UNIVERSITY OF DERBY

5CM507 Graphics

Lecture 09 Shadow Maps

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November 22, 2025

Last Week

- Normal mapping
- Cube Maps
- PBR Maps
- ...

Pre-session Readings

Shadows in painting

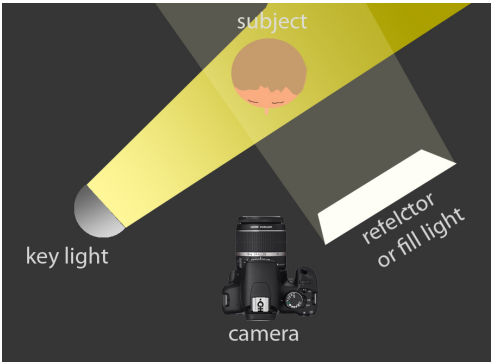
Light is connected with shadows
Shadows can

- Add depth and perspective
- Enhance realism
- Create contrast (chiaroscuro) in artworks and photography

Supper at Emmaus, Caravaggio, 1601, National Gallery, London

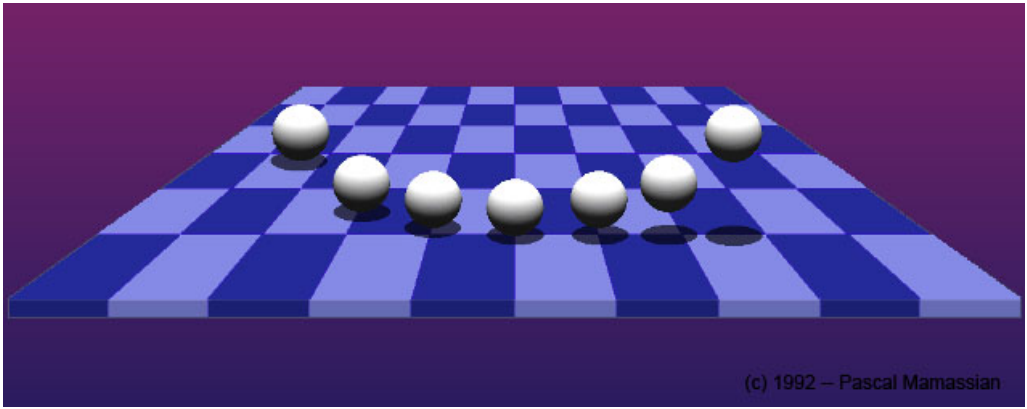
Rembrandt Lighting

The Rembrandt patch in Portrait of Johannes Wtenbogaert, 1633



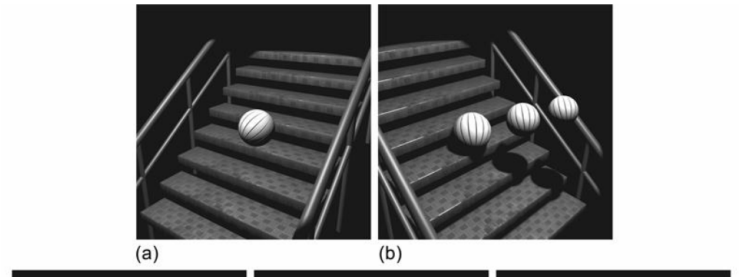
Rembrandt light setup

Shadows Provide Position and Depth Cues



Shadows provides depth cues

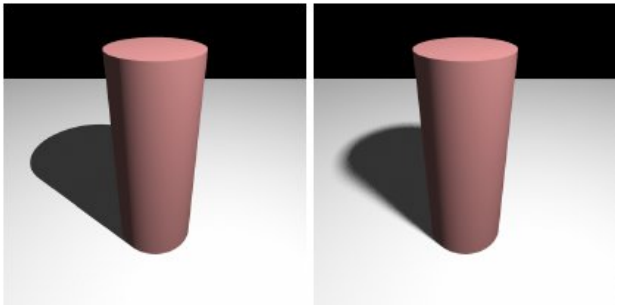
Shadows Provide Position and Depth Cues

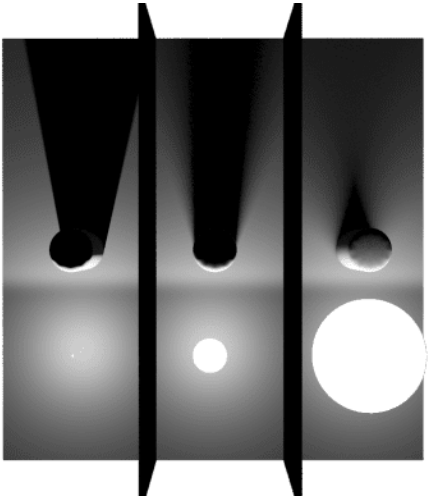


Shadows provides depth cues

Shadow Types

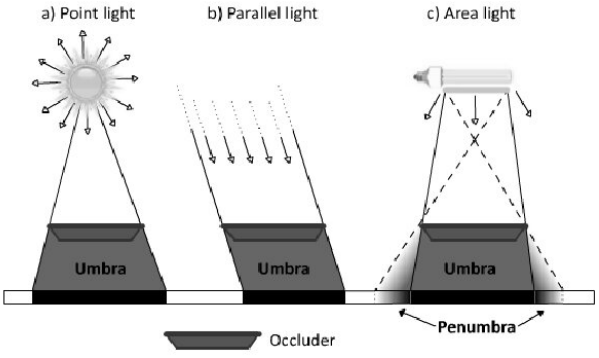
- Hard light example: direct sun light
- Soft light example: lamp with shade



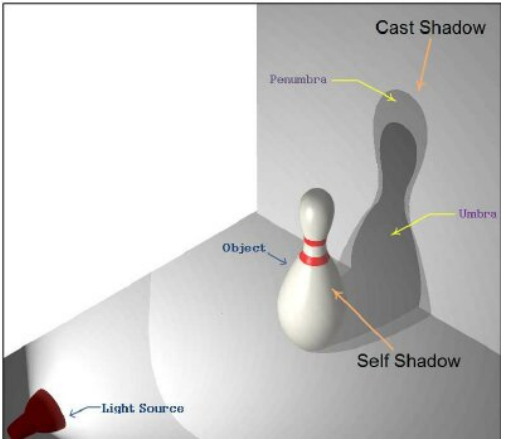


Hard and soft shadows

Shadow Types



Umbra and Penumbra

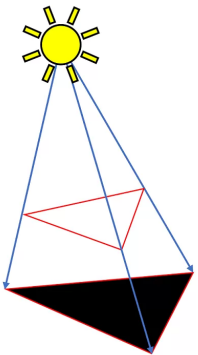


Shadow types

Projective Fake Shadows in Early Games

- Use a fake shadow polygon
- Shadows are totally opaque
- Project the polygon from the light source to the ground.

Projective shadows in Tomb Raider 1996



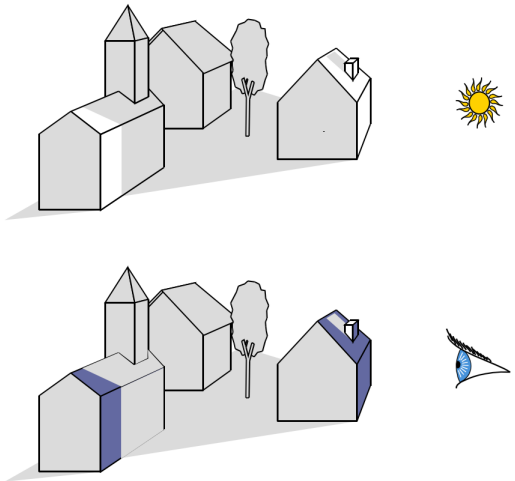
Lecture

Contents

Shadow Projection vs Perspective Projection

Analogy between lighting and viewing:

- A point light source : a camera
- Both cast “rays”
- Shadows: not “visible” from the light source
- Shadow computation: can make use of depth in perspective projection



Projection from a point light source vs perspective projection

Perspective Projection Revisited

$$v_{clip} = \mathbf{PVM}v \quad \mathbf{M} = \mathbf{TRS}$$

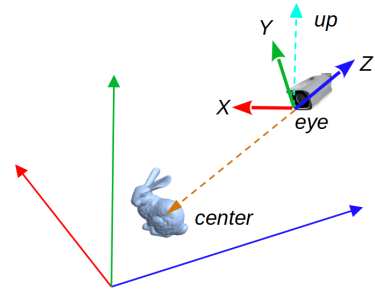
$$\mathbf{V} = \begin{bmatrix} {}^{w}X_c^x & {}^{w}X_c^y & {}^{w}X_c^z & -\vec{e} \cdot {}^{w}\vec{X}_c \\ {}^{w}Y_c^x & {}^{w}Y_c^y & {}^{w}Y_c^z & -\vec{e} \cdot {}^{w}\vec{Y}_c \\ {}^{w}Z_c^x & {}^{w}Z_c^y & {}^{w}Z_c^z & -\vec{e} \cdot {}^{w}\vec{Z}_c \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

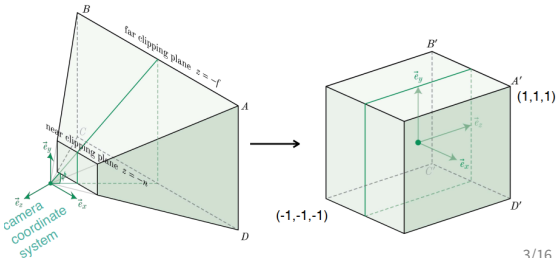
$$\mathbf{P} = \begin{bmatrix} \frac{2n}{r-l} & 0 & 0 & 0 \\ 0 & \frac{2n}{t-b} & 0 & 0 \\ 0 & 0 & -\frac{f+n}{f-n} & -\frac{2fn}{f-n} \\ 0 & 0 & -1 & 0 \end{bmatrix}$$

$$\mathbf{v}_{clip} = \begin{bmatrix} x_{clip} & y_{clip} & z_{clip} & w_{clip} = -z \end{bmatrix}^T$$

$$\text{OpenGL: } z_{norm} = -\frac{z'}{z} \in [\overbrace{-1}^{\text{near}}, \overbrace{1}^{\text{far}}]$$

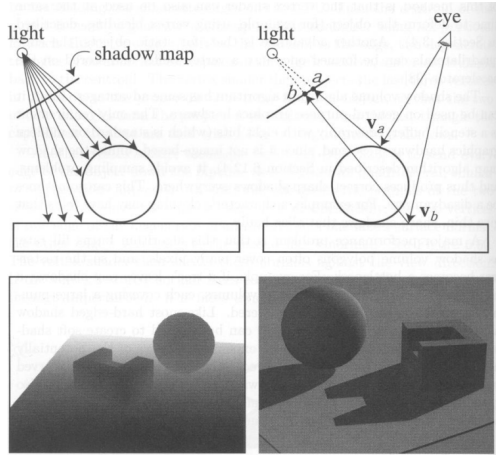
$$depth_{z\text{-}buffer} = \frac{z_{norm}+1}{2} \in [0, 1]$$





Shadow Maps

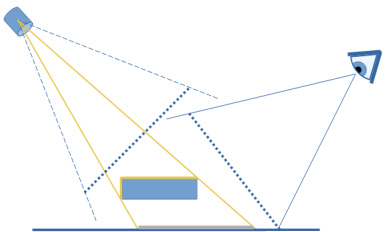
- Limitations
  - Single light source
  - Hard shadows
- Shadow Map: a depth map from a light source
  - closest scene depth from light source
  - like z-buffer, depth range : $[\overbrace{0}^{\text{near}}, \overbrace{1}^{\text{far}}]$
- Shadowing : if a point is “visible” by the light source
  - In shadow: $z > d_{map}$, behind lighted surfaces
  - Not in shadow: $z \leq d_{map}$



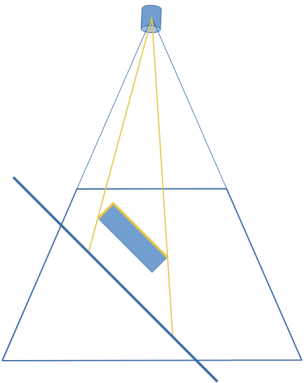
[Foley et al. “Computer Graphics Principles and Practice”]

Shadow Map Generation

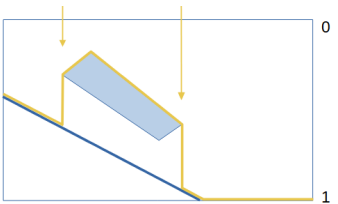
Take the light as the camera; Offscreen rendering; Save the depth buffer.



Top view of the scene



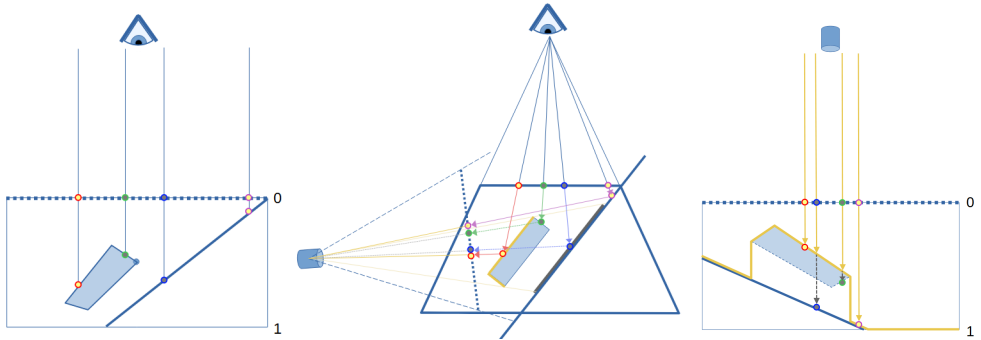
Projection from the light source



Depth map

Shadow Generation I

- Calculate the **light view and projection matrices**
- Reproject the 3D fragment back in the light source space
- Compare the re-projected fragment depth with that in the shadow map



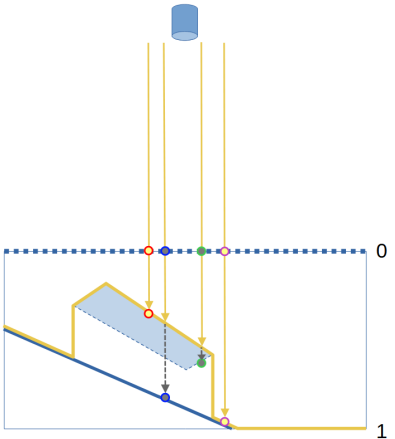
Take the 3D fragment | Reproject the 3D fragment | Compare the depth

Shadow Generation II

Larger light space depth $z \iff$ Further from the light source

Compare the re-projected fragment depth with the shadow map

- $z' > ShadowMap(x', y')$
  - Further from lighted surfaces $\Rightarrow$ In shadow
- $z' \leq ShadowMap(x', y')$
  - On the lighted surface $\Rightarrow$ Not in shadow



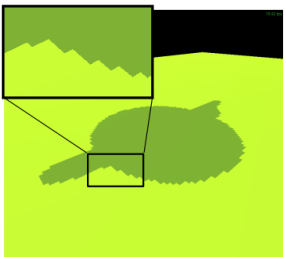
Shadow Map Artifacts

- Aliasing
- Surface Acne
- Peter Panning

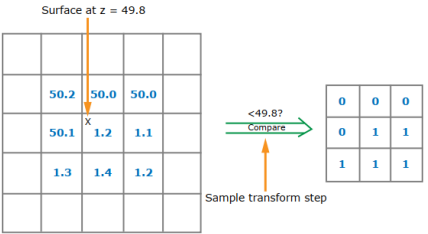
Shadow Aliasing Solutions

1. Increasing shadow map resolution;

2. Percentage-Closer Filtering: Filter the result of the shadow test (weighted average of comparison results)



Jagged shadow edges



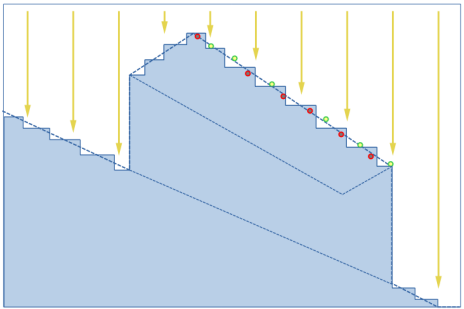
Filtering

Smoothed Shadow Boundary

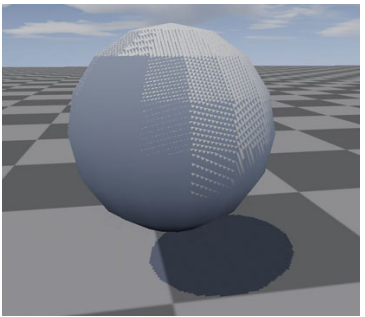
Shadow Acne

Visible points taken as shadows due to z-fighting.

Solutions: 1. Depth offsetting; 2. Front face culling.



Shadow map depth precision problem

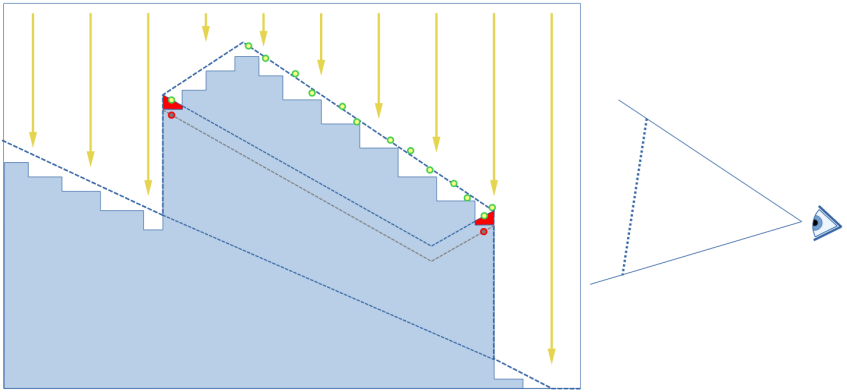


Shadow acne

Using Depth Bias

Subtract the depth of the point by a small bias.

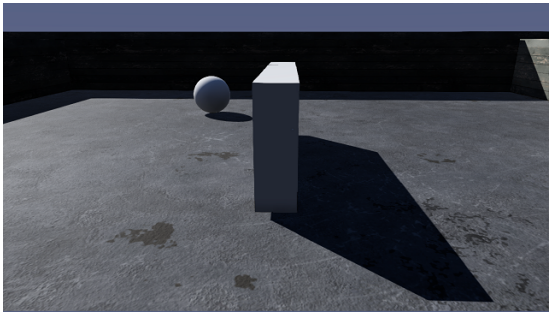
Equivalent to moving the geometry towards the light source.



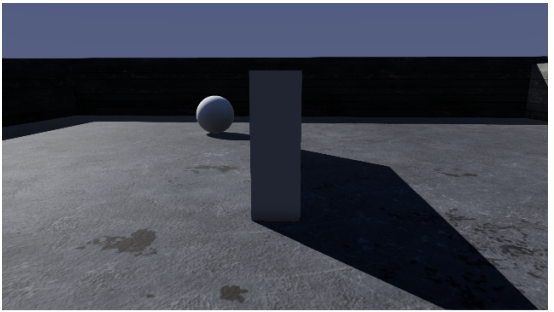
Depth bias

Shadow Peter Panning

A large bias make the shadow detaches from the object.



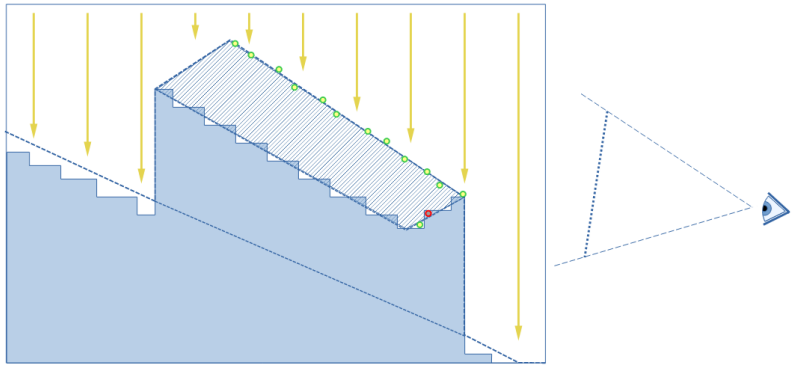
Peter Panning



Without Peter Panning

Using Front Face Culling

- Shadow acne happens on the visible/front surface of a solid object.
- Use the back faces (front face culling) of a solid object when rendering the depth map
- Can avoid using a bias.

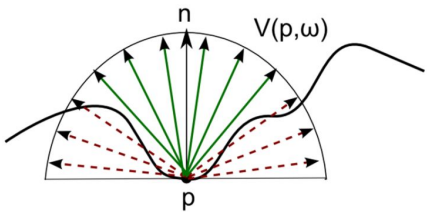


Using the depth of back faces in a shadow map

Ambient Occlusion

Ambient Occlusion

- The average amount of self-occlusion occurring at the point on the surface.
- Creates the illusion of simulated soft shadows by darkening areas where light has difficulty reaching.
- precompted
  - open sky : estimating the amount of visible sky for each point,
  - indoor : walls as origins of the ambient light.



Ambient Occlusion Computing

Ambient Occlusion

Tomb Raider Example (Click to have interactive comparisons)

Ambient Occlusion in Tomb Raider

Summary

- Shadow Maps
- Shadow Map Artifacts
- Ambient Occlusion

Questions?

Chinese shadows