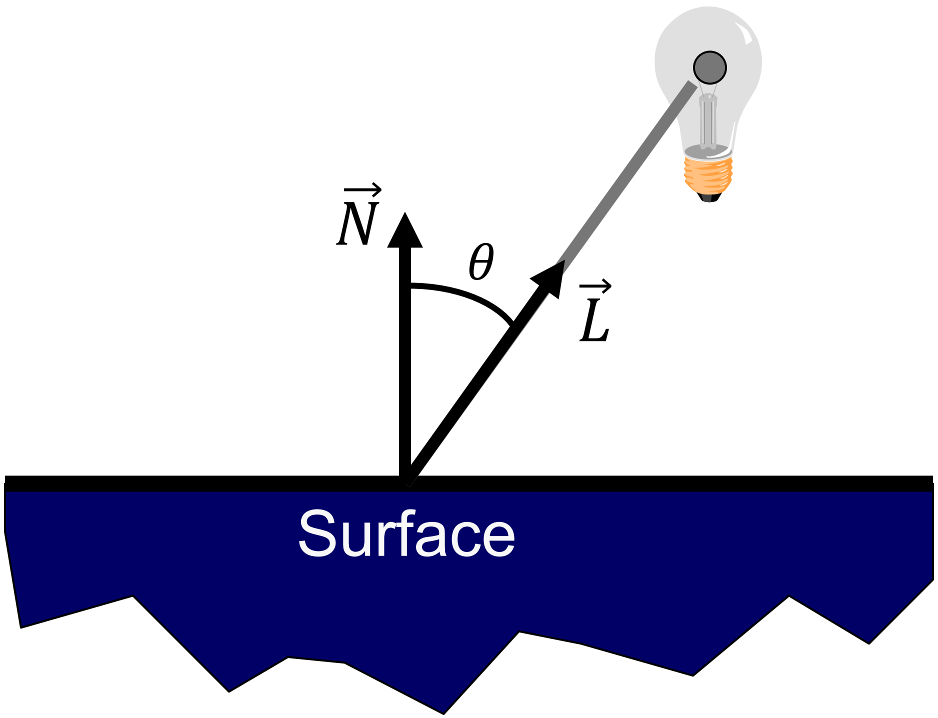




$$I = I_E + K_A \cdot I_L^A + \sum_L \left(\boldsymbol{T}(\boldsymbol{s},\boldsymbol{t}) \langle \vec{N}, \vec{L} \rangle + K_S \cdot \langle \vec{V}, \vec{R}(\vec{L}) \rangle^{K_n} \right) \cdot I_L$$

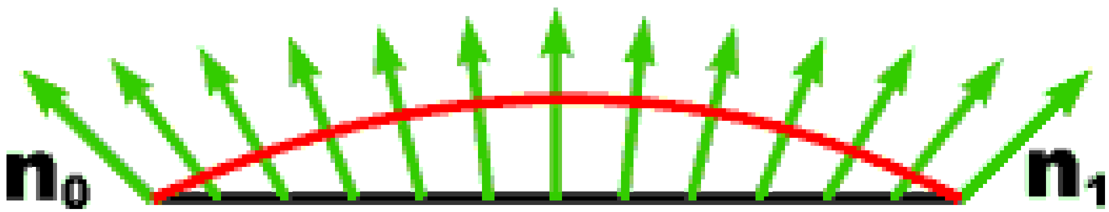
Bump Mapping

Recall that many parts of our lighting calculation depend on surface normals



$$I = I_E + K_A \cdot I_L^A + \sum_L \left(\langle \boxed{\vec{N}}, \vec{L} \rangle + K_S \cdot \langle \vec{V}, \boxed{\vec{R}}(\vec{L}) \rangle^{K_n} \right) \cdot I_L$$

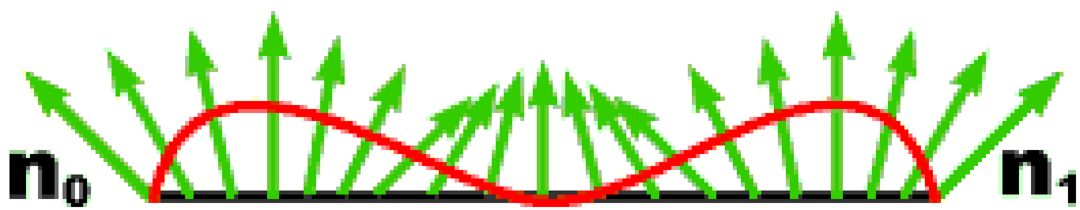
Bump Mapping



Phong shading performs per-pixel lighting calculations with the interpolated normal

⇓

approximates a smoothly curved surface



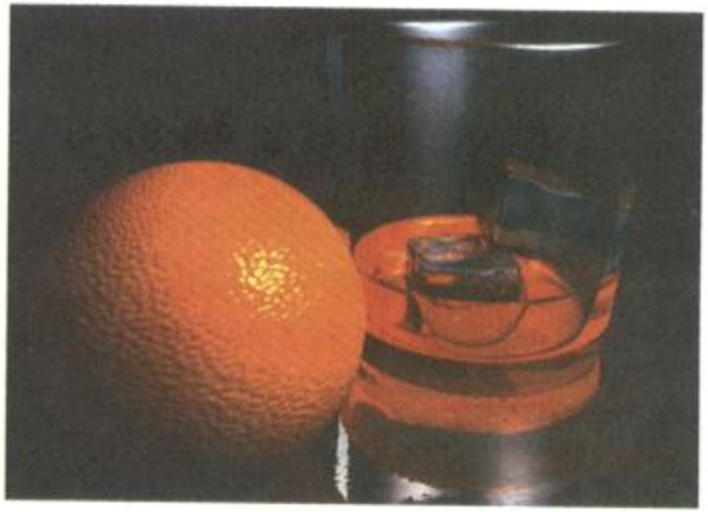
Bump maps encode the normals in the texture

⇓

approximates a more complex undulating surface

P. Rheingans

Bump Mapping



Bump mapping does not change object silhouette

H&B Figure 14.100

Environment Mapping

Goal:

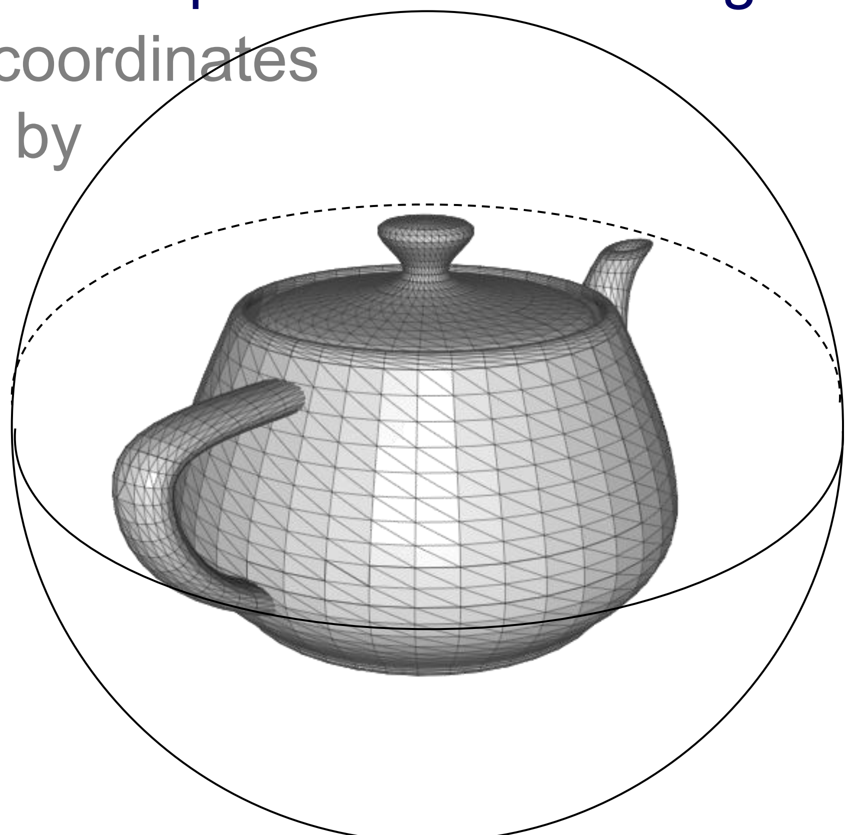
Render shiny surfaces so they the reflect the world.

Environment Mapping

Goal:

Render shiny surfaces so they the reflect the world.

- Pre-compute a map of the surrounding environment
- Set texture coordinates dynamically by reflecting



Environment Mapping

<u>Goal</u>:

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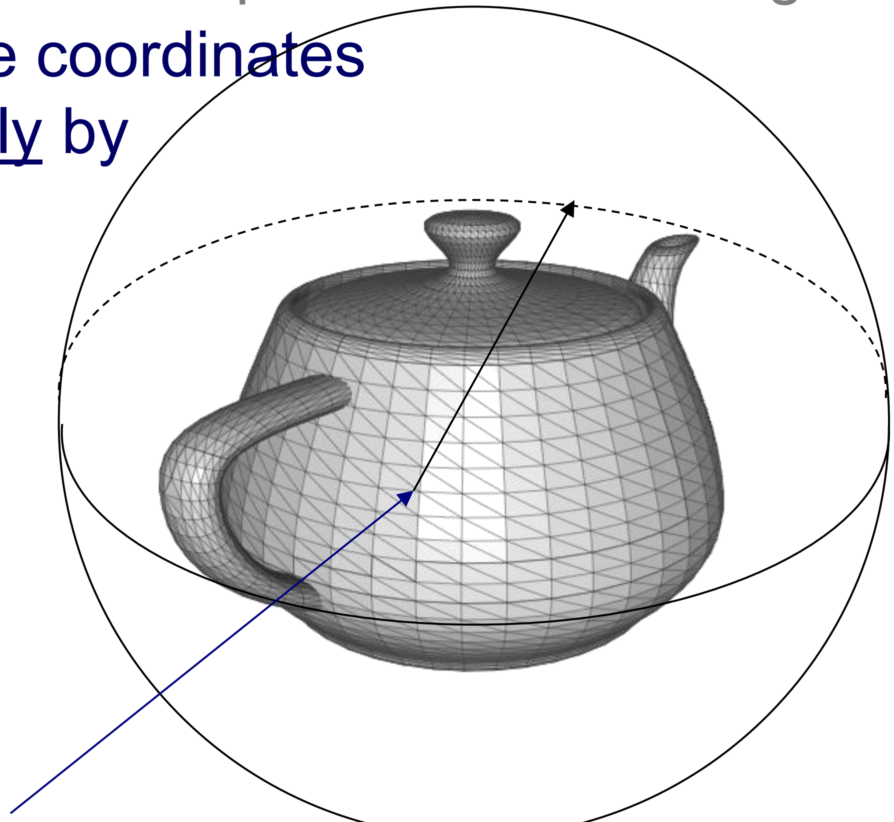

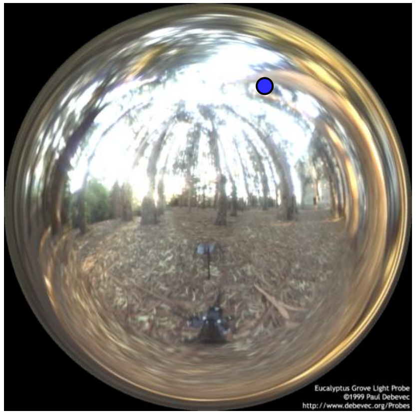

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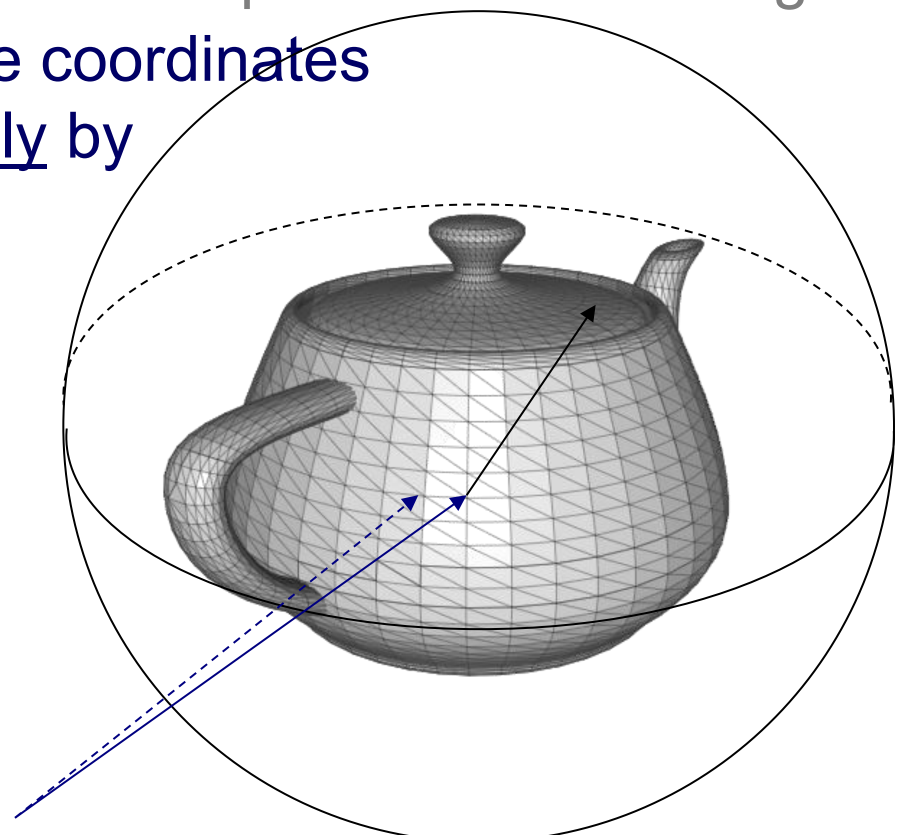

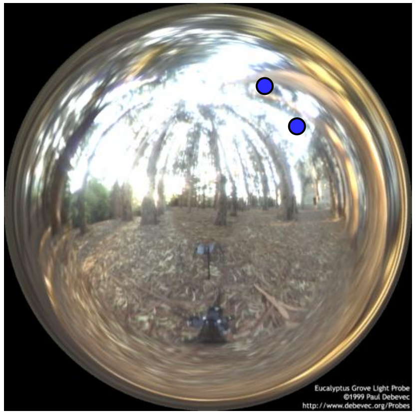

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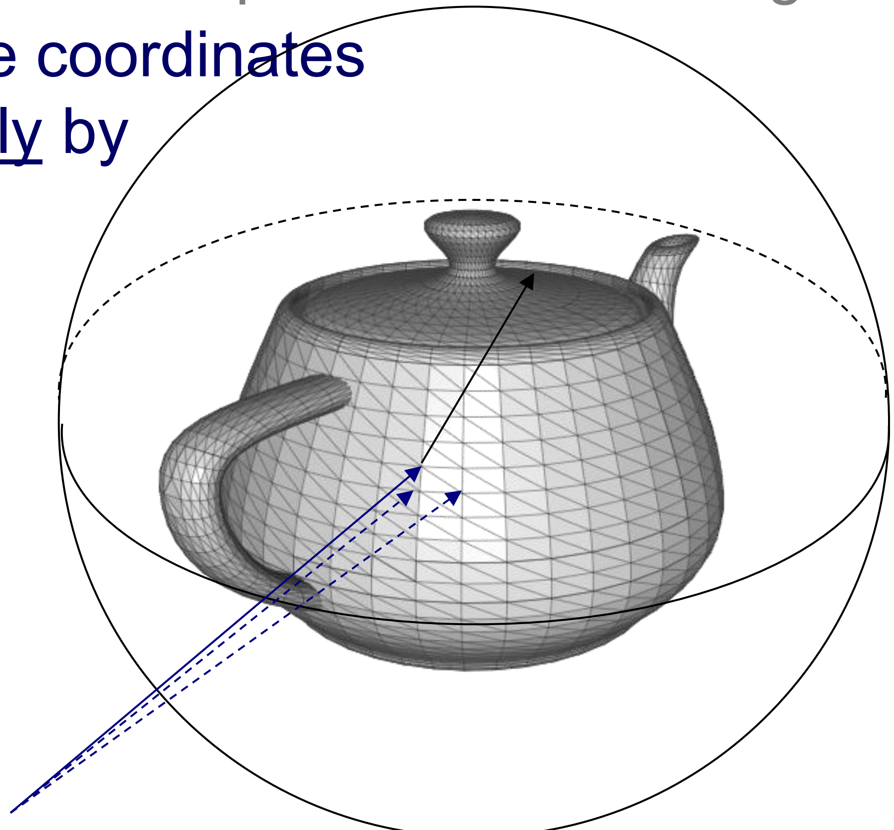

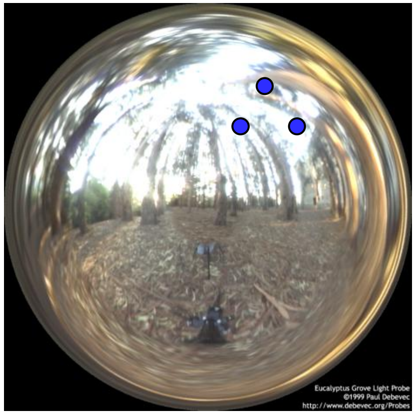

Environment Mapping

<u>Goal</u>:

Render shiny surfaces so they the reflect the world.

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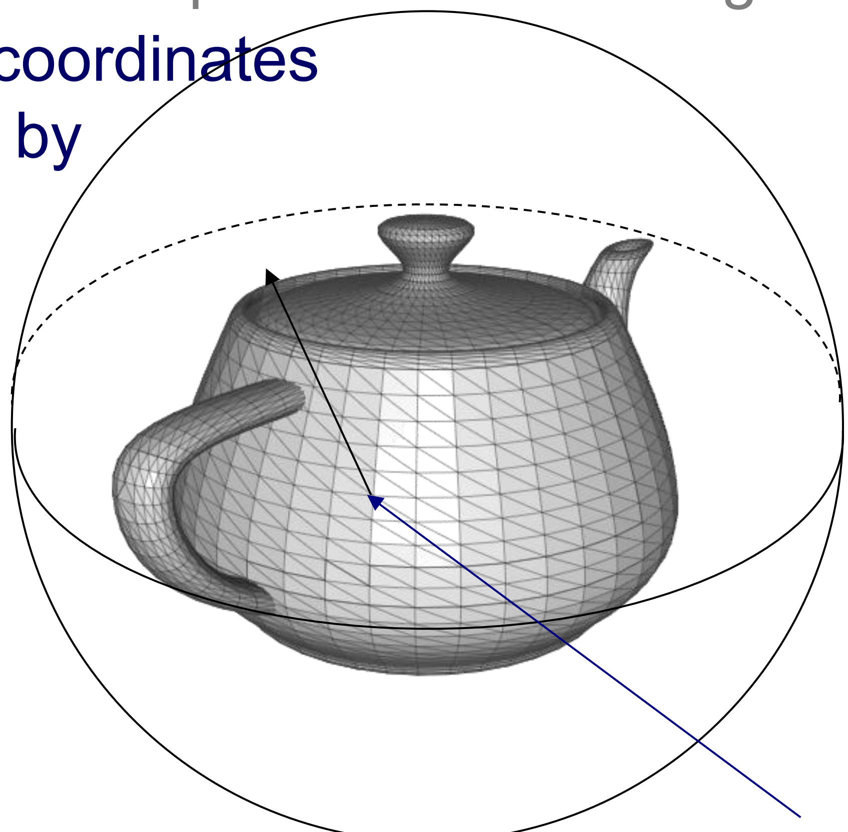


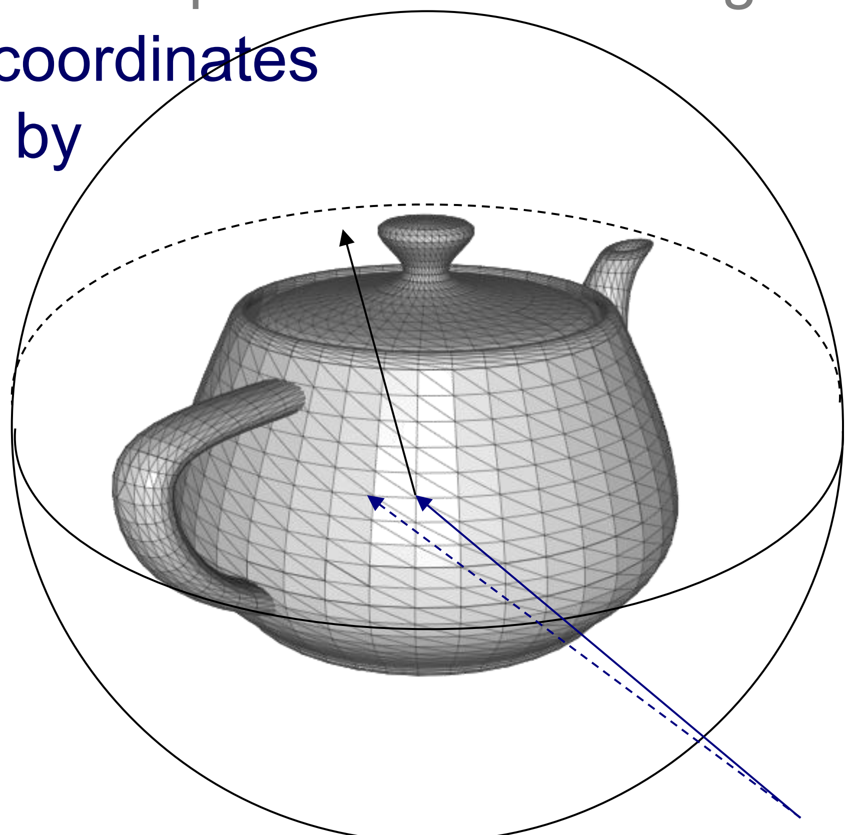
For the same triangle, changing the position of the camera changes the texture coordinates.

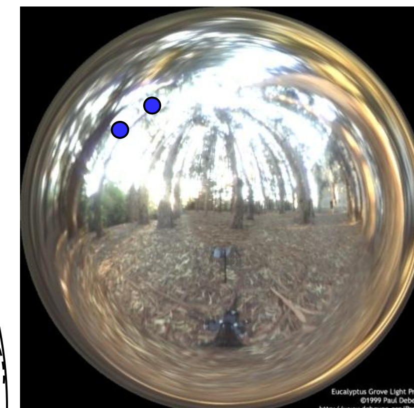
Environment Mapping

Goal:

Render shiny surfaces so they the reflect the world.

- Pre-compute a map of the surrounding environment
- Set texture coordinates dynamically by reflecting





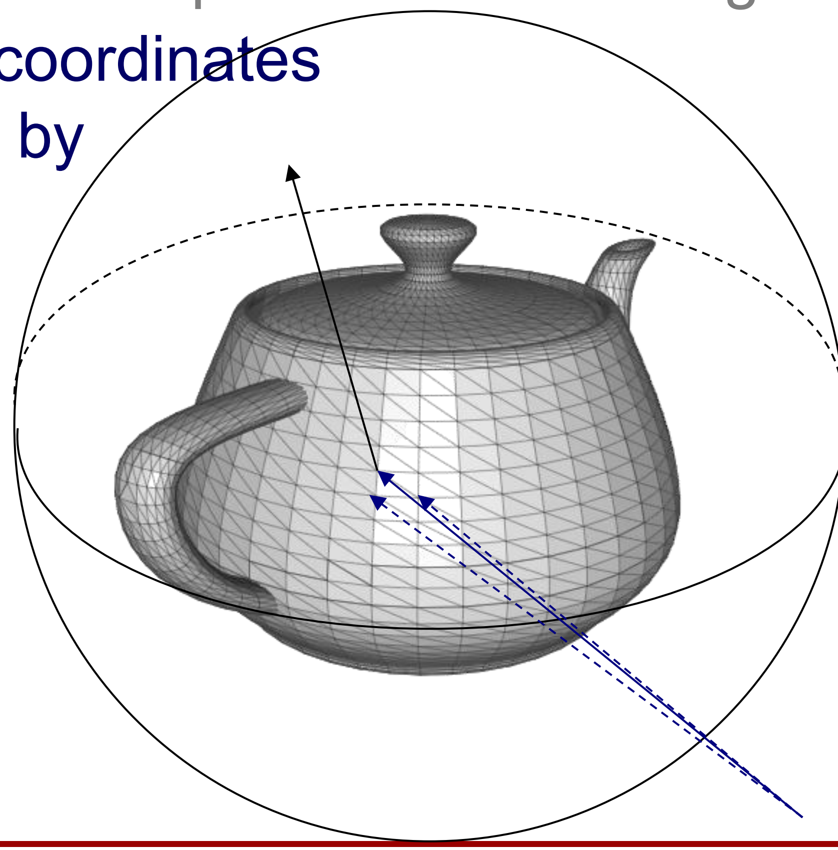
For the same triangle, changing the position of the camera changes the texture coordinates.

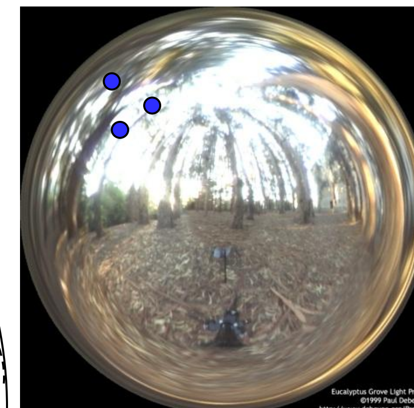
Environment Mapping

<u>Goal</u>:

Render shiny surfaces so they the reflect the world.

- Pre-compute a map of the surrounding environment
- Set texture coordinates <u>dynamically</u> by reflecting





For the same triangle, changing the position of the camera changes the texture coordinates.

Environment Mapping

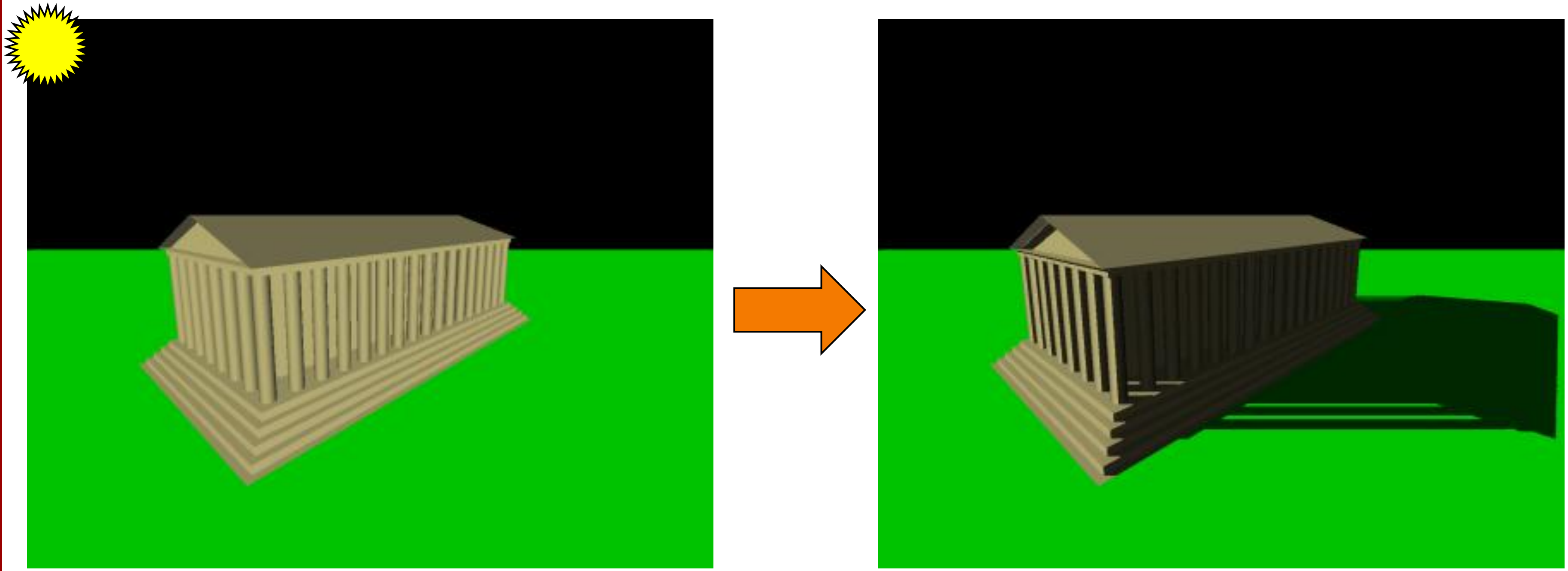
Goal:

Render shiny surfaces so they the reflect the world.

P. Debevec

Shadow Mapping (Williams 1978)

Test if surface is in shadow when computing the contribution to the lighting equation.



Images courtesy of https://en.wikipedia.org/wiki/Shadow_mapping

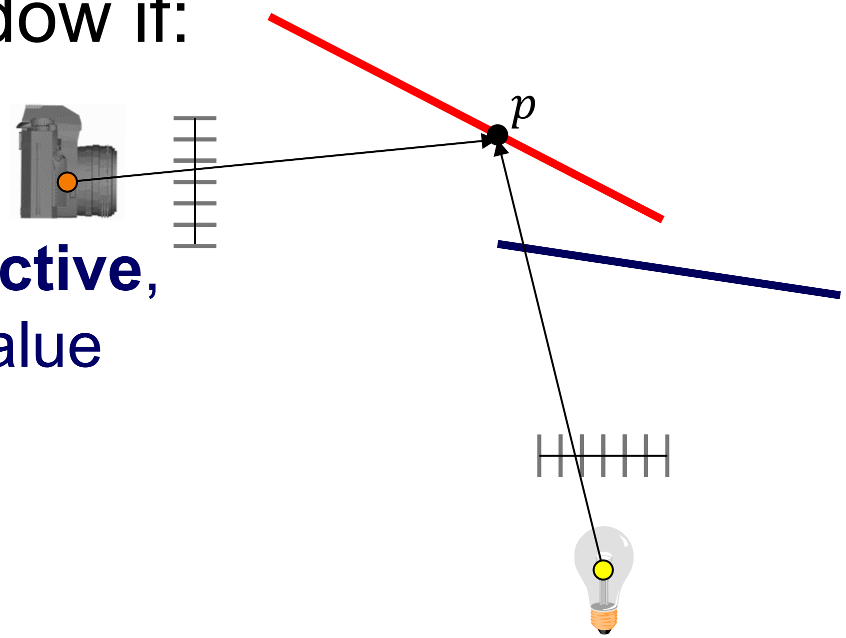
Shadow Mapping (Williams 1978)

Q: Is a point p, seen by the camera, in shadow with respect to the light?

A: The point is not in shadow if:

- The light "sees" p.

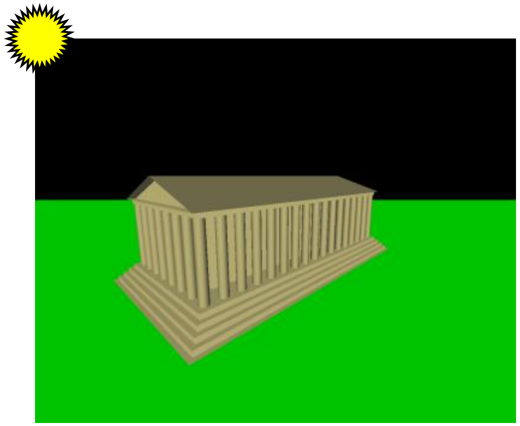
⇒ **Rendering the scene from the light's perspective**, p's z-coordinate is the value stored in the z-buffer.



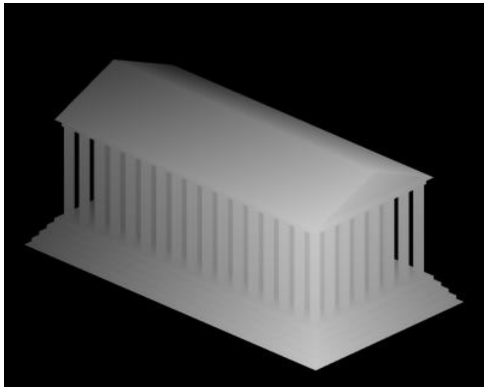
Shadow Mapping (Williams 1978)

Algorithm:

- **Render the scene from the light's perspective** and read back the z-buffer/shadow map.
- For each pixel in the camera view, compute its z-coordinate relative to the light



Camera view



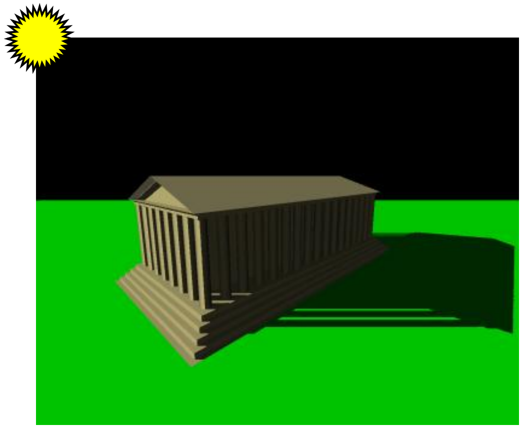
Shadow map

Images courtesy of https://en.wikipedia.org/wiki/Shadow_mapping

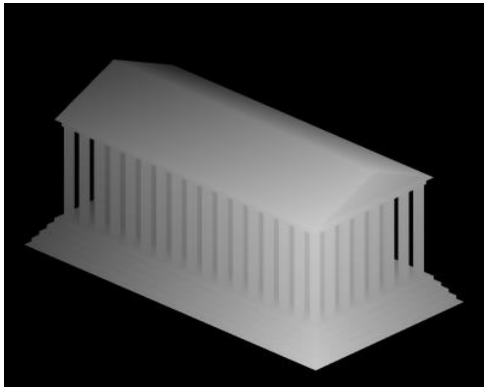
Shadow Mapping (Williams 1978)

<u>Algorithm</u>:

- **Render the scene from the light's perspective** and read back the z-buffer/shadow map.
- For each pixel in the camera view, compute its z-coordinate relative to the light
  - » If it's further back than the value in the shadow map, it's in shadow
  - » Otherwise, it's illuminated



Camera view



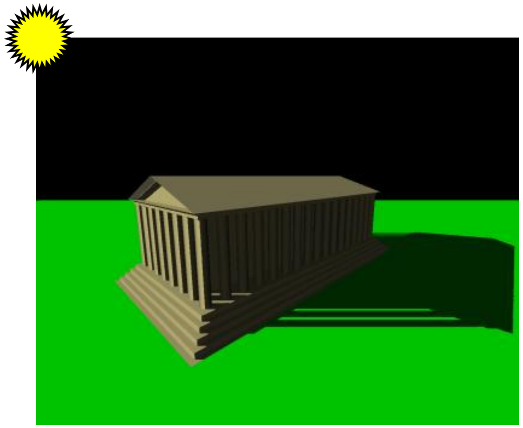
Shadow map

Images courtesy of https://en.wikipedia.org/wiki/Shadow_mapping

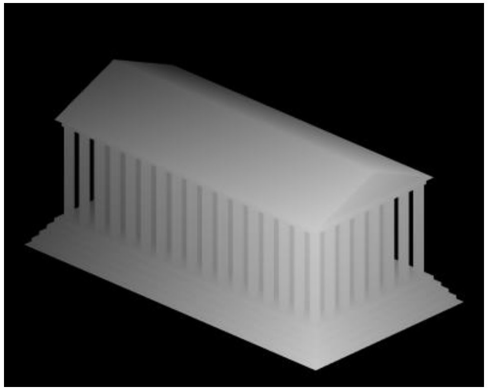
Shadow Mapping (Williams 1978)

<u>Note</u>:

- The projection used for rendering from the light-source depends on the type of light:
  - » Directional → Parallel
  - » Point → Perspective
- Need to use multiple shadow maps if there are multiple lights in the scene



Camera view



Shadow map

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