Hard Shadows

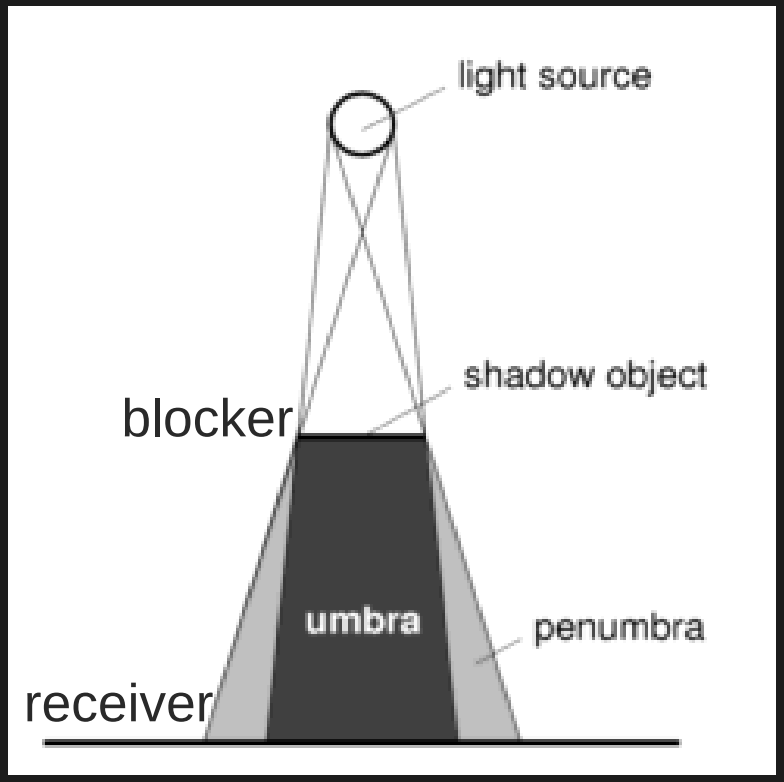
Digital Image Synthesis

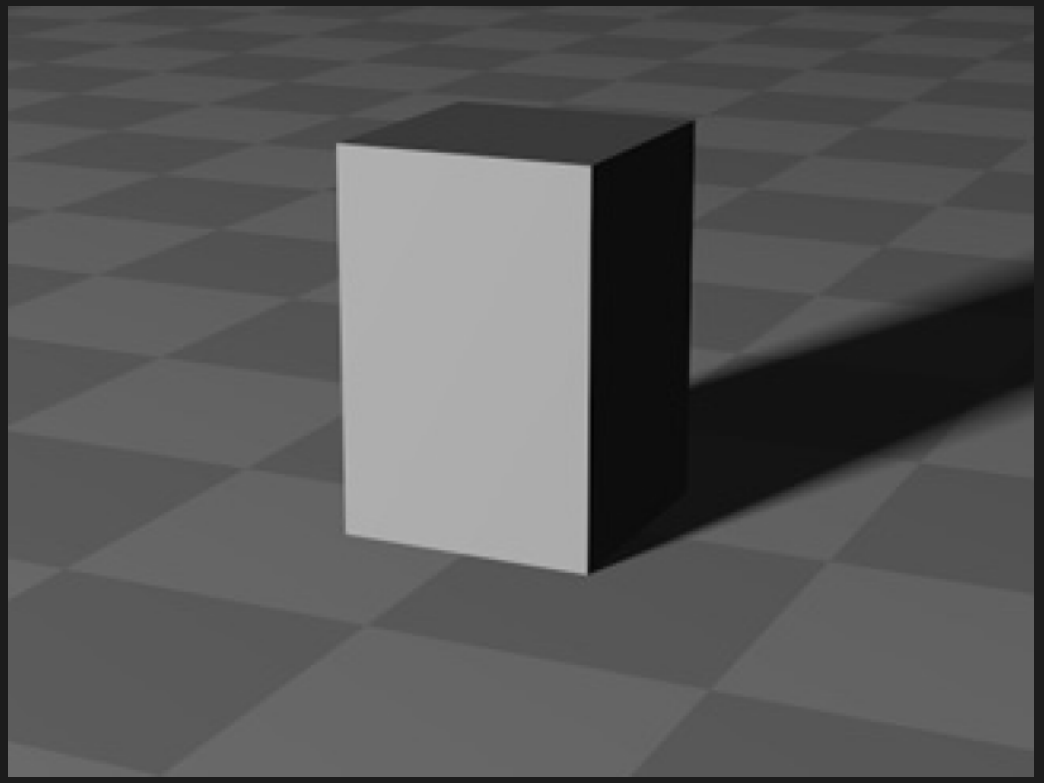
1/4/2007

With slides from Eric Chan, Pradeep Sen, Marc Stamminger, Ravi Ramamoorthi, Brandon Lloyd

Why shadows

- Crucial for spatial and depth perception

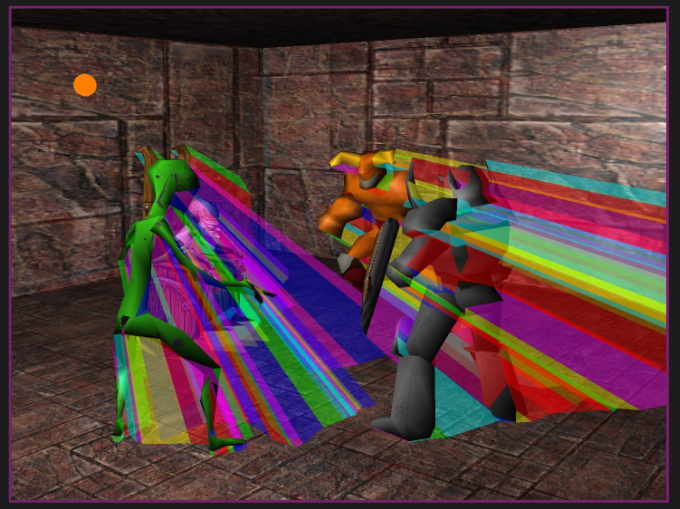




Two Algorithms from the 1970's

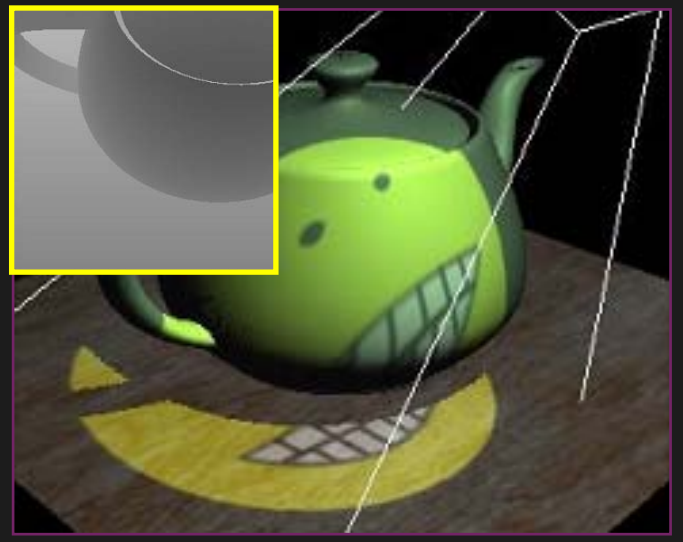
Shadow volumes (Crow 1977)

- Object-space
- Accelerated by hardware stencil buffer
- Large fillrate consumption



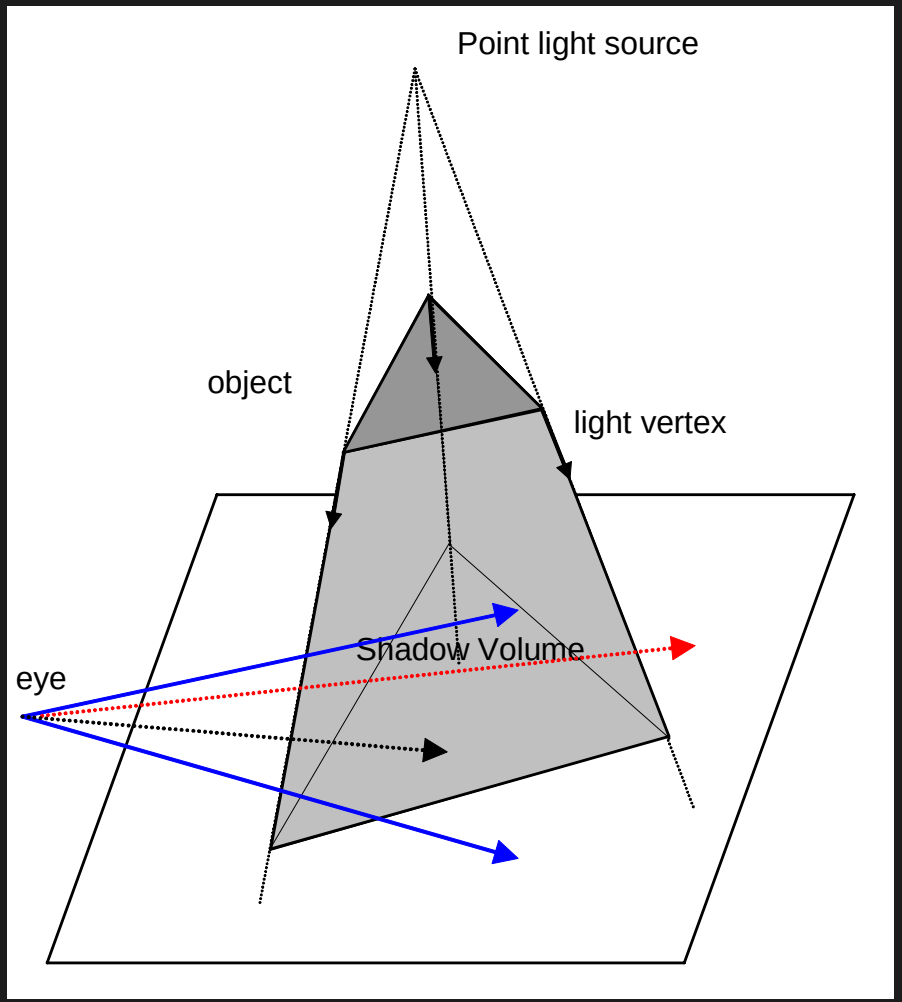
Shadow maps (Williams 1978)

- Image-space
- Fast and simple
- Supported in hardware
- Undersampling artifacts



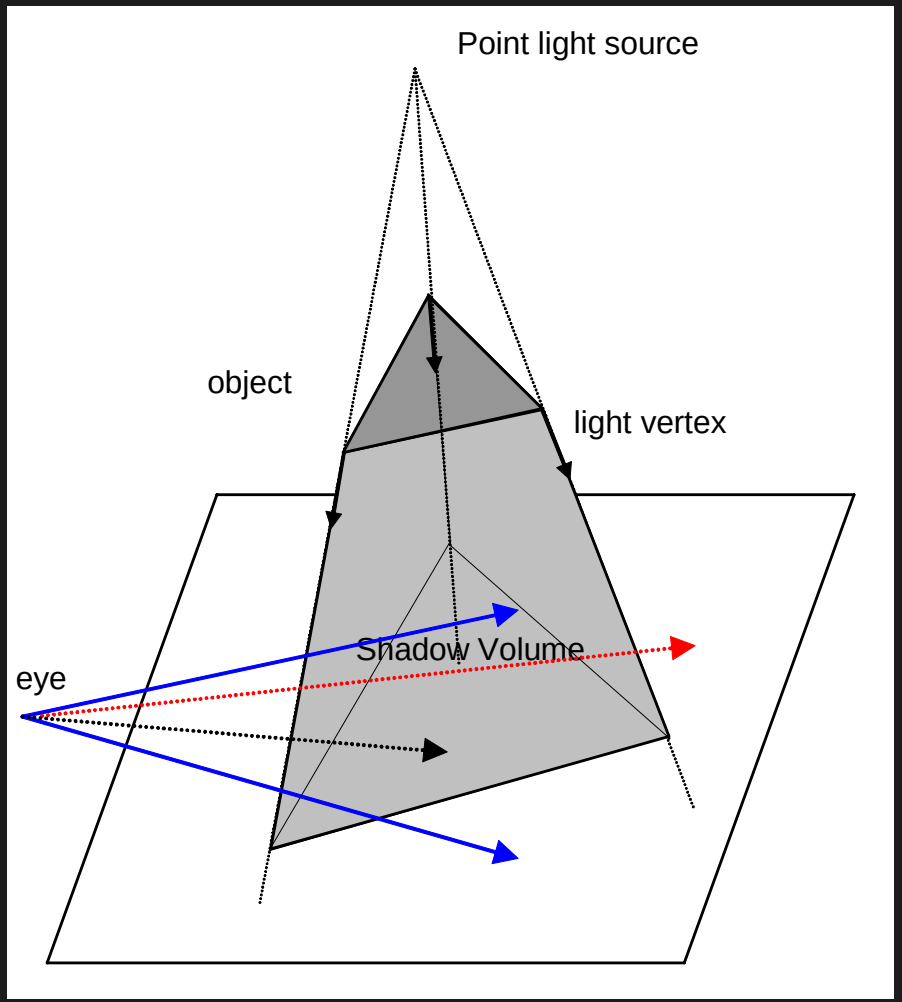
Shadow volumes

- Create volumes of space in shadow from a point light
- Each triangle creates 3 projecting quads



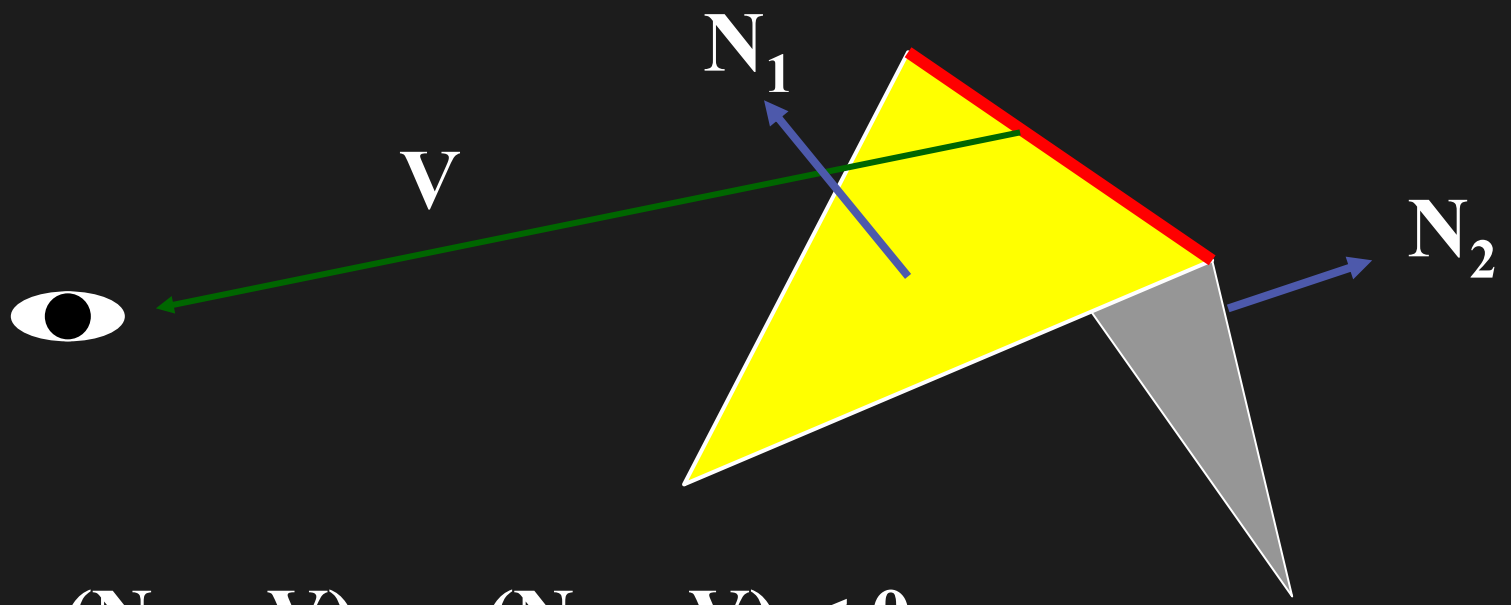
Using the volume

- To test a point, count the number of polygons between it and eye
- If more front-facing than back-facing polygons, then it is in shadow



Creating volumes

- Use the silhouette to speed up
- What is silhouette?



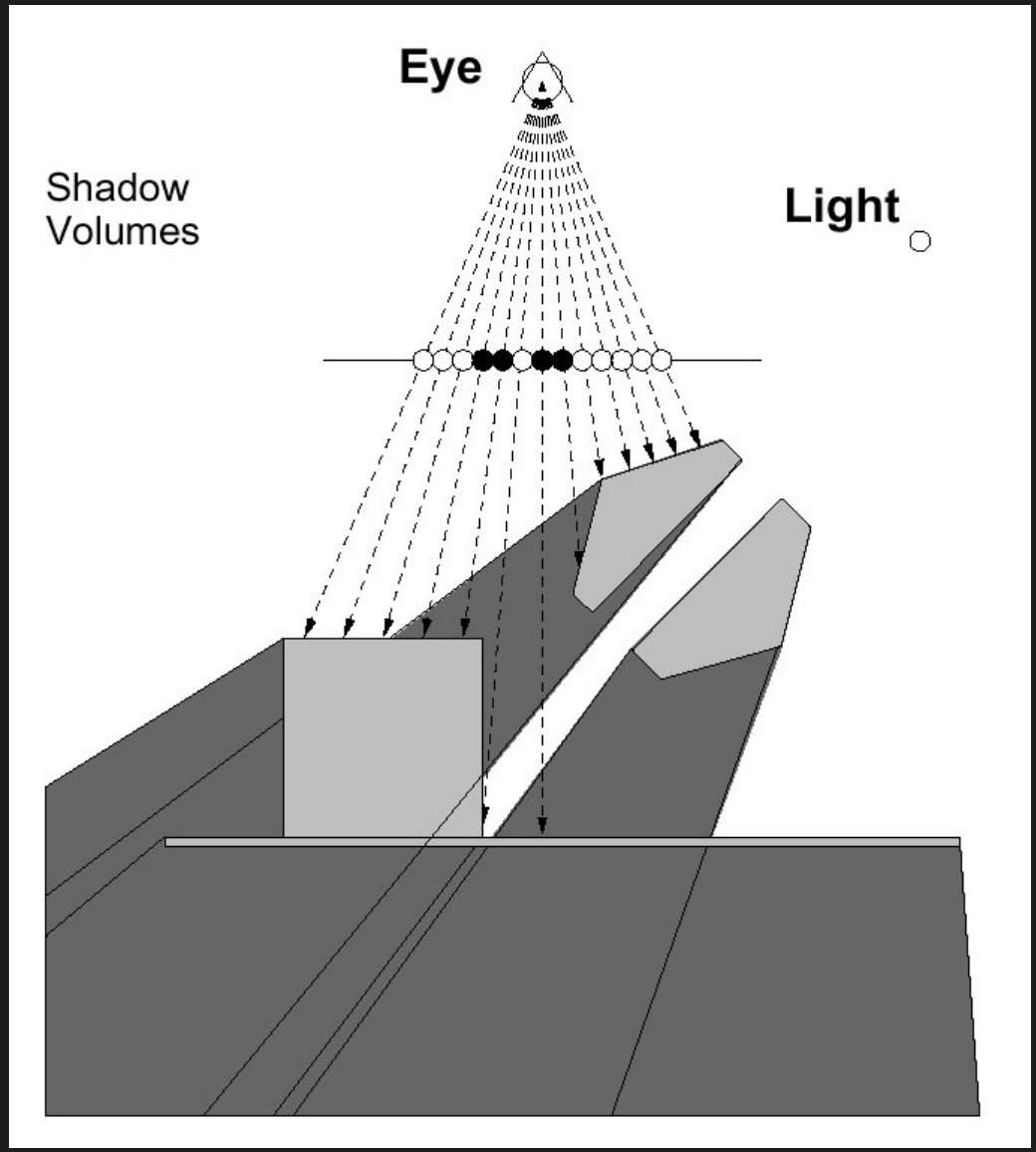
$$(N_1 \cdot V) \cdot (N_2 \cdot V) < 0$$

Shadow volume algorithm

- Finding volumes
- Rendering
  - Render scene into z-buffer, freeze z-buffer
  - Draw front-facing quads, increment stencil buffer
  - Draw back-facing quads, decrement stencil buffer
  - If (cnt==0) lit else shadowed

Multiple shadow volumes

- To test a point, count the number of polygons between it and eye
- If more front-facing than back-facing polygons, then it is in shadow



Shadow Mapping

Lance Williams: Brute Force in image space (shadow maps in 1978, but other similar ideas like Z buffer, bump mapping using textures and so on)

Completely image-space algorithm

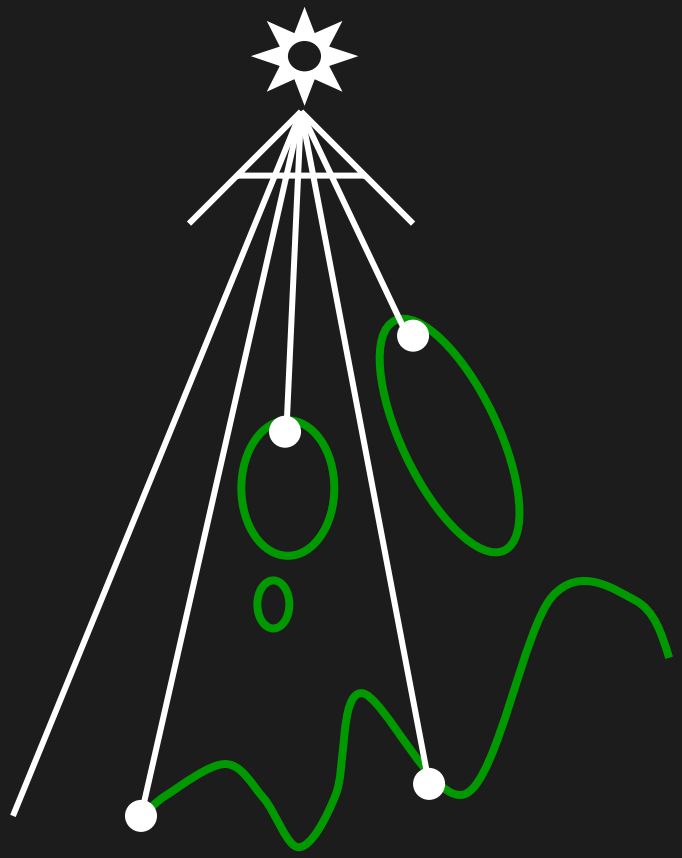
- no knowledge of scene's geometry is required
- must deal with aliasing artifacts

Well known software rendering technique

- Basic shadowing technique for Toy Story, etc.

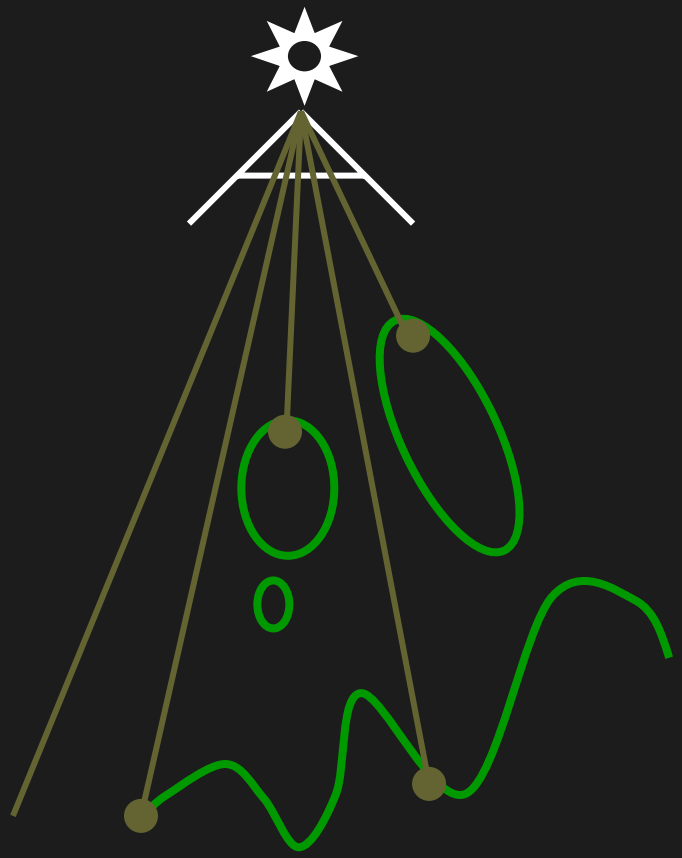
Phase 1: Render from Light

Depth image from light source



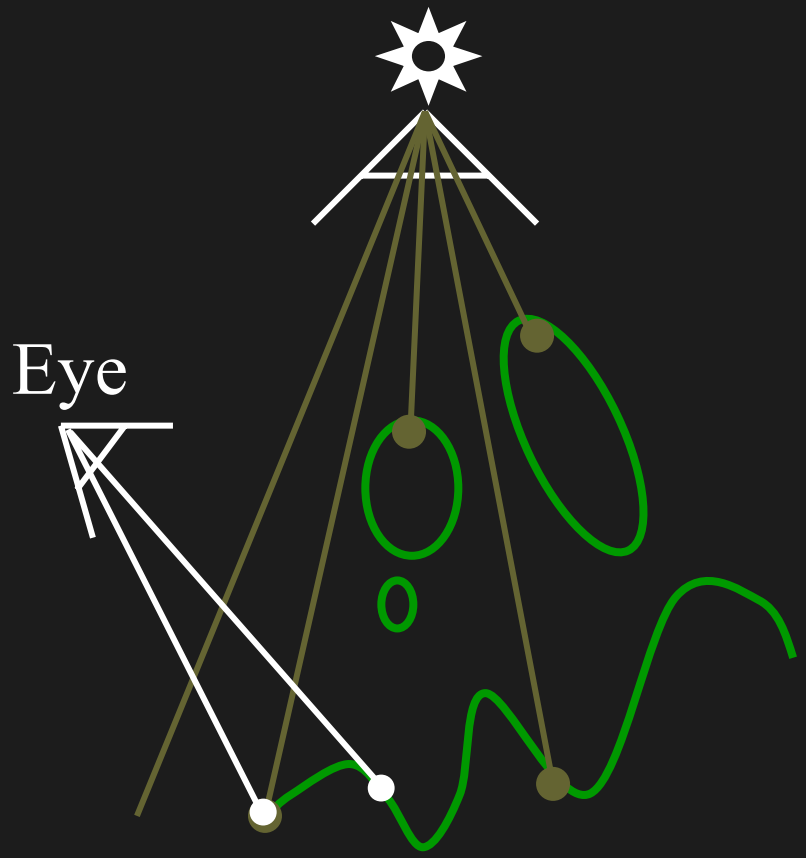
Phase 1: Render from Light

Depth image from light source



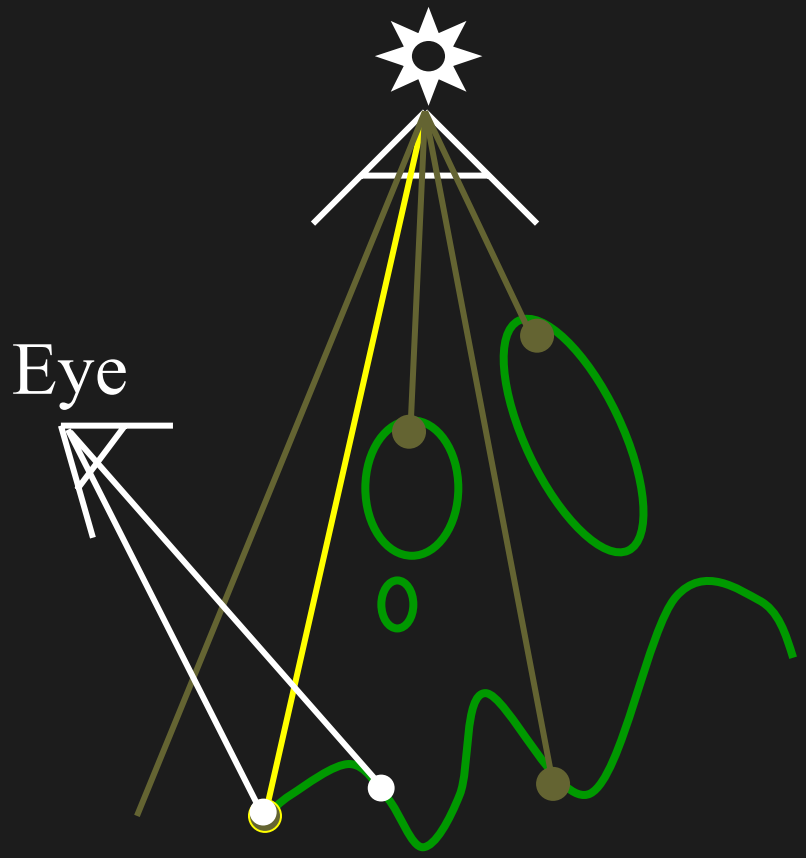
Phase 2: Render from Eye

Standard image (with depth) from eye



Phase 2+: Project to light for shadows

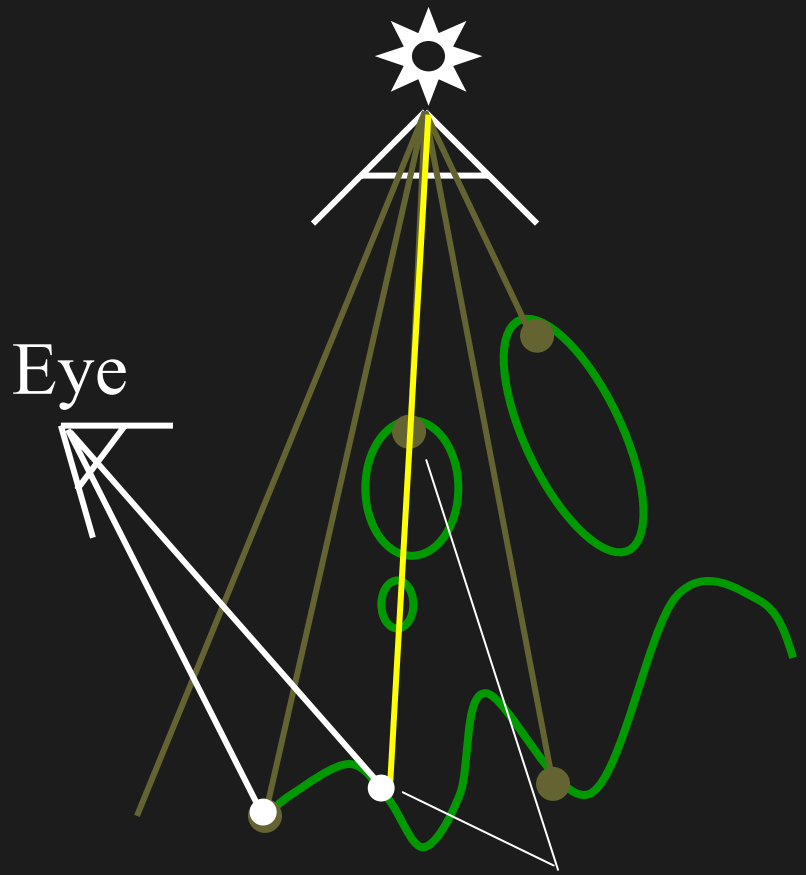
Project visible points in eye view back to light source



(Reprojected) depths match for light and eye. VISIBLE

Phase 2+: Project to light for shadows

Project visible points in eye view back to light source

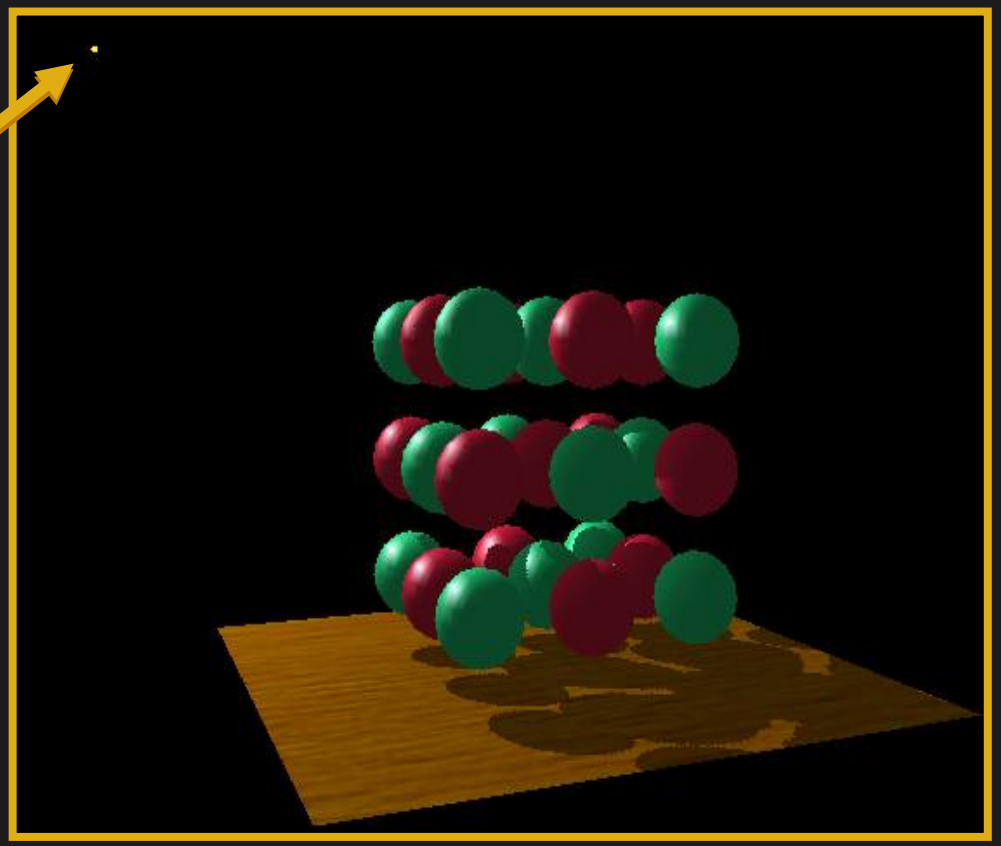


(Reprojected) depths from light, eye not the same. BLOCKED!!

Visualizing Shadow Mapping

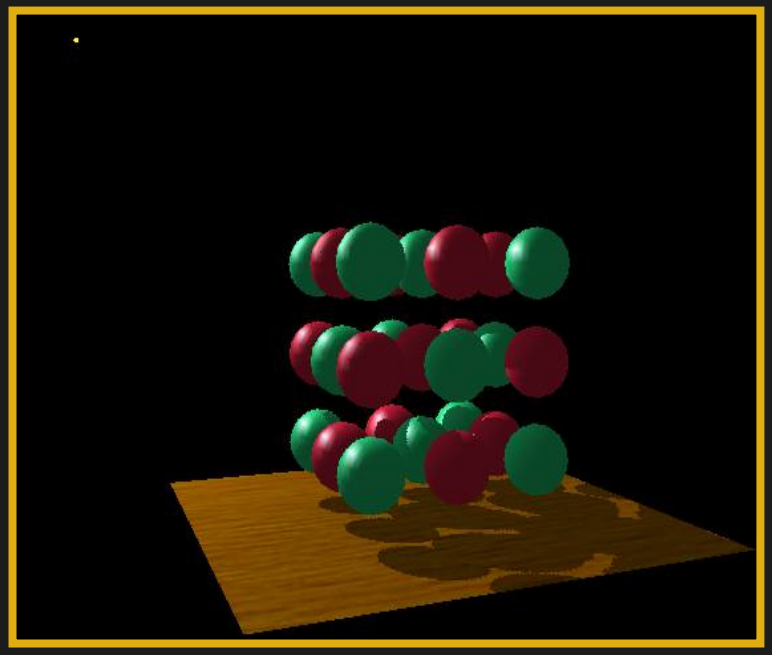
A fairly complex scene with shadows

the point light source

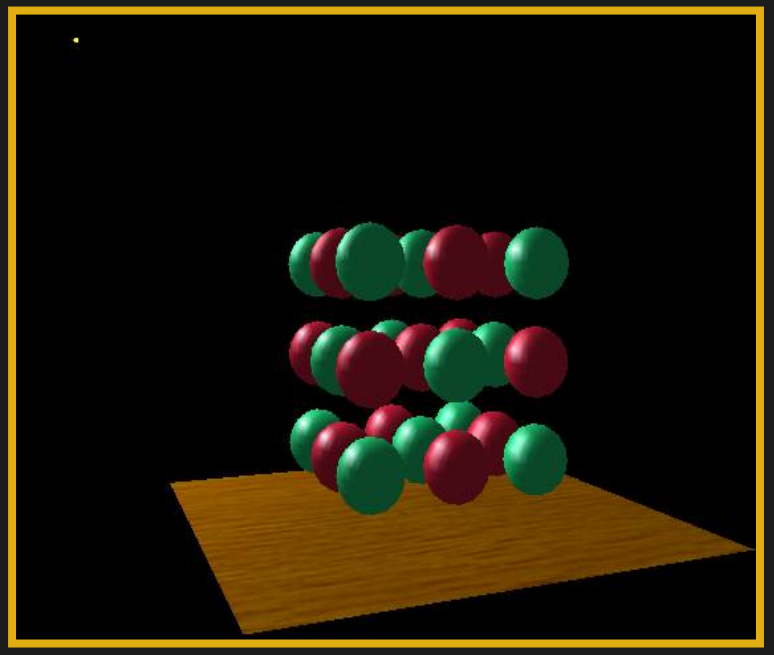


Visualizing Shadow Mapping

Compare with and without shadows



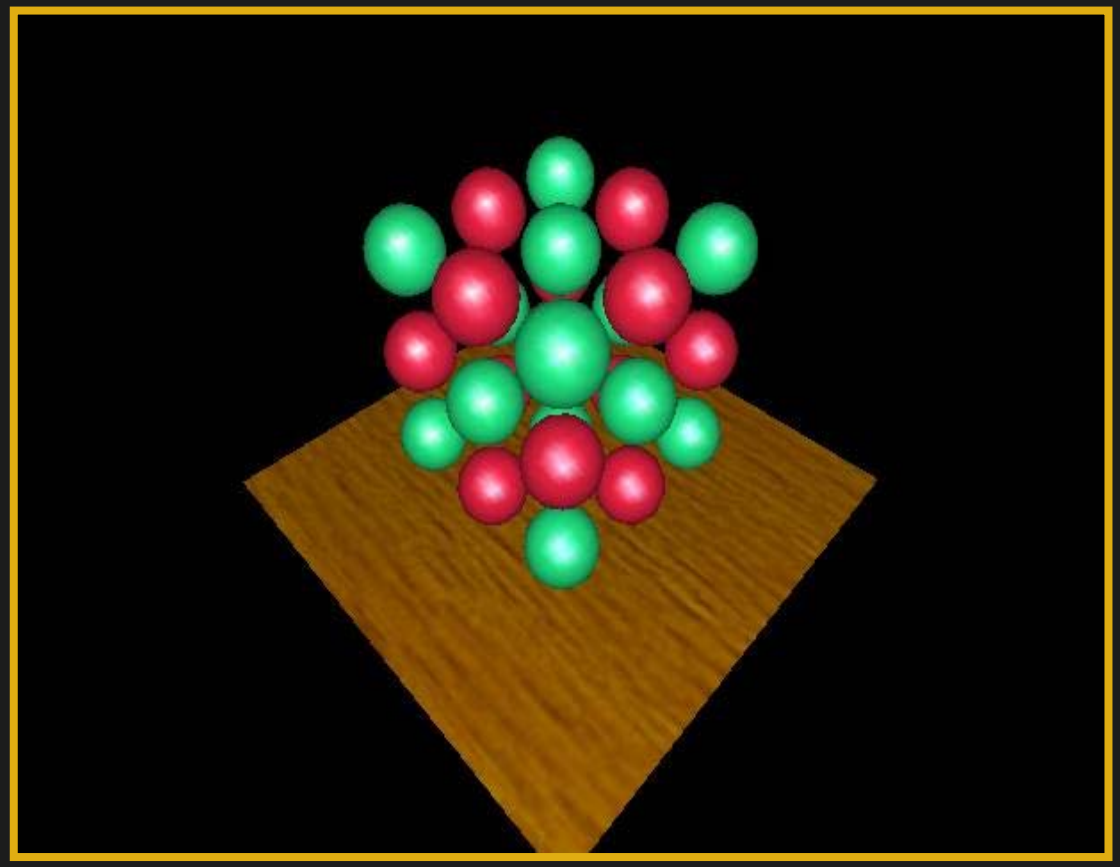
with shadows

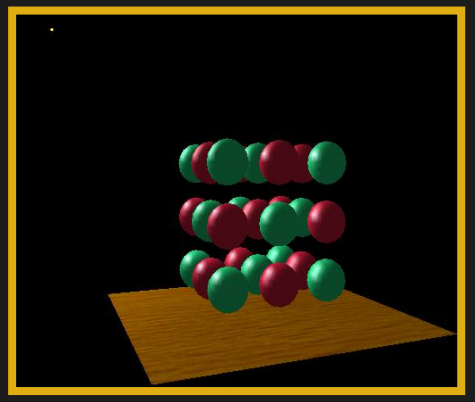


without shadows

Visualizing Shadow Mapping

The scene from the light's point-of-view

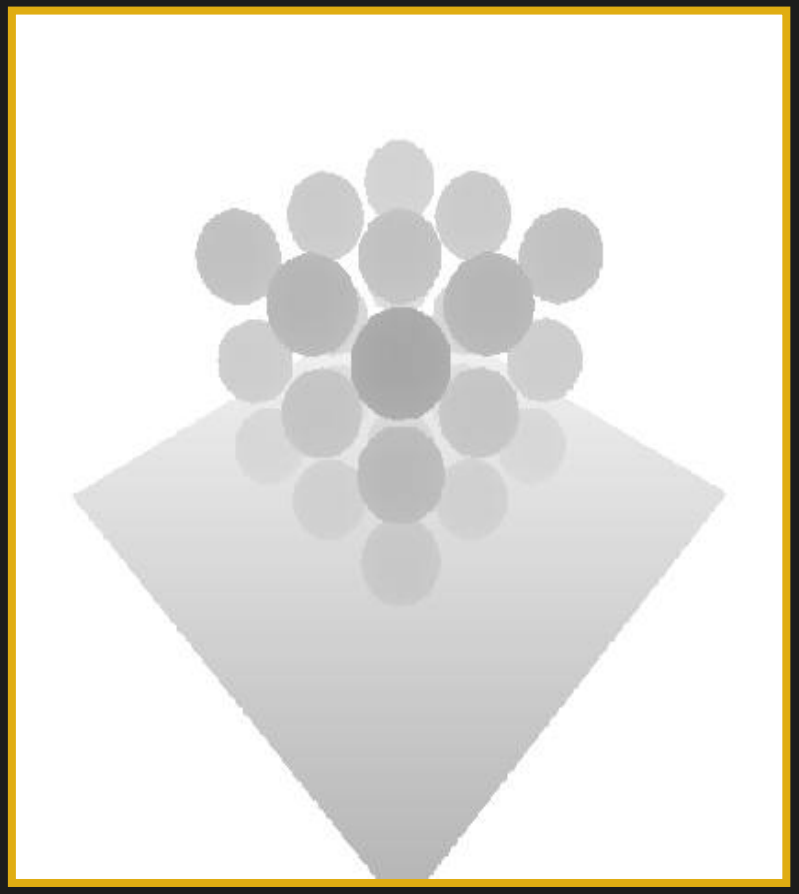


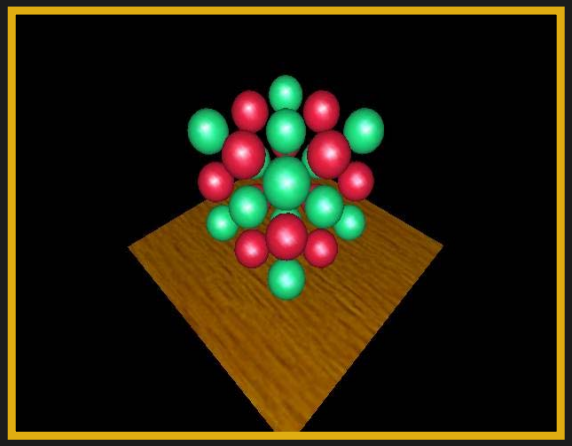


FYI: from the eye's point-of-view again

Visualizing Shadow Mapping

The depth buffer from the light's point-of-view

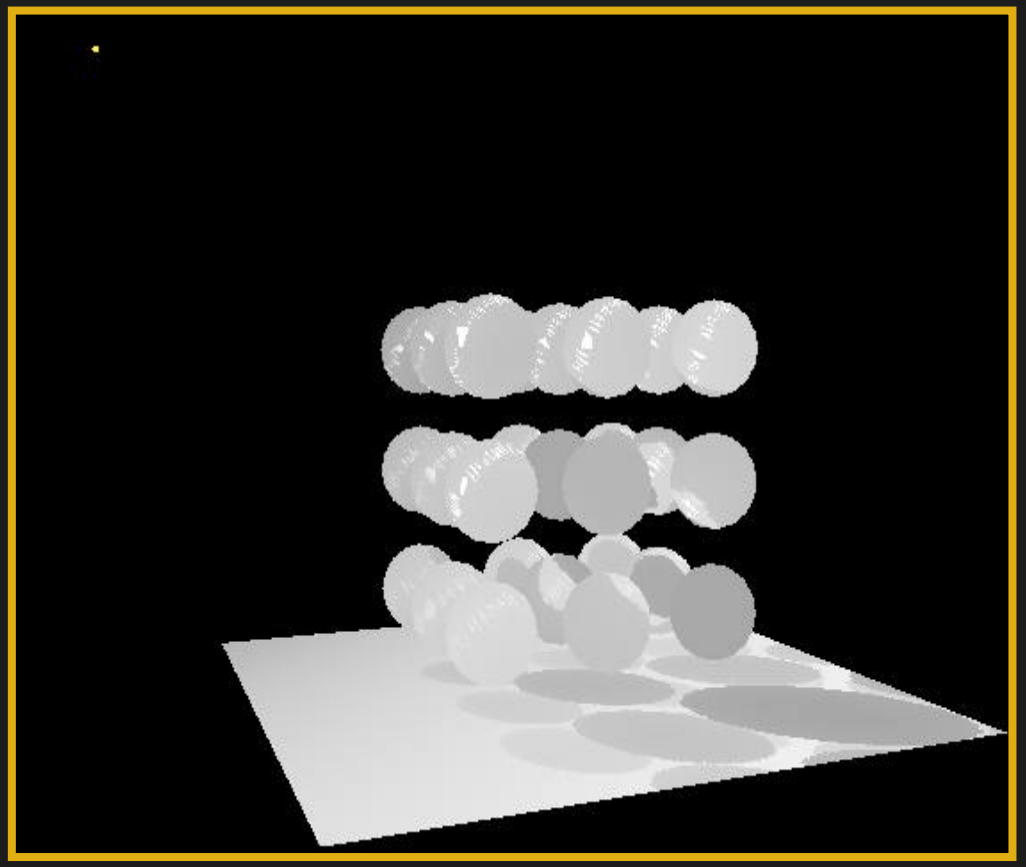


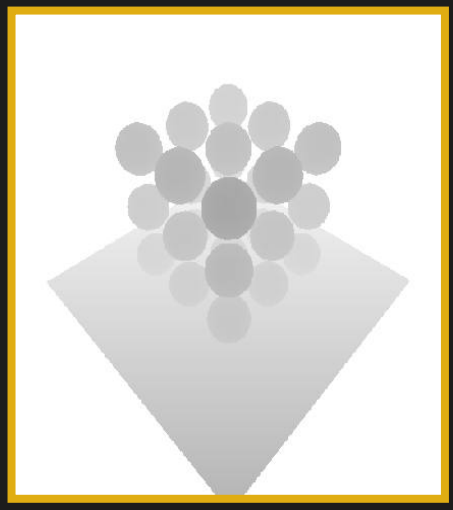


FYI: from the light's point-of-view again

Visualizing Shadow Mapping

Projecting the depth map onto the eye's view



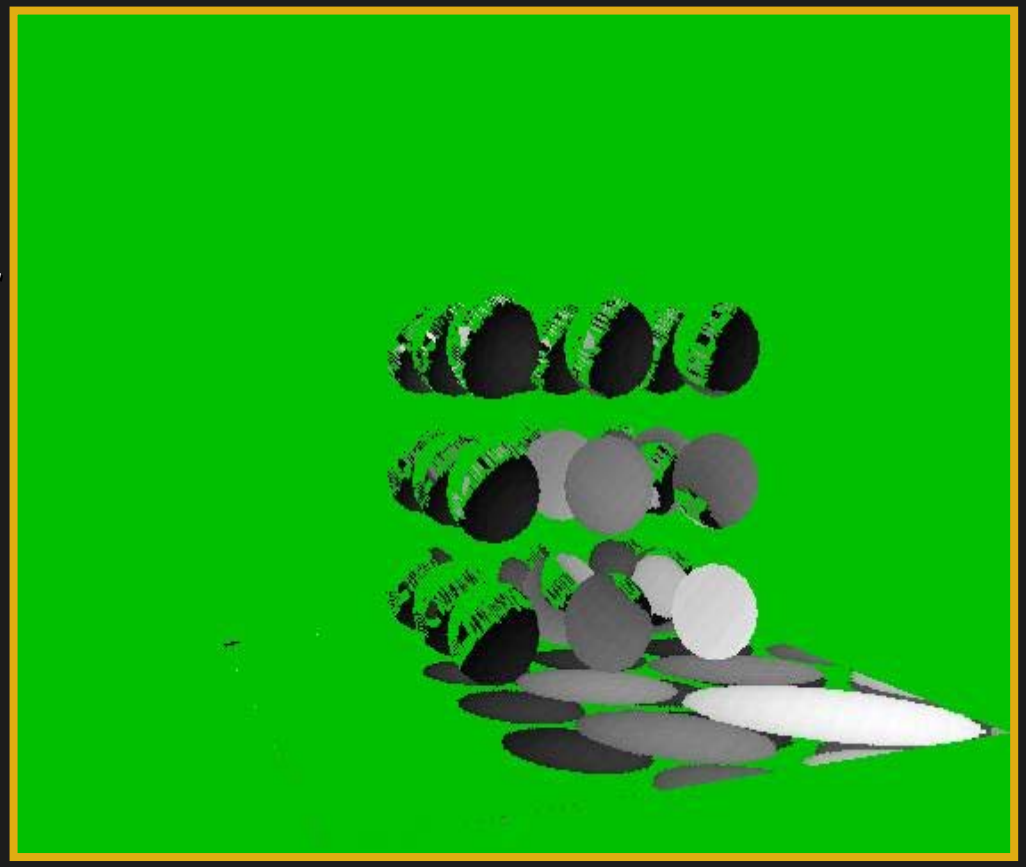


FYI: depth map for light's point-of-view again

Visualizing Shadow Mapping

Comparing light distance to light depth map

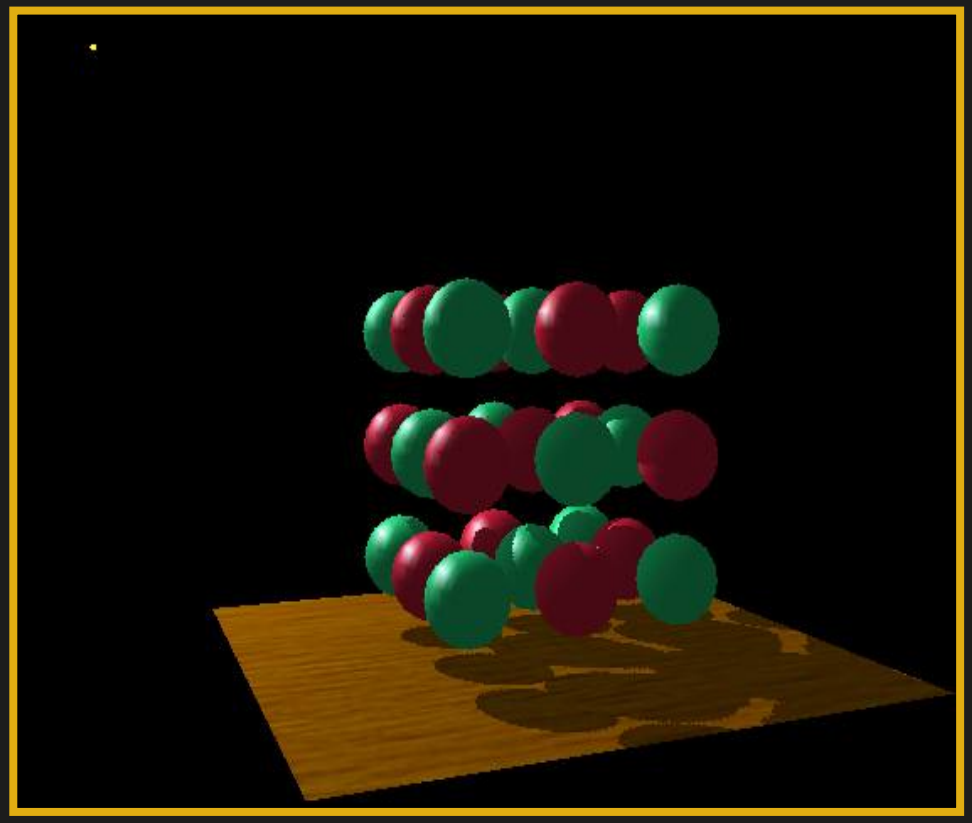
Green is where the light planar distance and the light depth map are approximately equal



Non-green is where shadows should be

Visualizing Shadow Mapping

Scene with shadows



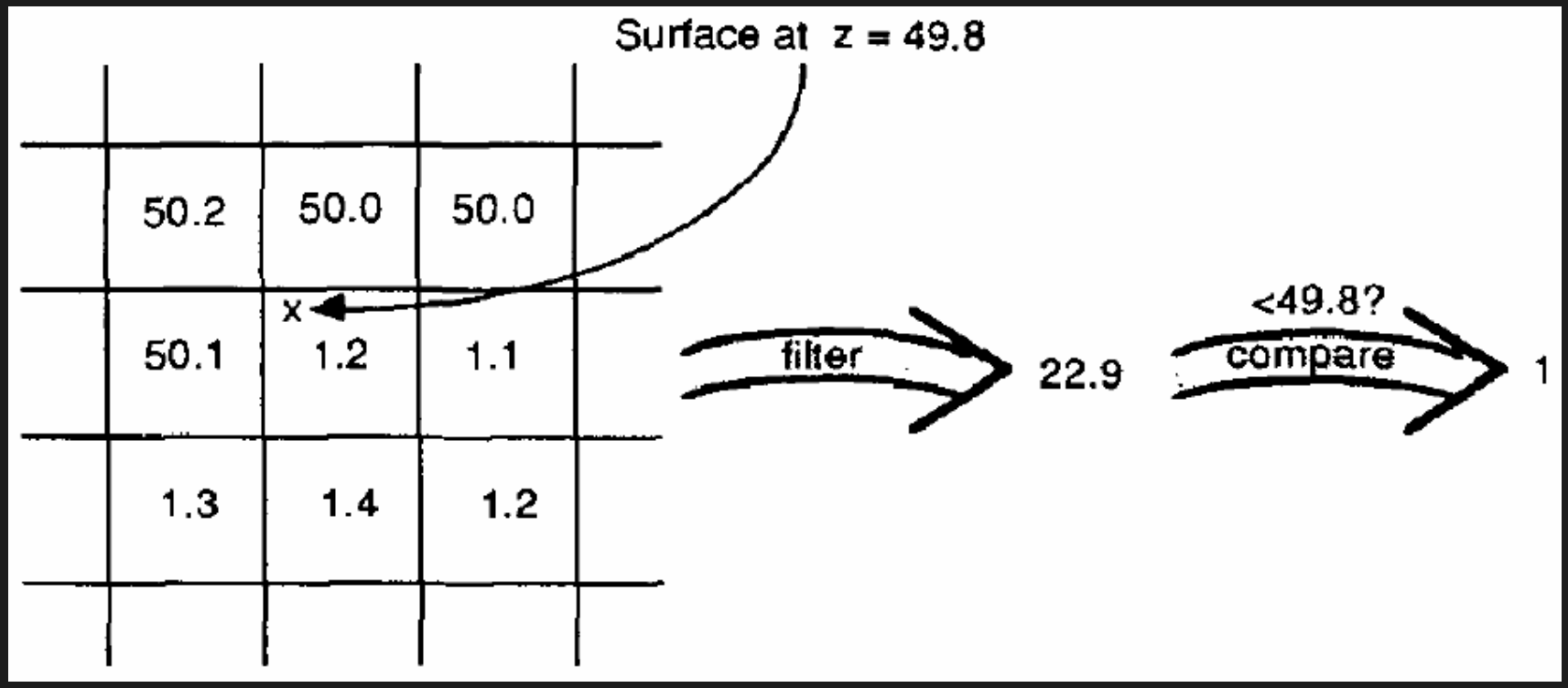
Notice how specular highlights never appear in shadows

Notice how curved surfaces cast shadows on each other

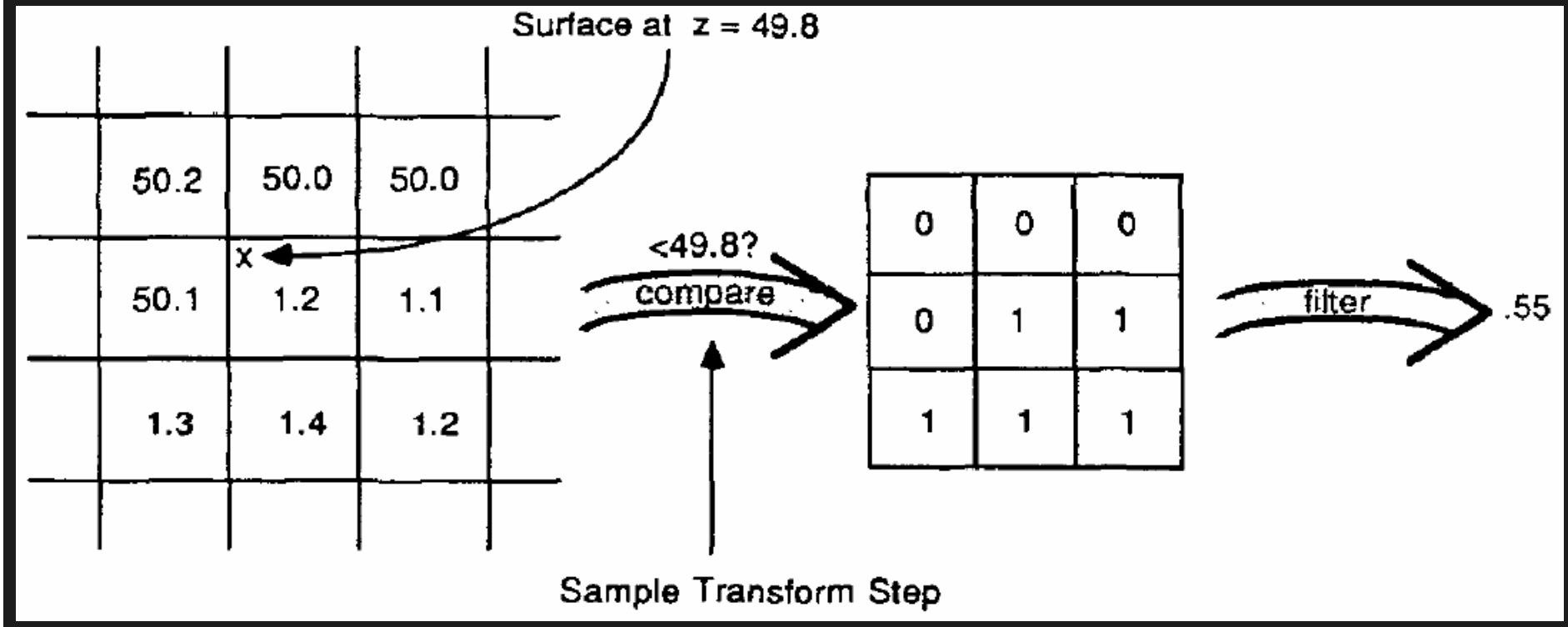
Comparison

- Shadow volumes
  - Pros: accurate, high-quality
  - Cons: fill-rate limited, hard to implement robustly
- Shadow maps
  - Pros: fixed resolution, fast, simple
  - Cons: bias, aliasing

Percentage Closer filtering [Reeves 1987]

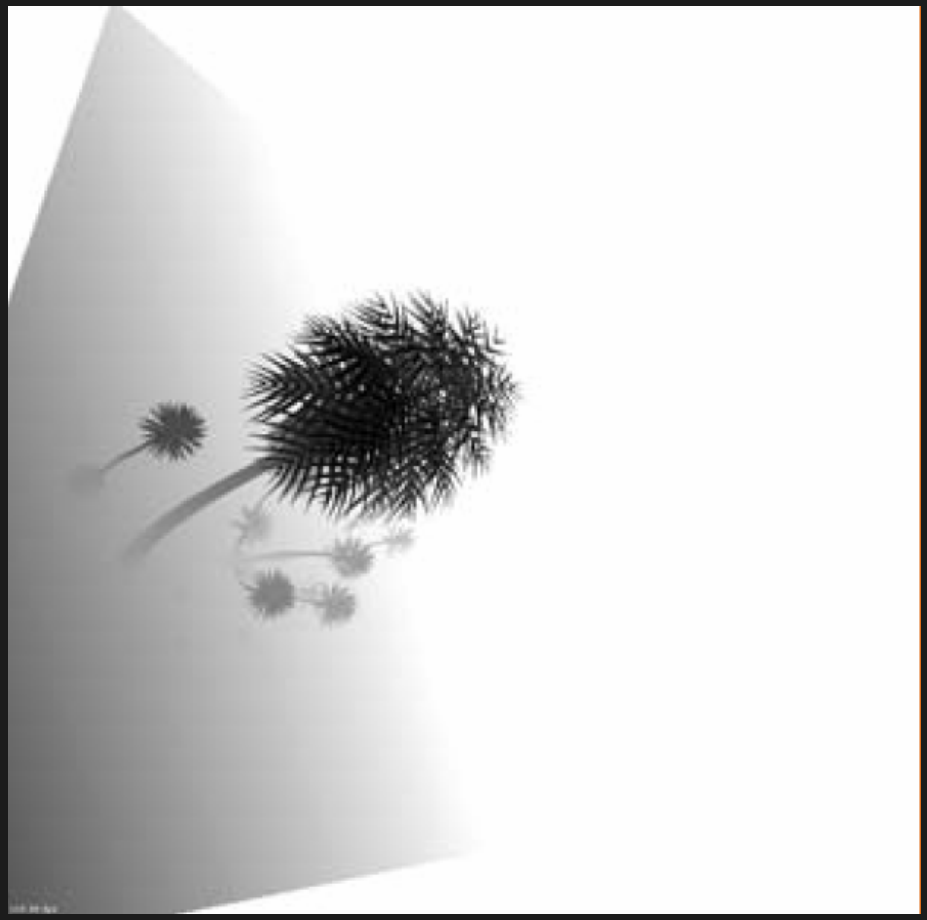


Percentage Closer filtering [Reeves 1987]

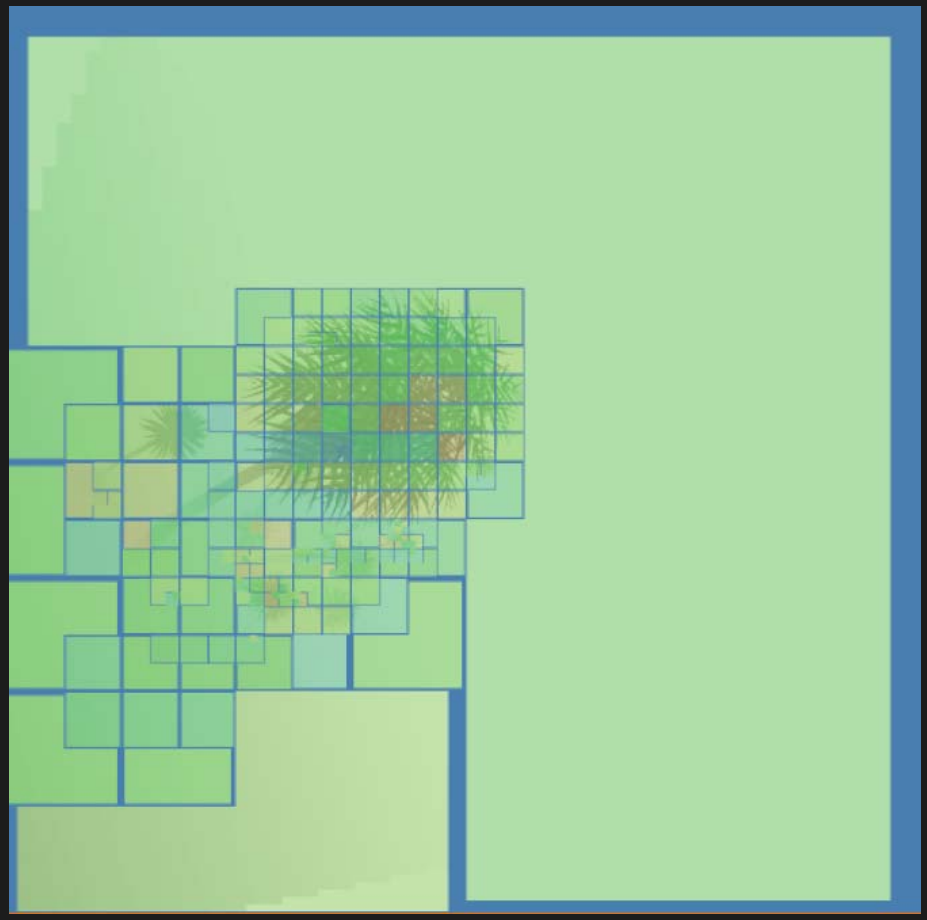


Provides anti-aliasing at shadow map edges,
not soft shadows in the umbra/penumbra sense

Adaptive shadow maps [Fernando 2001]

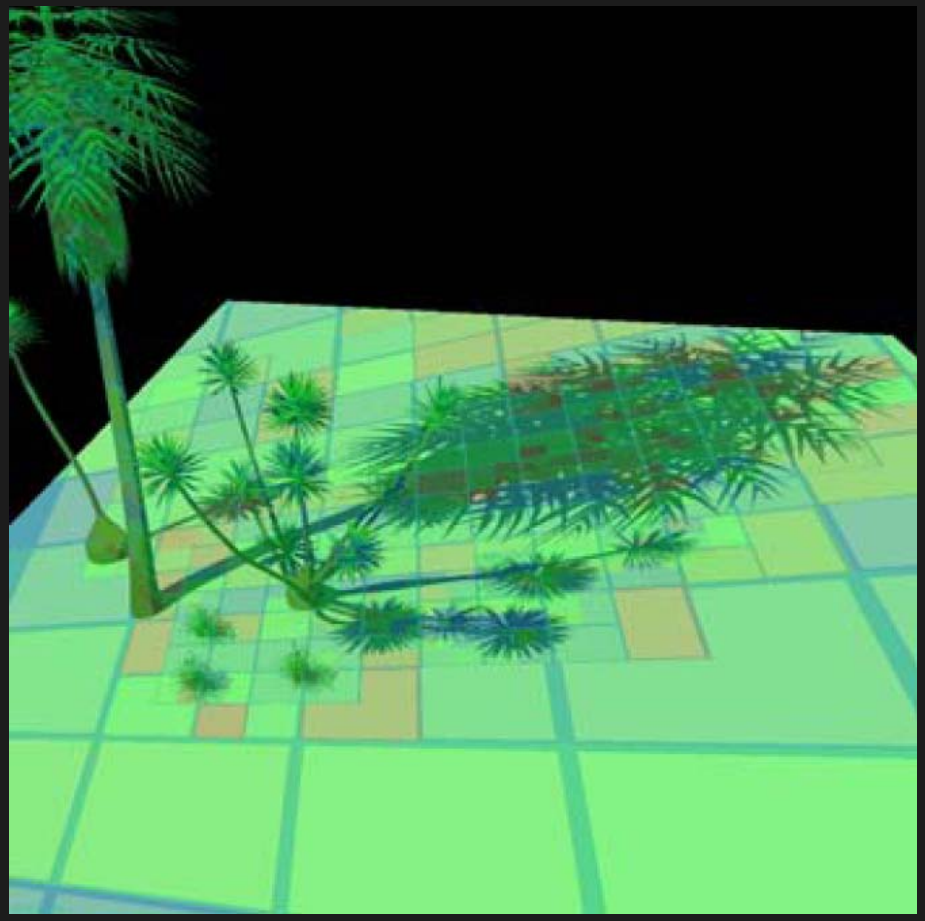


high-resolution shadow map

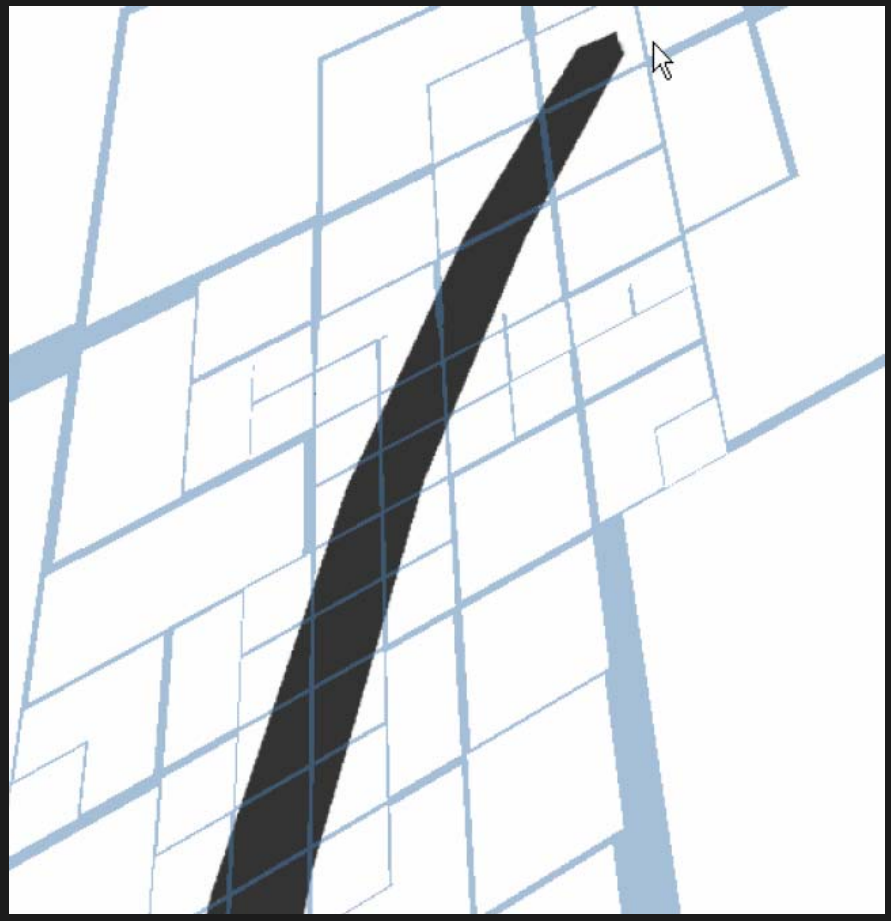


adaptive shadow map

Adaptive shadow maps



rendering



details

Adaptive shadow maps

Pros:

- Progressive and view-dependent
- Confined to a user-specified memory limit, use LRU policy to delete nodes

Cons:

- Not easy to map to GPU; [Lefohn et. al. 2005] has mapped it to GPU recently

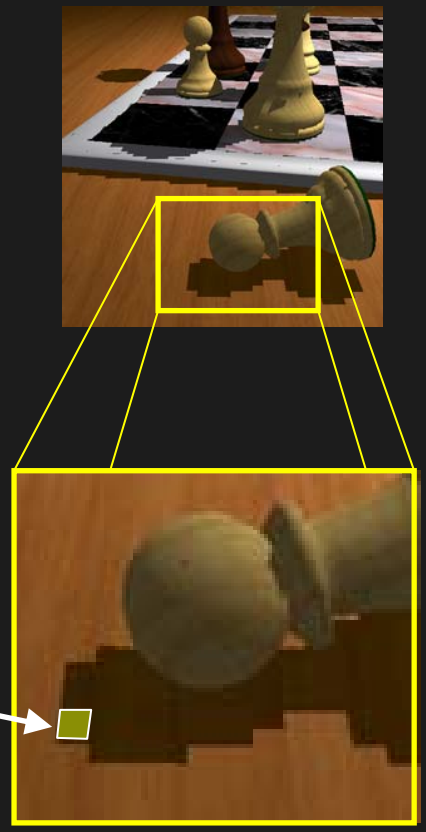
Perspective Shadow Maps

Marc Stamminger
George Drettakis

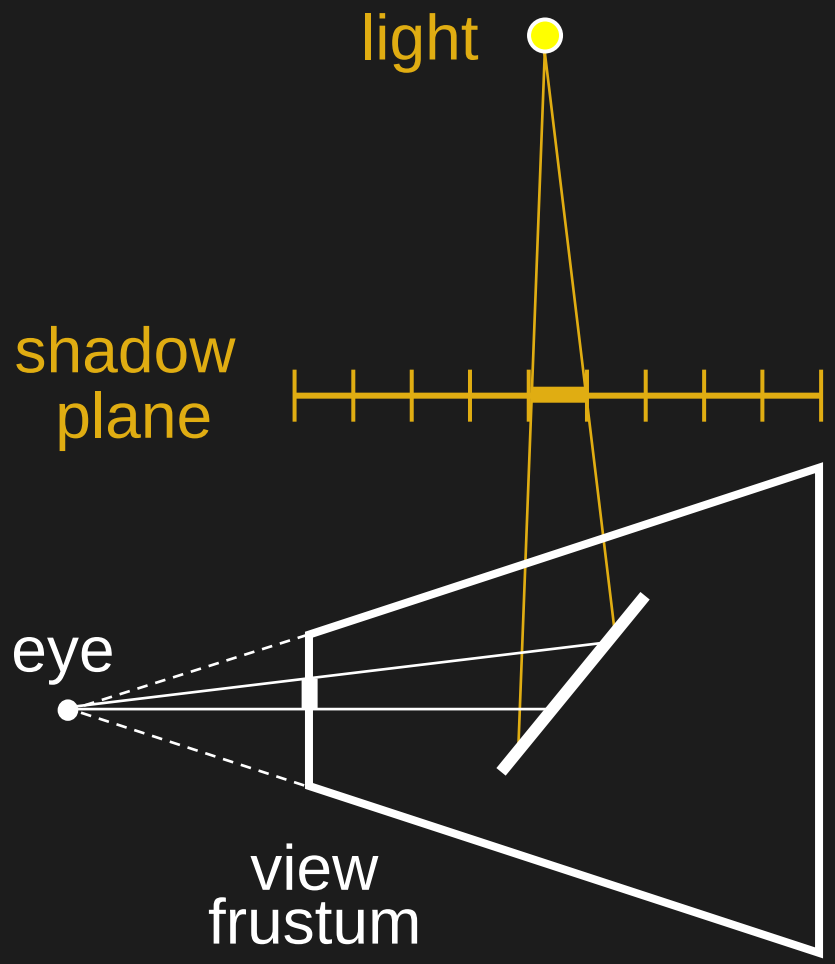
SIGGRAPH 2002

shadow map aliasing

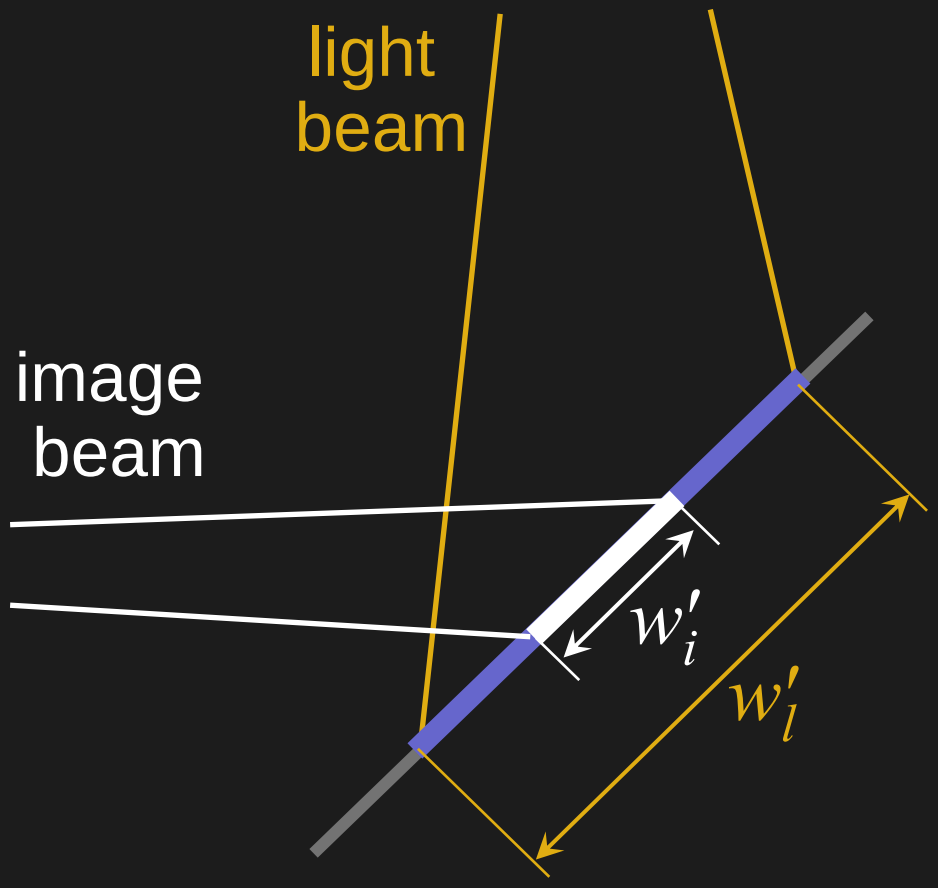
prone to aliasing
- when zooming into shadow boundaries

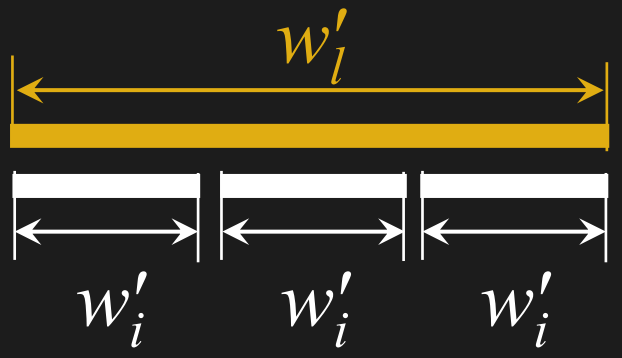


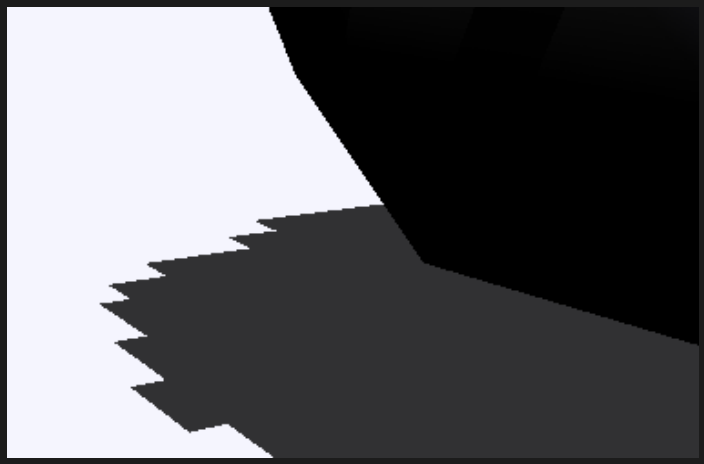
Aliasing error



Aliasing error





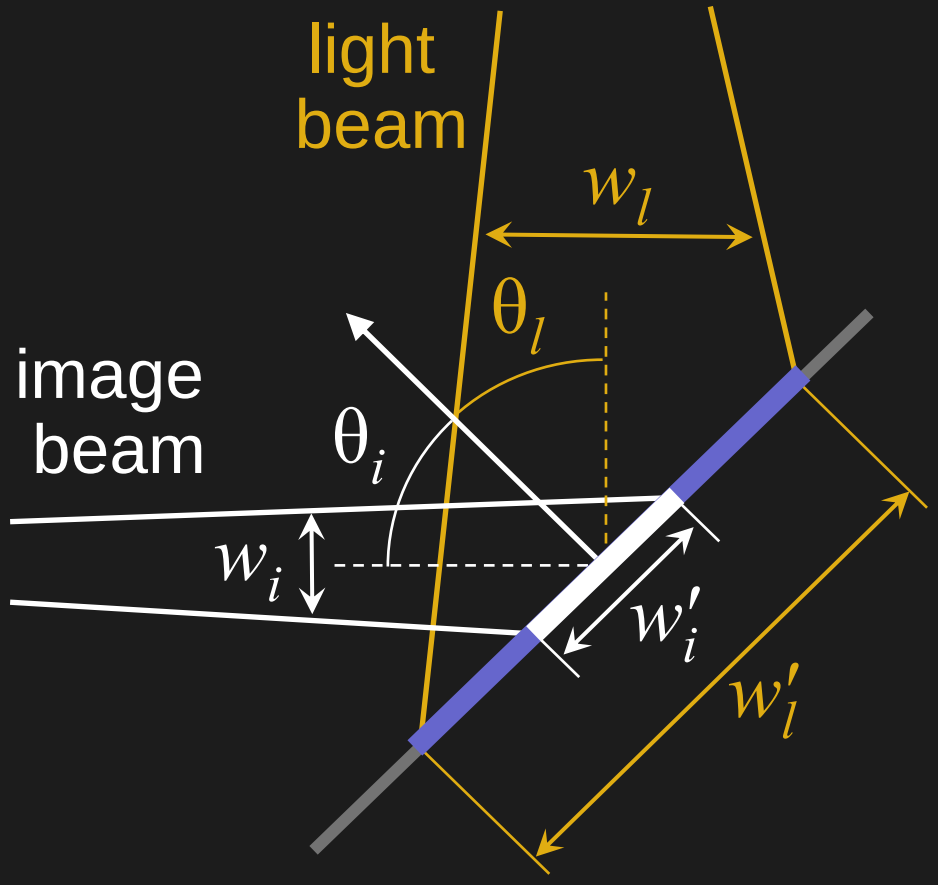


Aliasing error

$$w_l \approx d_l \cdot r_l \qquad w_i \approx d_i \cdot r_i$$

distance to light

shadow buffer pixel size

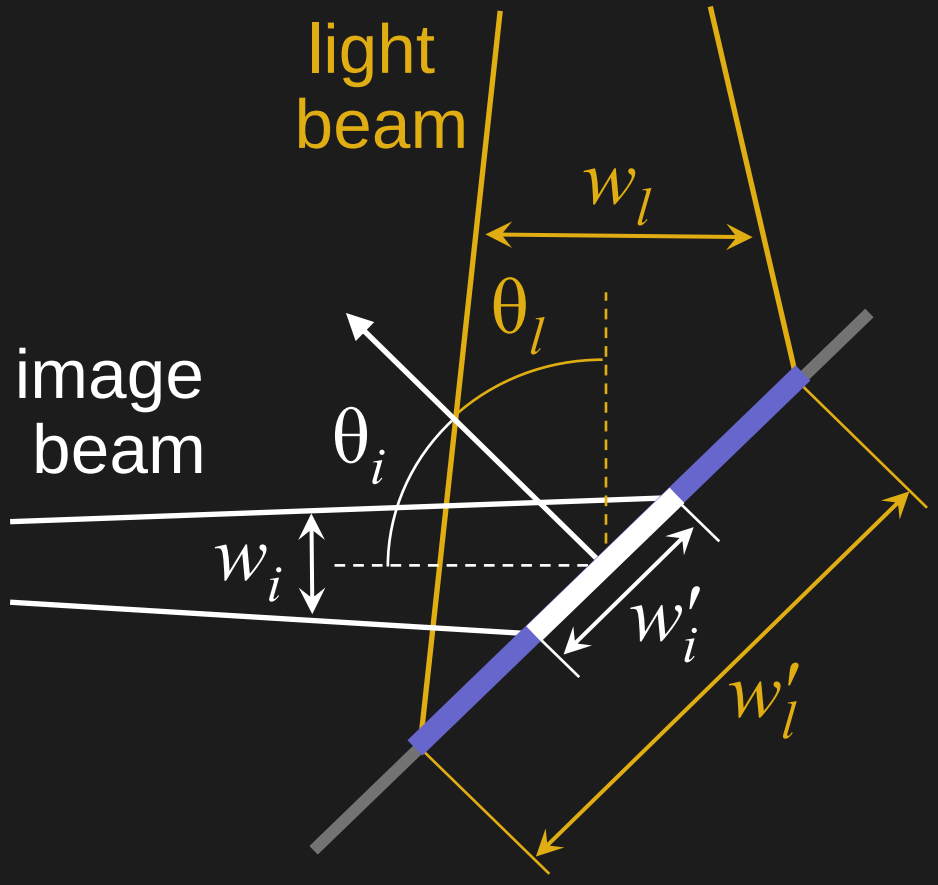


$$m = \frac{w_l'}{w_i'} \approx \frac{w_l}{w_i} \frac{\cos\ \theta_i}{\cos\ \theta_l}$$

$\frac{w_l}{w_i}$ **Perspective aliasing**

$\frac{\cos\ \theta_i}{\cos\ \theta_l}$ **Projection aliasing**

Aliasing error

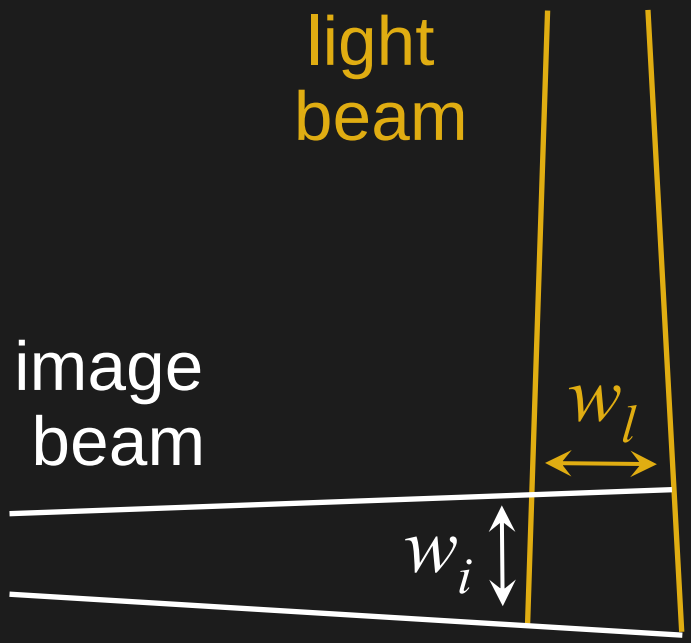


$$m = \frac{w_l'}{w_i'} \approx \frac{w_l}{w_i} \frac{\cos\ \theta_i}{\cos\ \theta_l}$$

$\frac{w_l}{w_i}$ **Perspective aliasing**

~~$\frac{\cos\ \theta_i}{\cos\ \theta_l}$ **Projection aliasing**~~

Controlling aliasing error



To eliminate perspective aliasing:

$$w_l \leq w_i$$

Light beam width depends on:

- Shadow map resolution
- Parameterization

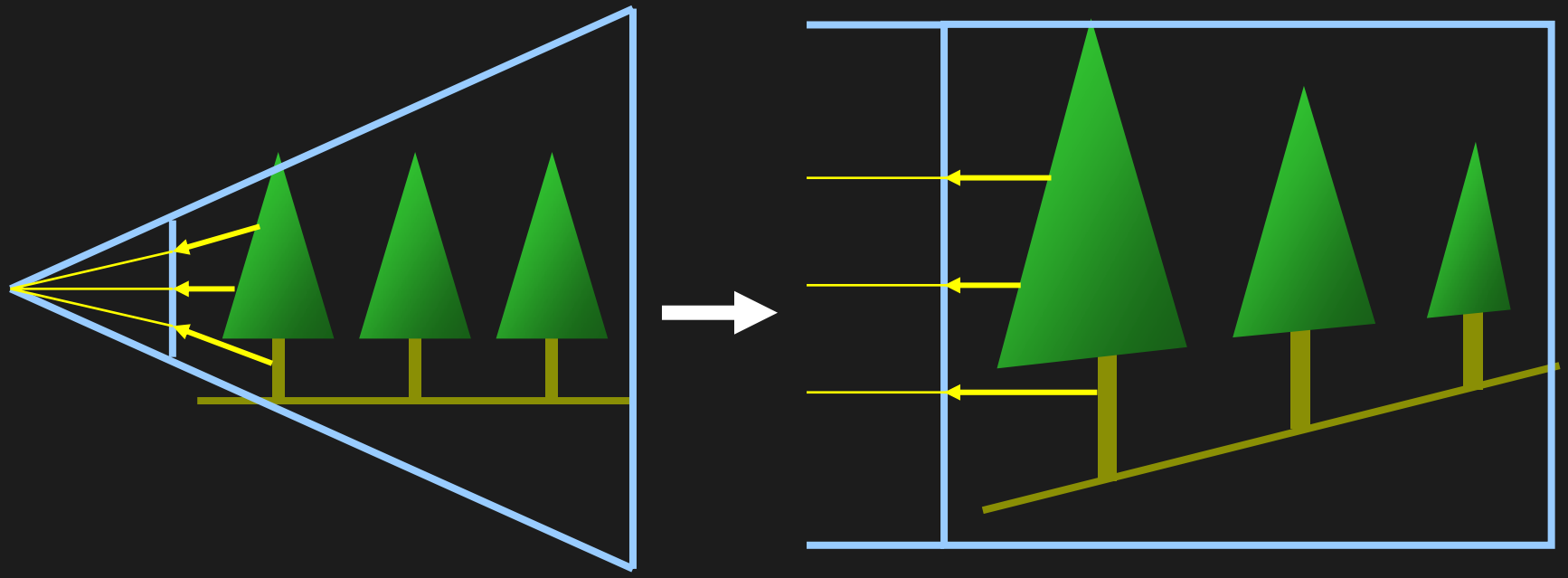
We have freedom to choose where and how to set up shadow buffer

It should be adaptive to view; this means that shadow buffer has to be recomputed for view changes

perspective transformation

normalizing transformation
[Foley] p.258-271

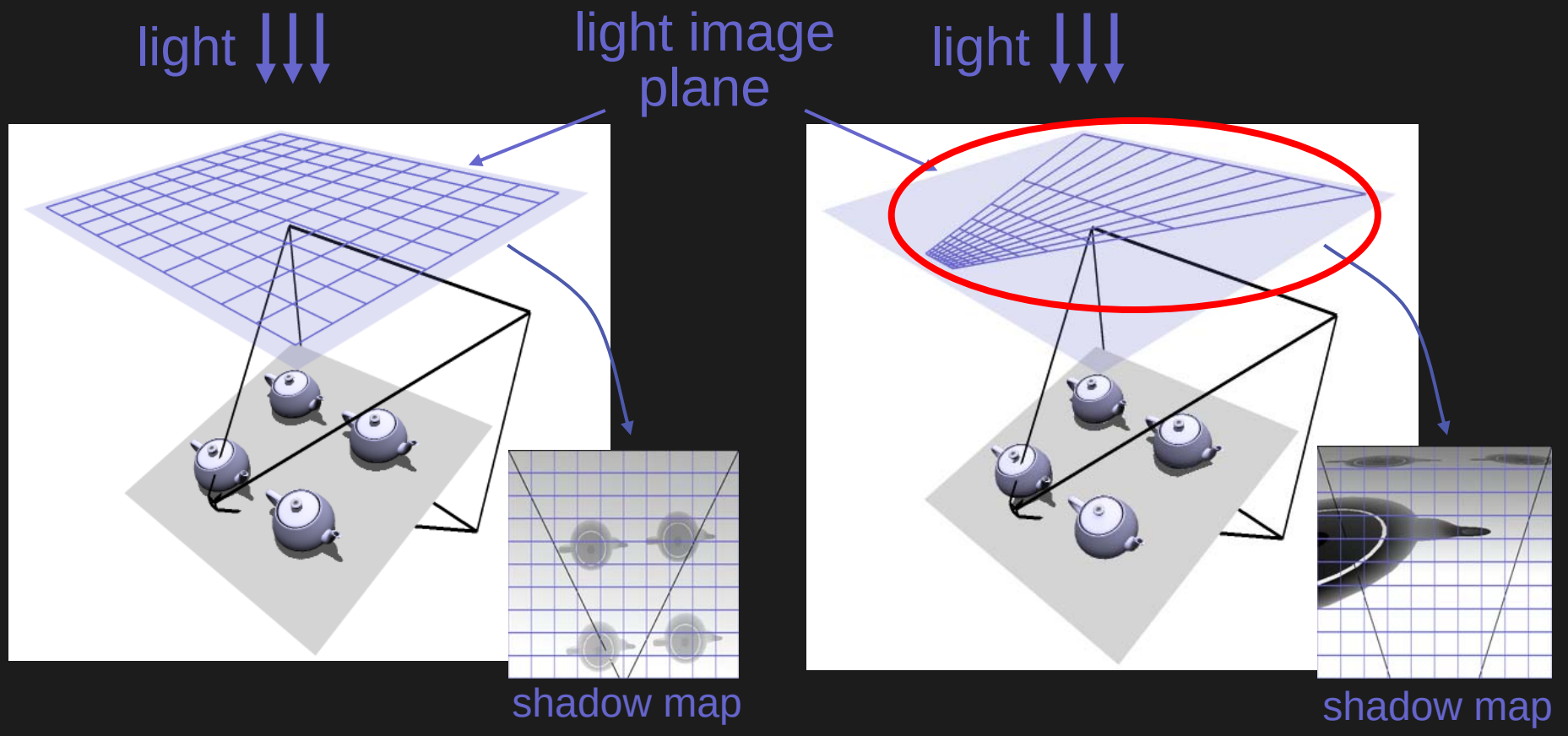
fixed w_i



world space

post-perspective space

Parameterization

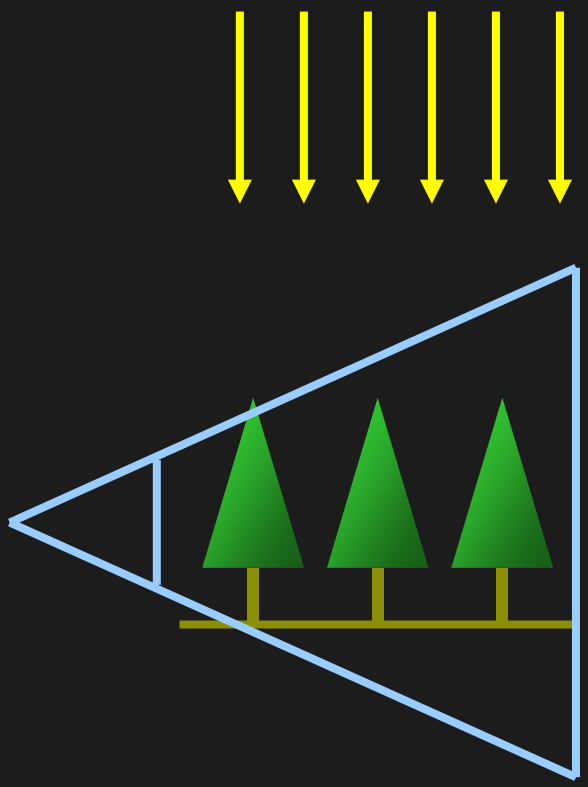


Standard

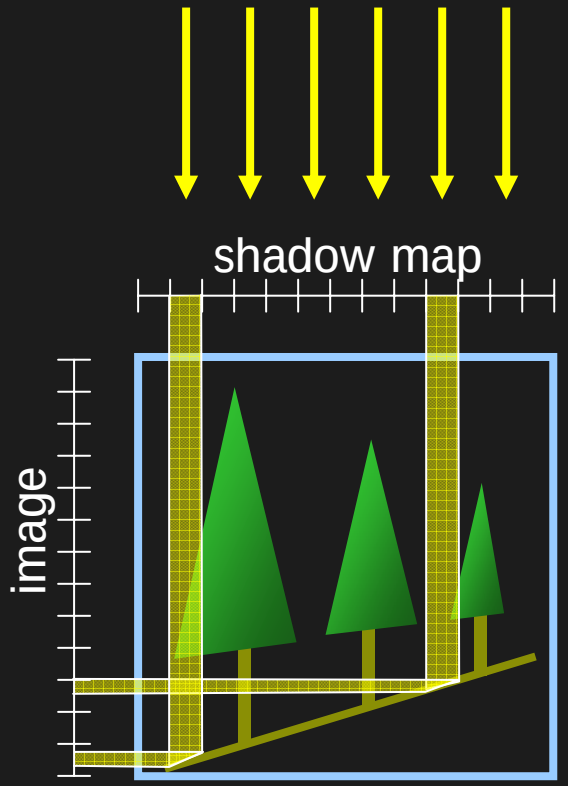
Perspective warped

perspective shadow map

standard shadow map



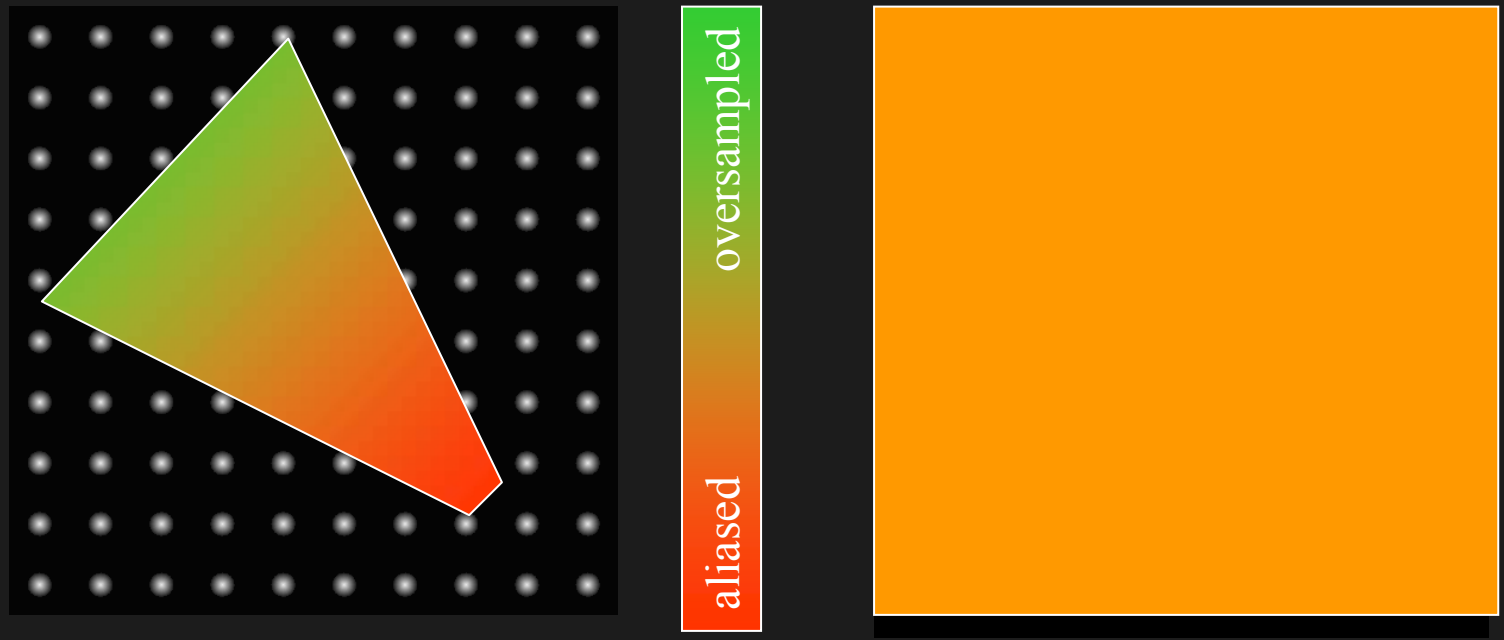
perspective shadow map



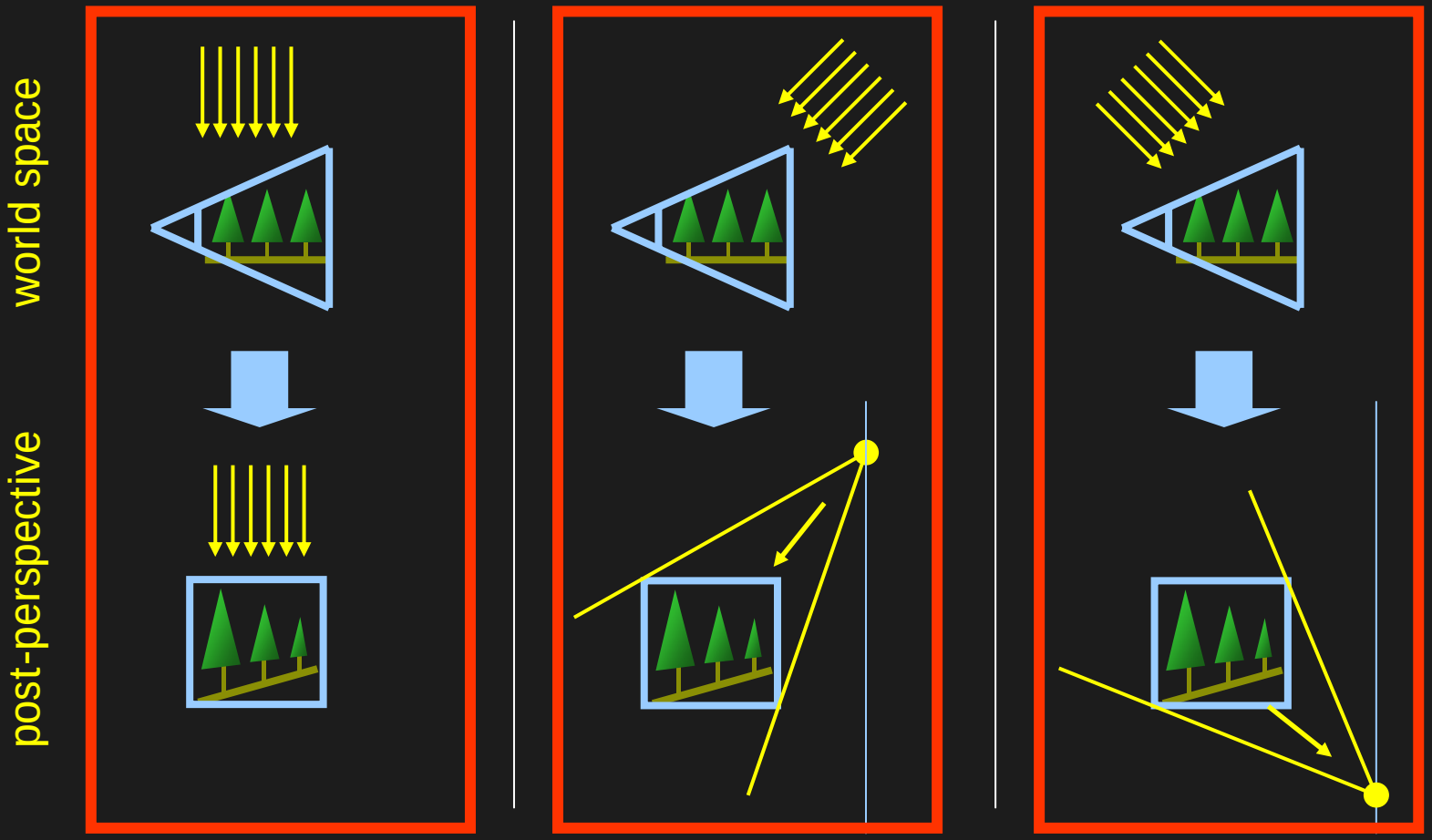
perspective shadow map

standard shadow map

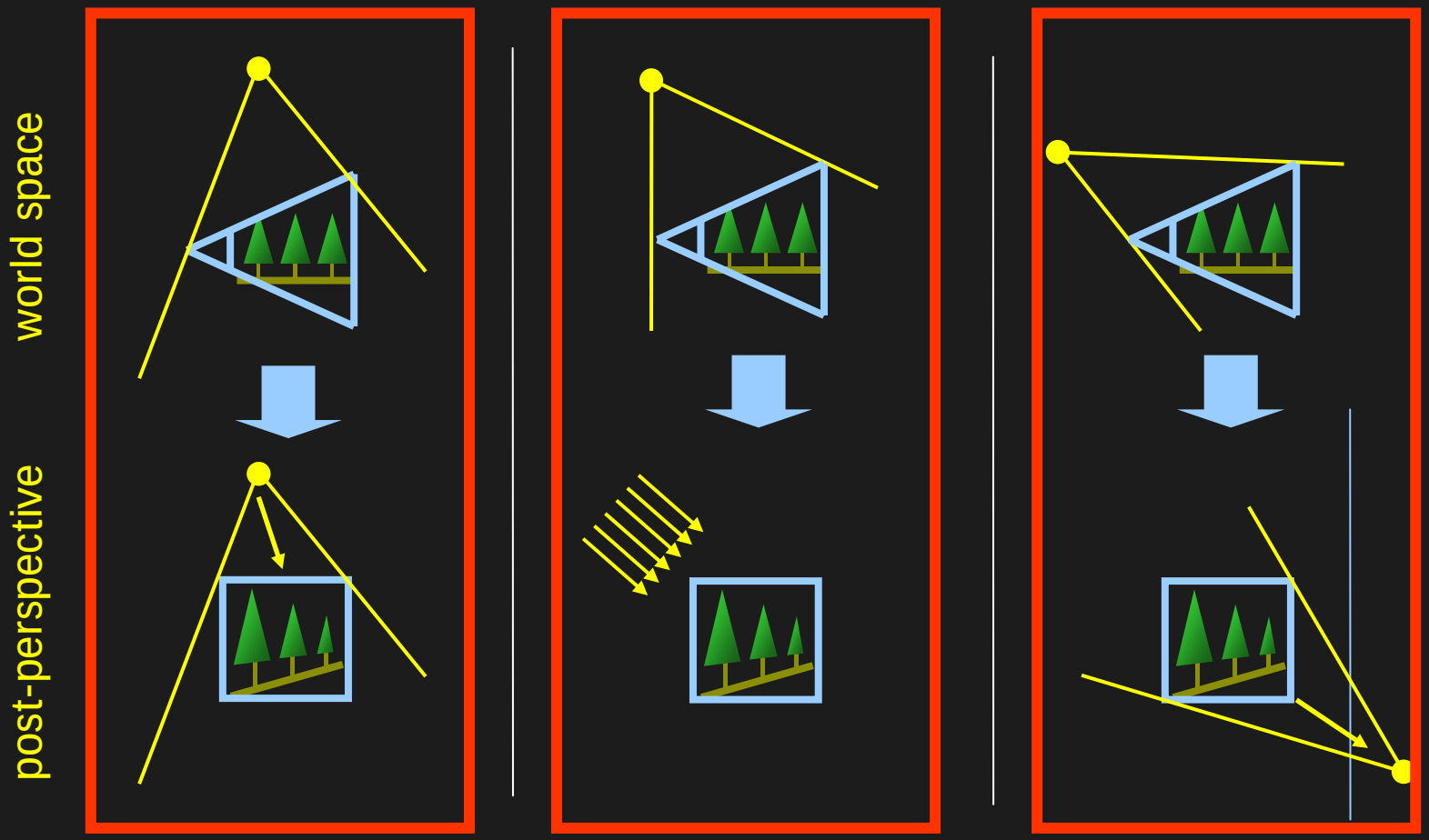
perspective shadow map



parallel light transformation



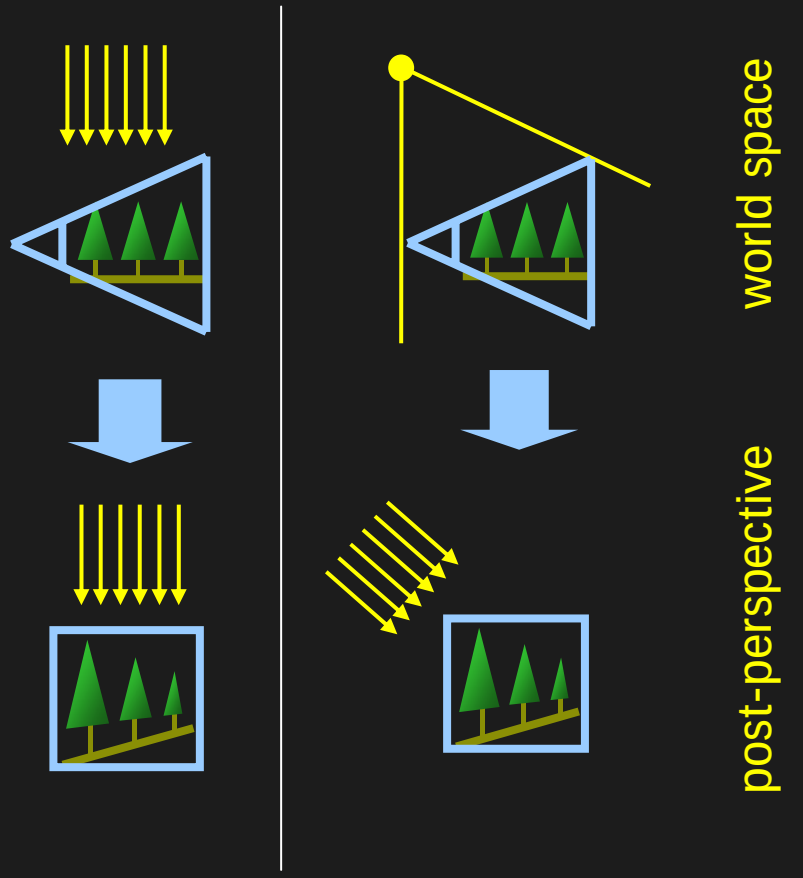
point light transformation



discussion

best case: fixed w_l

- parallel light in post-perspective space
- no new perspective distortion



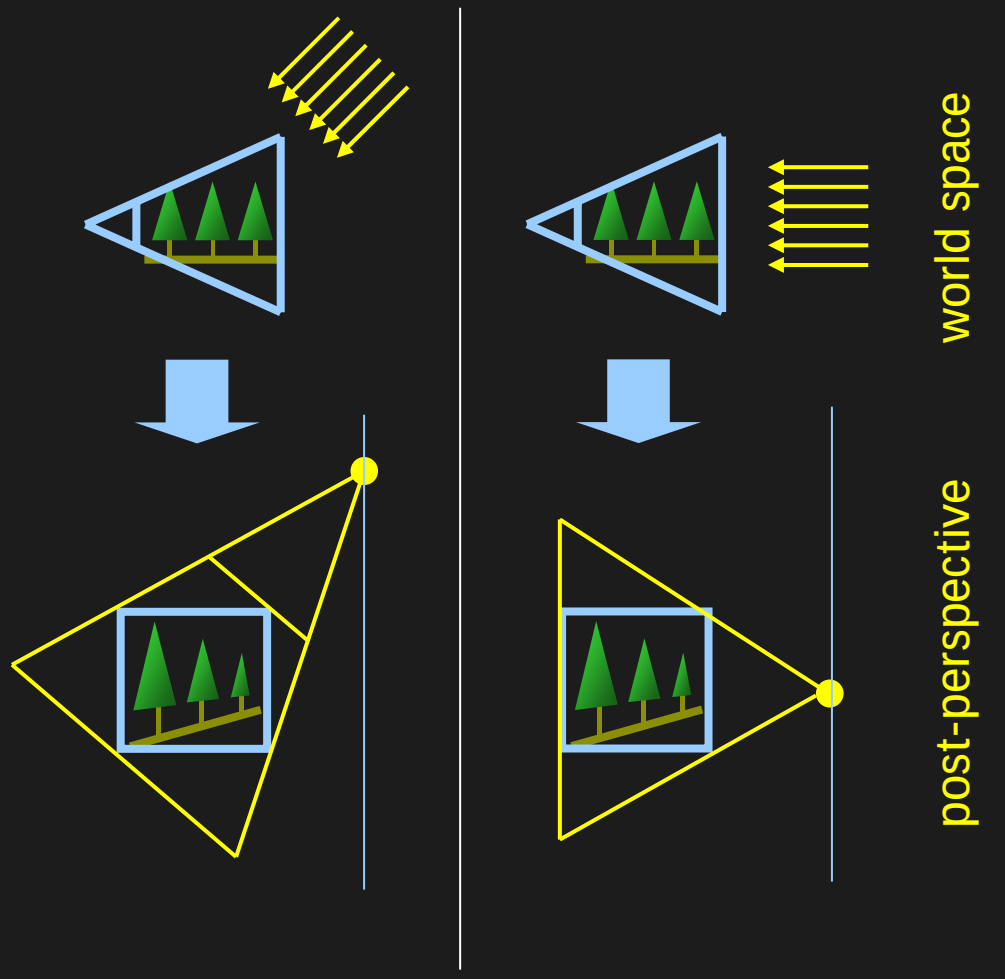
discussion

non-optimal case:

- point light close to frustum

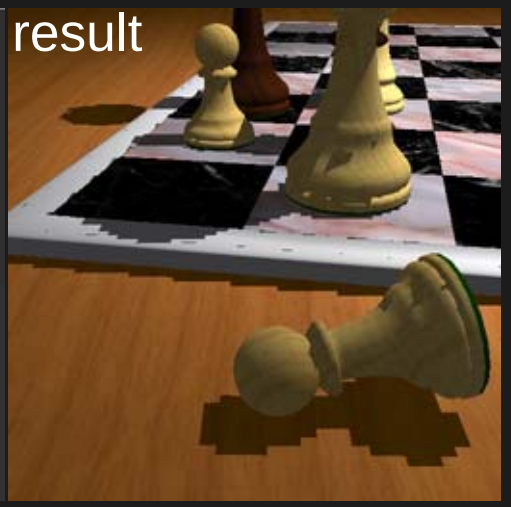
worst case:

- becomes uniform shadow map

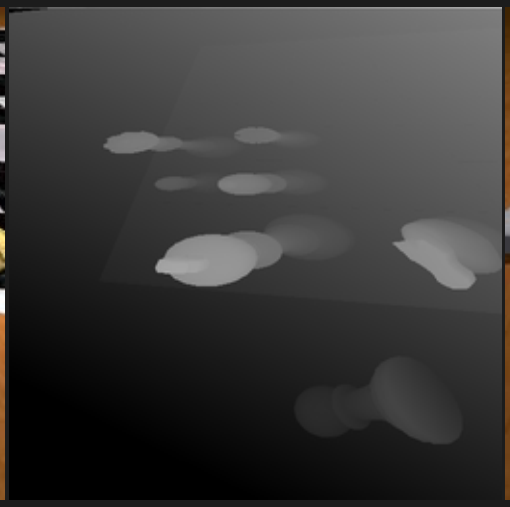


Perspective shadow map

Shadow map



Perspec-tive Shadow map



Shadow maps

Perspective Shadow maps

conclusion

perspective shadow maps

- shadow map in post-perspective space
- just another shadow map matrix
- non-uniform shadow map resolution
- not always possible to find a good solution
- needs recomputation per frame
- minimal overhead for dynamic scenes

Shadow Silhouette Maps

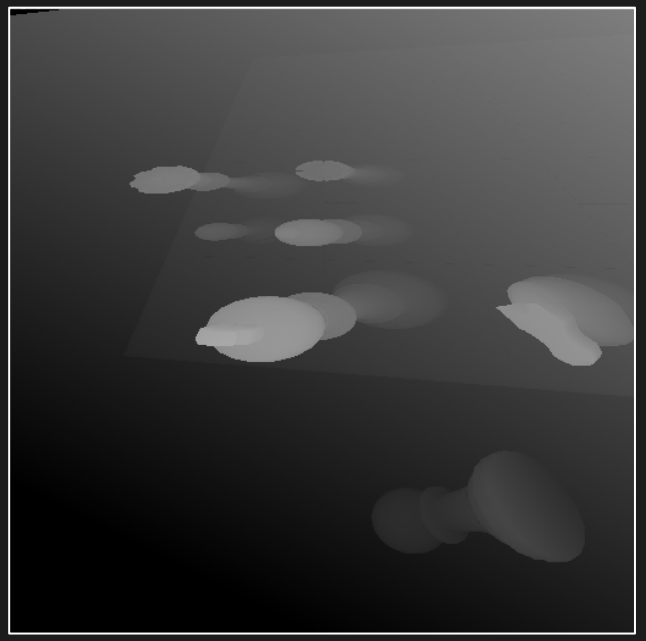
Pradeep Sen
Mike Cammarano
Pat Hanrahan

SIGGRAPH 2003
(slides from Eric Chan)

Motivation

Why another shadow algorithm?

Why not use perspective shadow maps?



Stamminger and Drettakis, SIGGRAPH 2002

Perspective Shadow Maps

Addresses perspective aliasing

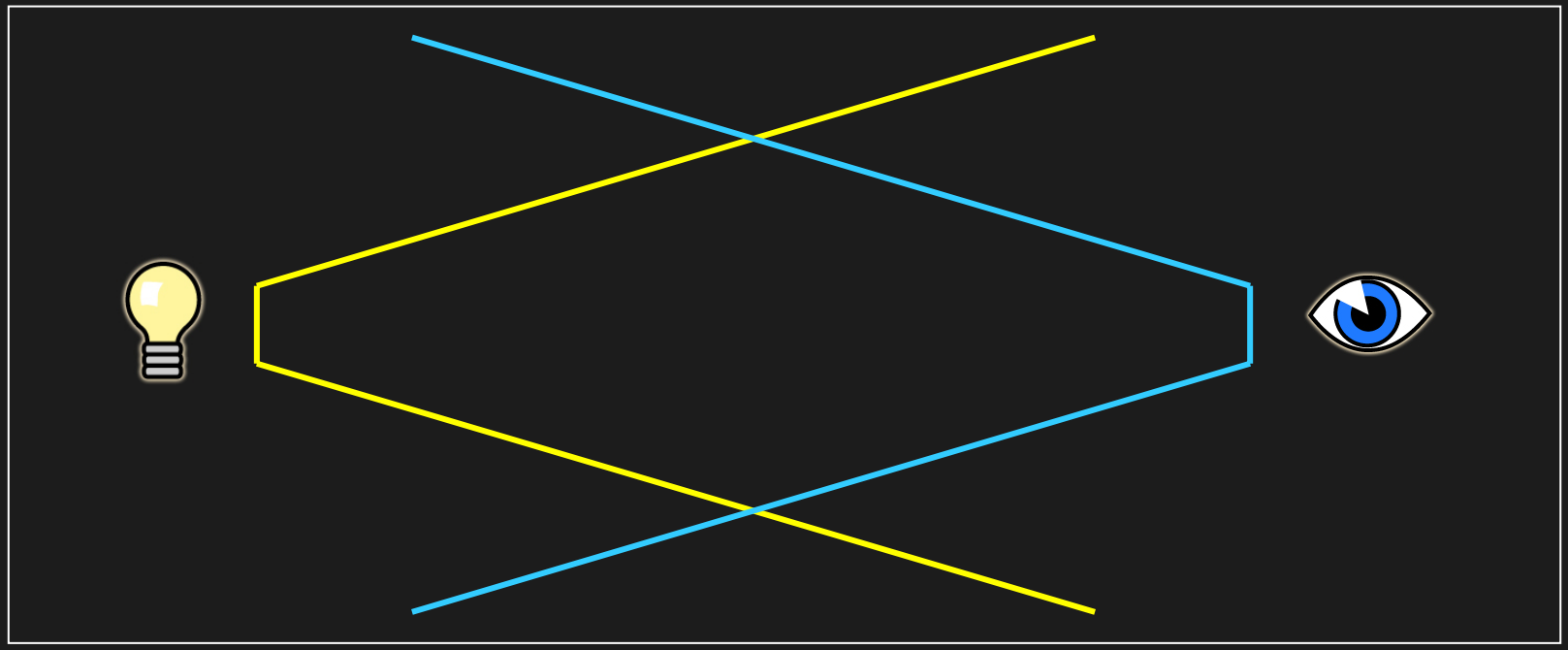
Optimizes distribution of depth samples

Difficulties:

Does not handle projection aliasing

Dueling frusta problem

Dueling Frusta Problem

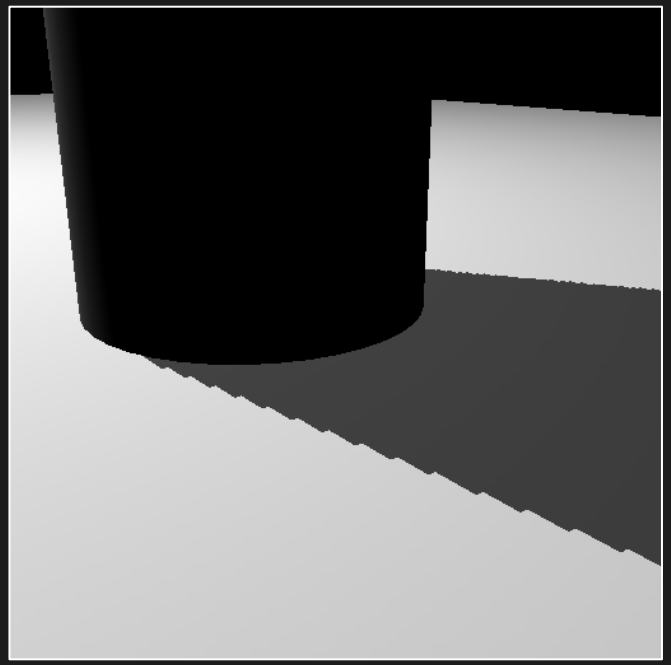


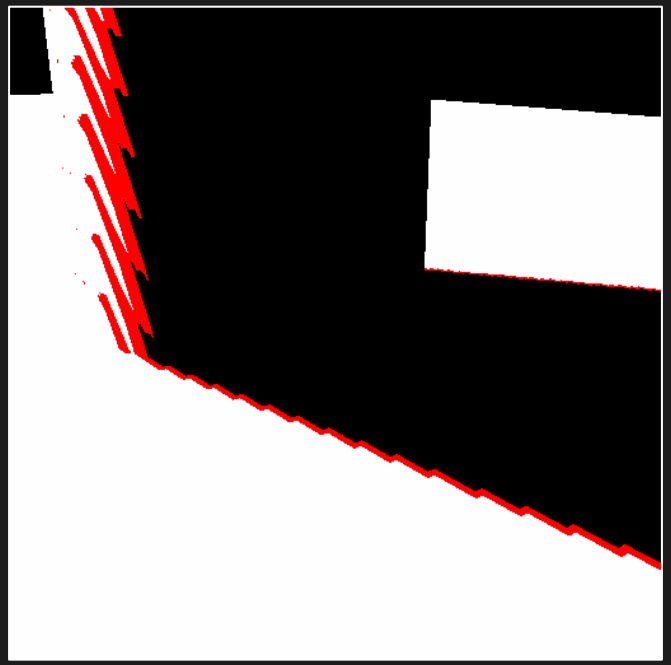
Observation

Shadow maps

undersampling can occur anywhere

artifacts visible only at shadow edges

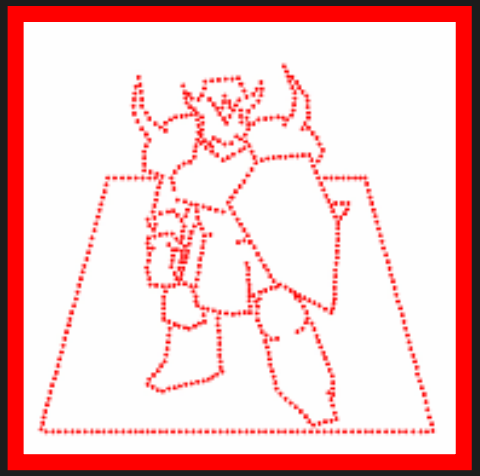




How To Fix Silhouettes?

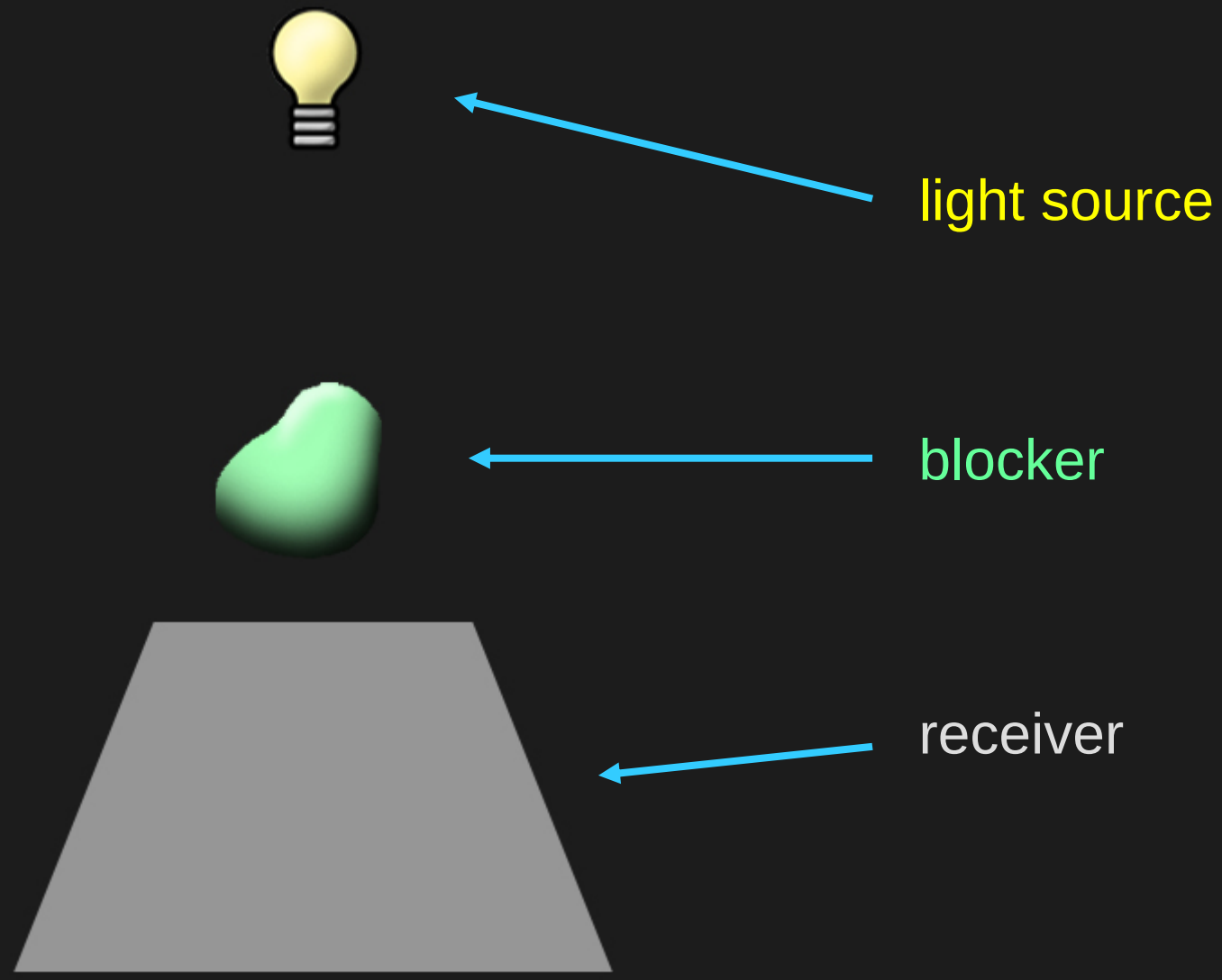
One solution:
use a better silhouette approximation

depth map

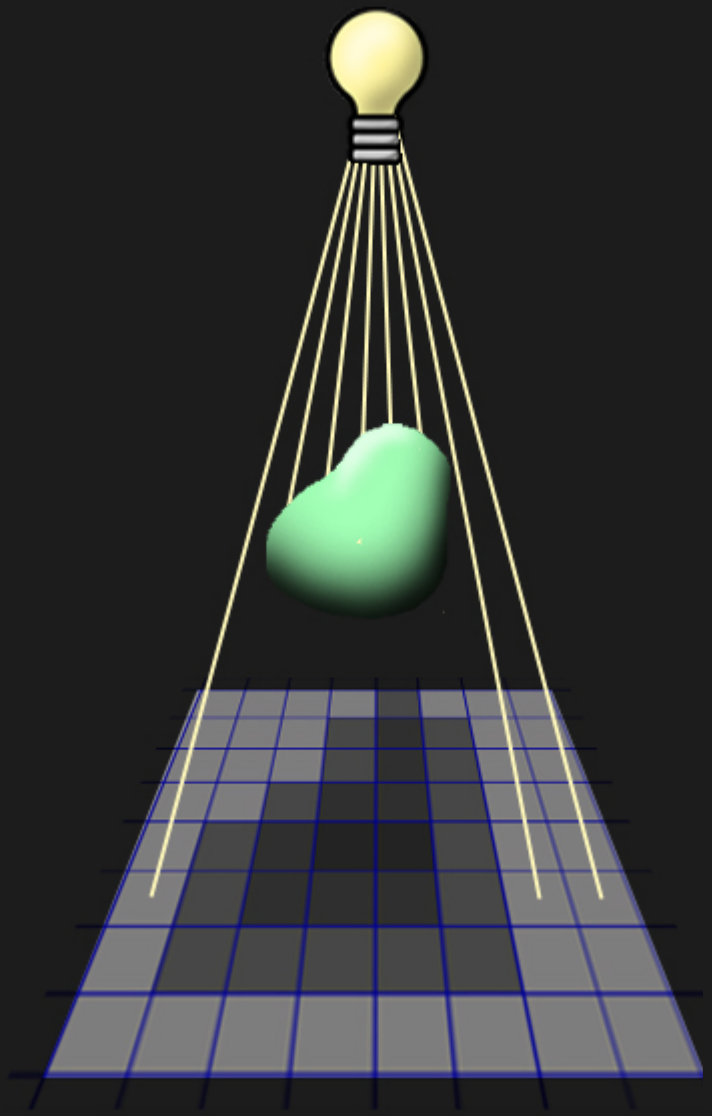


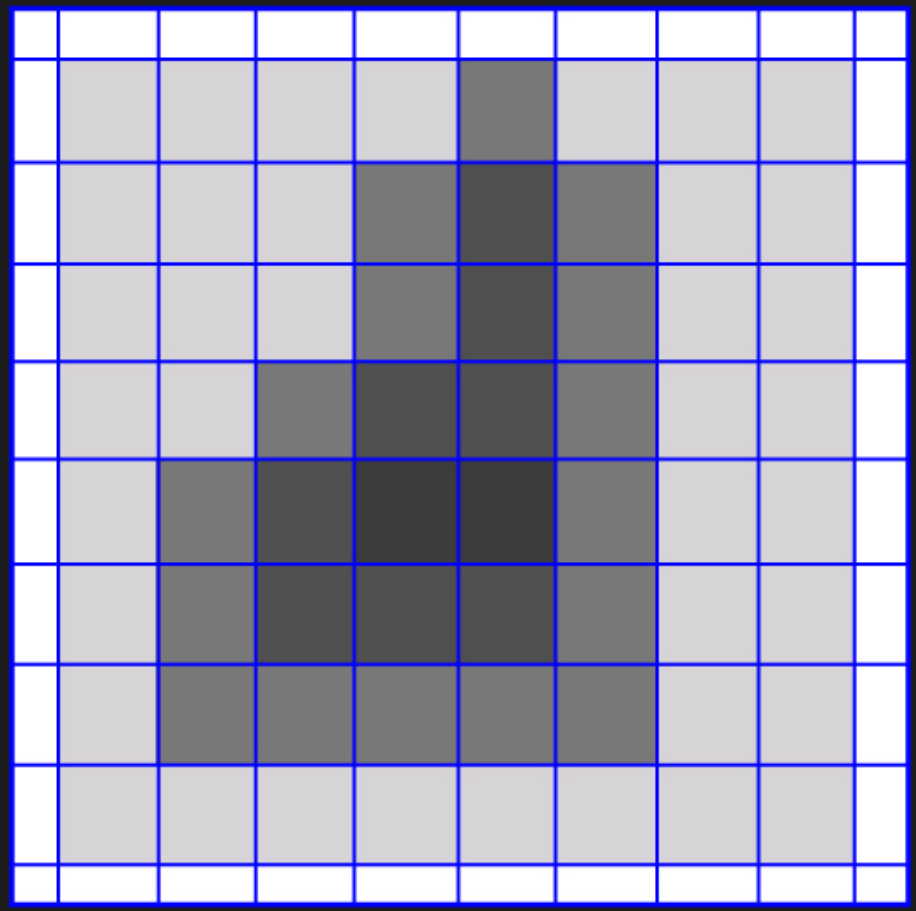
silhouette map

Shadow Map (Review)



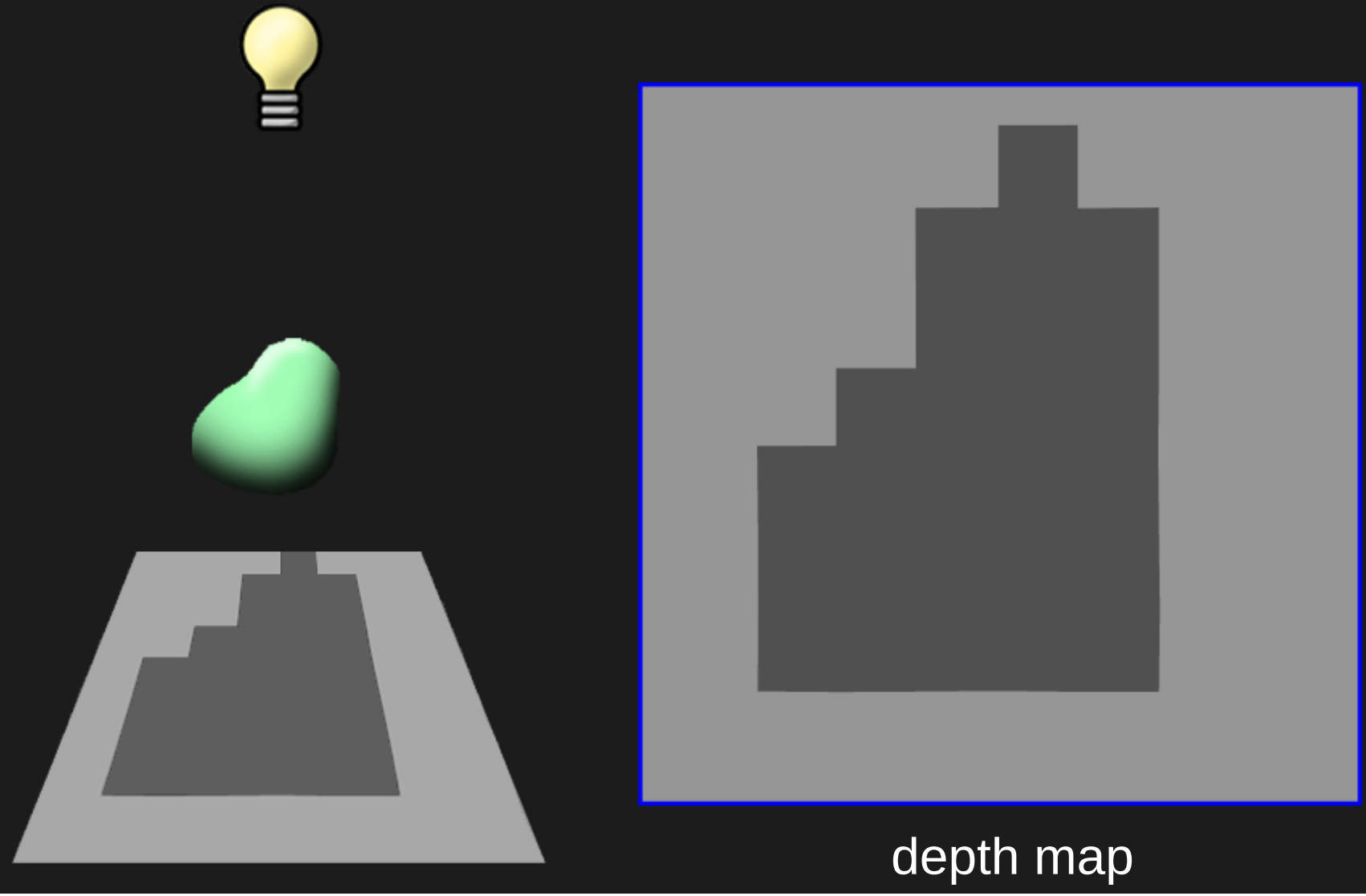
Shadow Map (Review)





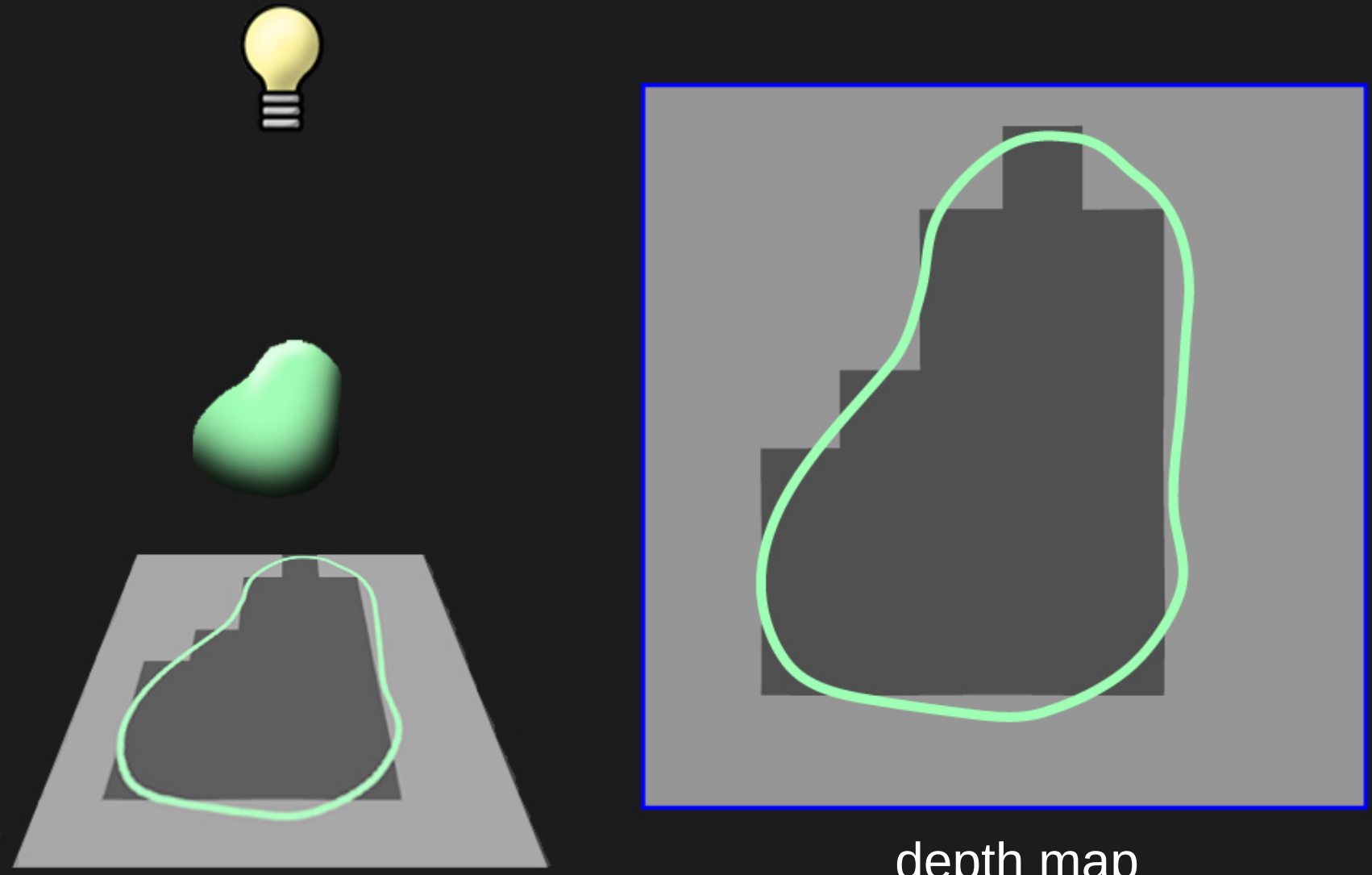
depth map

Shadow Map (Review)



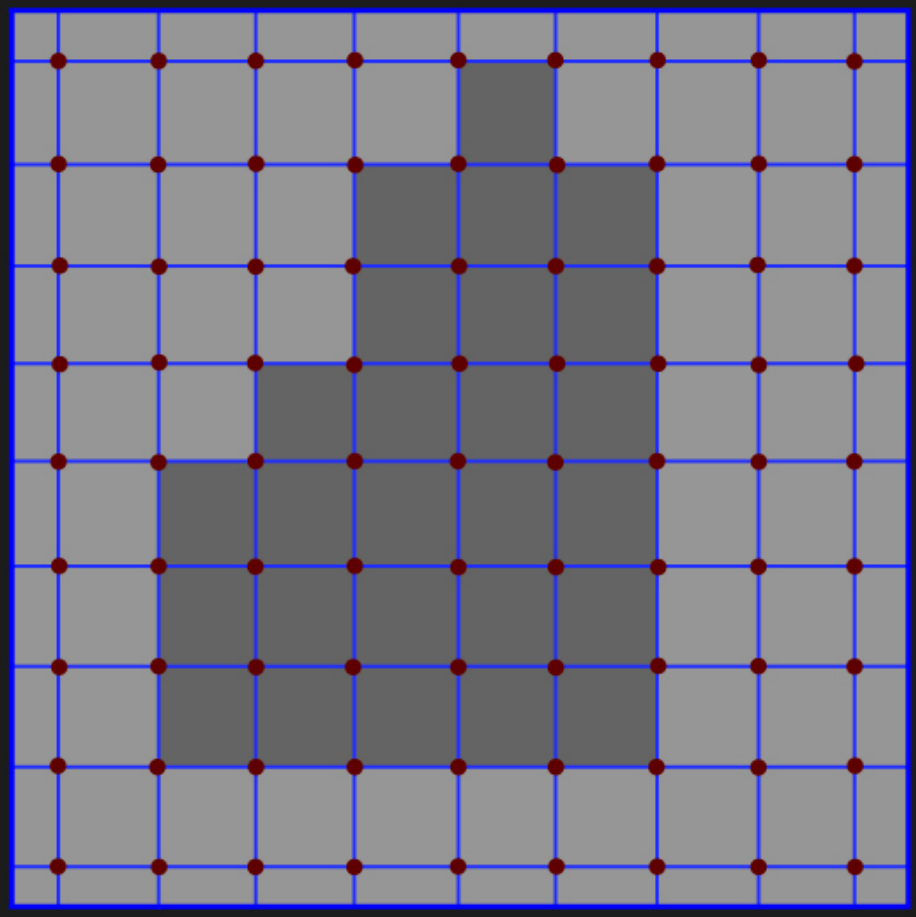
depth map

Shadow Map (Review)



depth map

Depth Mesh

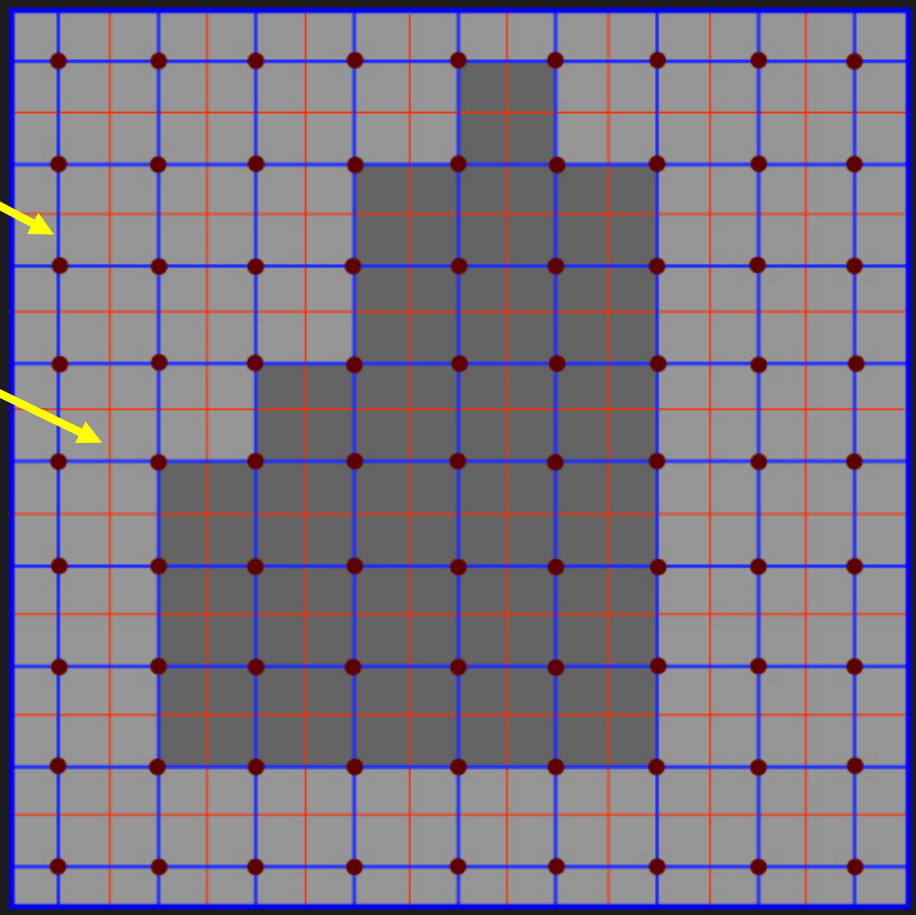


depth mesh (sampling grid)

Depth Mesh

original grid (blue)

dual grid (red)



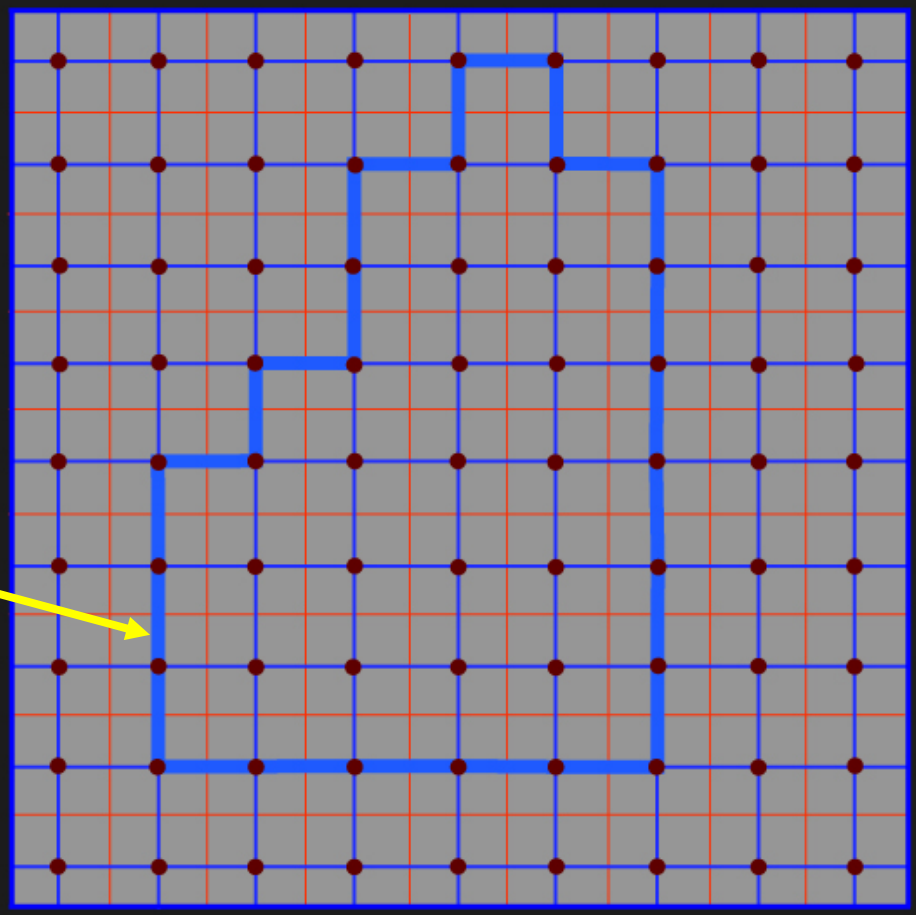
depth mesh + dual mesh

Depth Mesh

original grid (blue)

dual grid (red)

discrete silhouette boundary



depth mesh + dual mesh

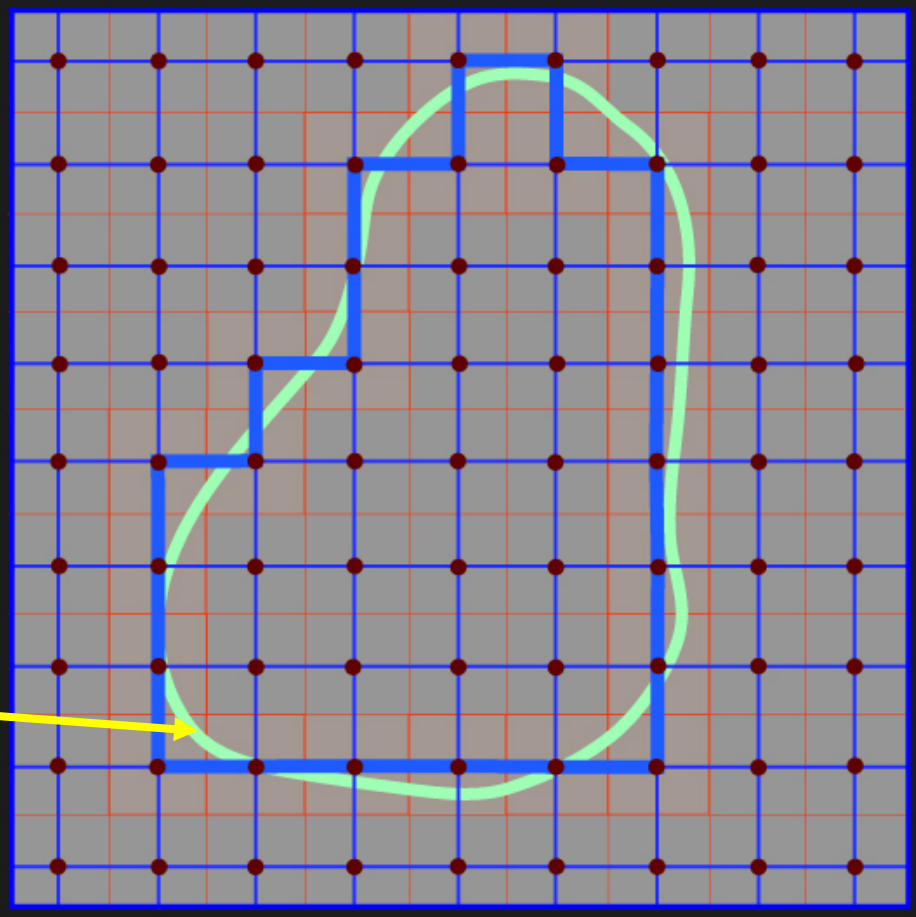
Depth Mesh

original grid (blue)

dual grid (red)

discrete silhouette boundary

continuous silhouette boundary (green)



depth mesh + dual mesh

Depth Mesh

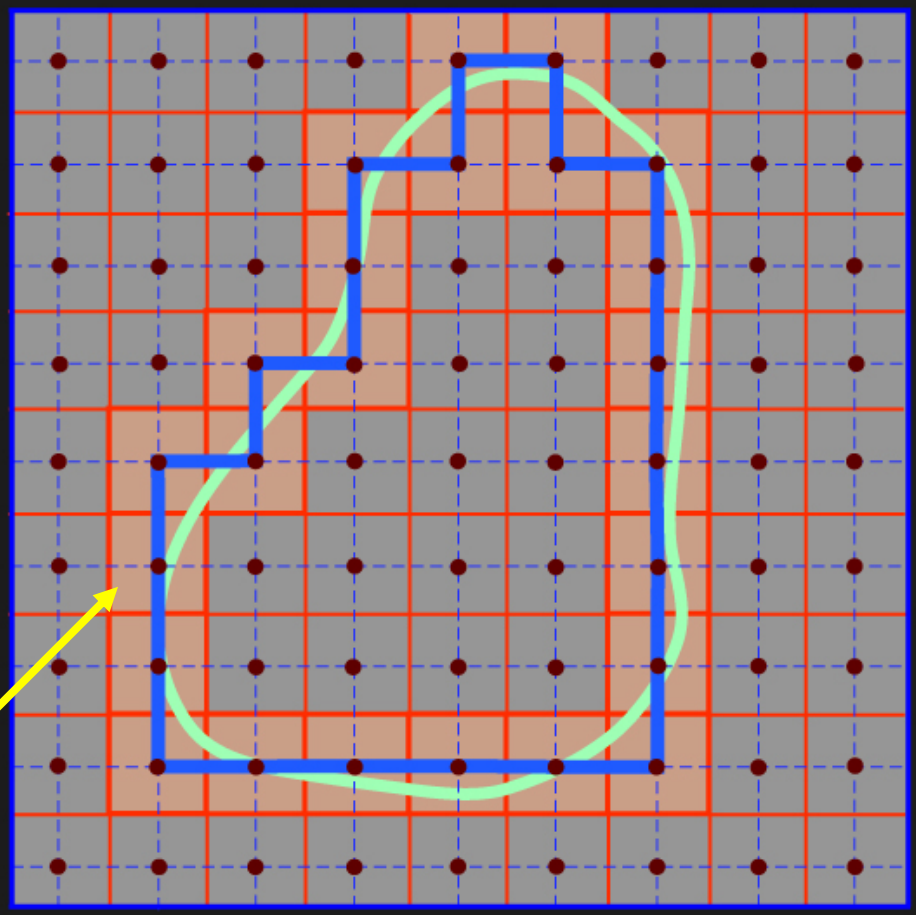
original grid (blue)

dual grid (red)

discrete silhouette boundary

continuous silhouette boundary (green)

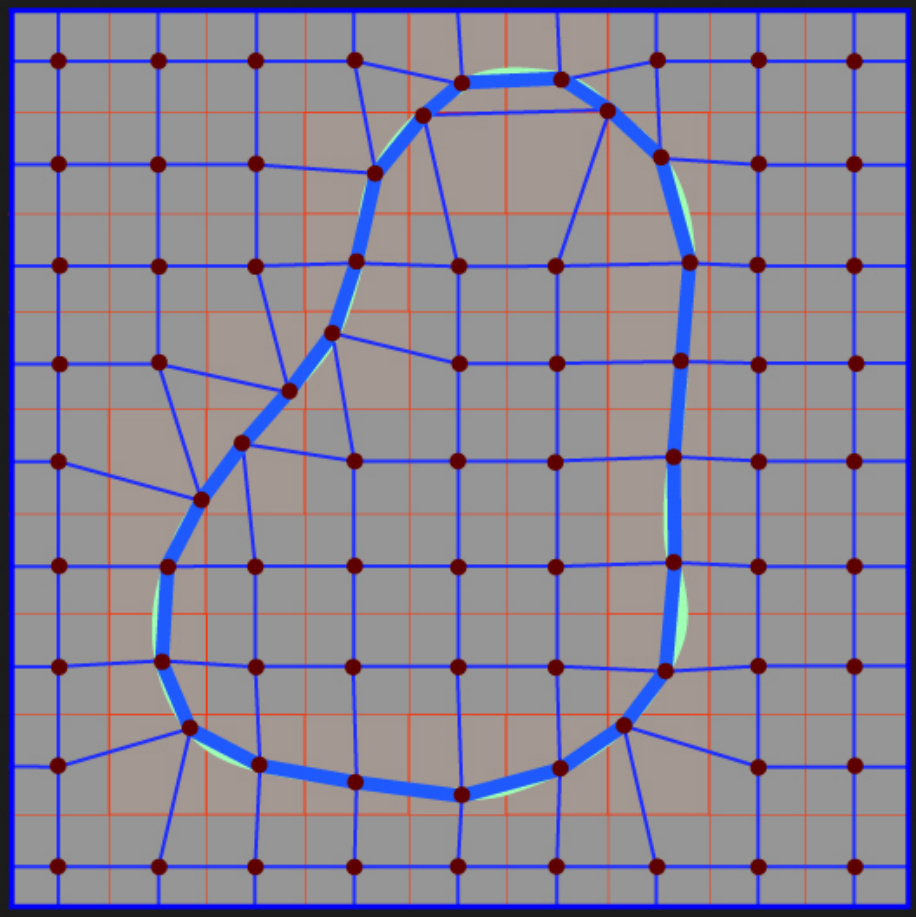
silhouette map pixels



depth mesh + dual mesh

Depth Mesh Deformation

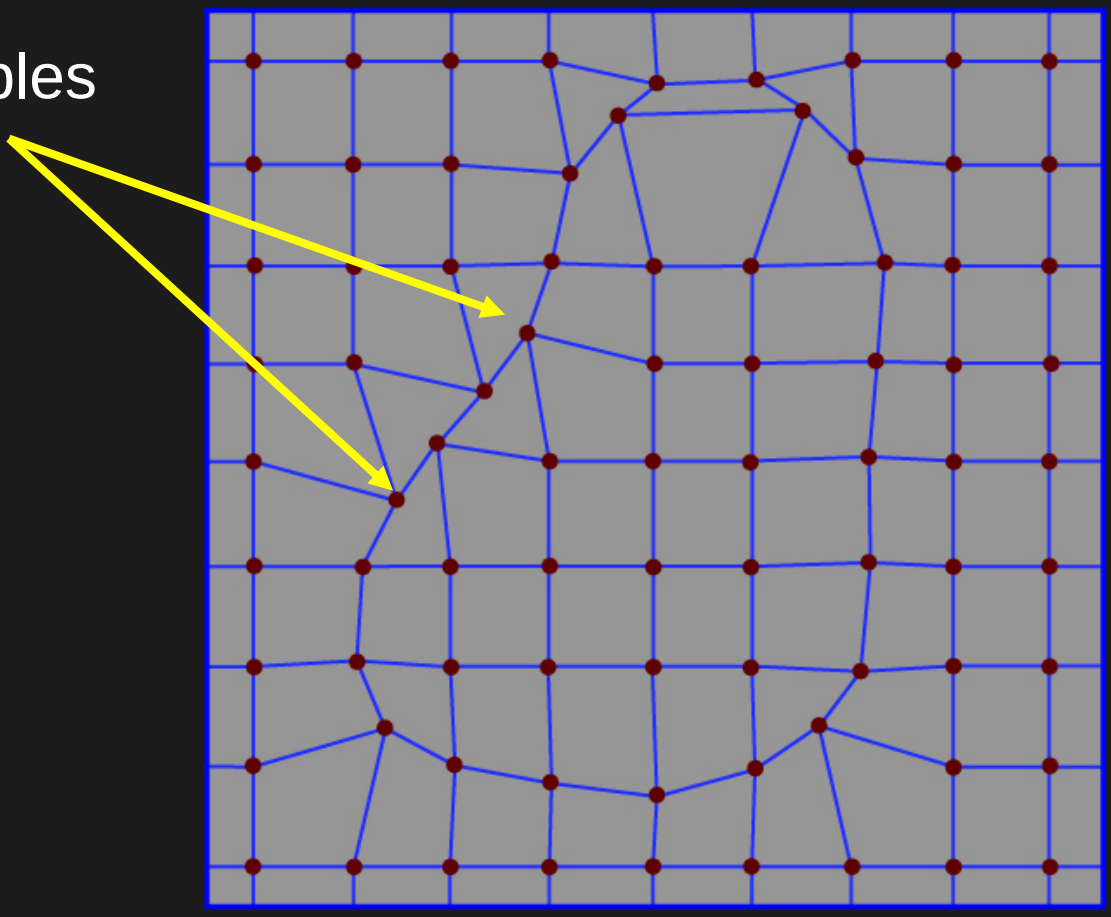
Move depth samples
to lie on silhouette curve



deformed depth mesh

Depth Mesh Deformation

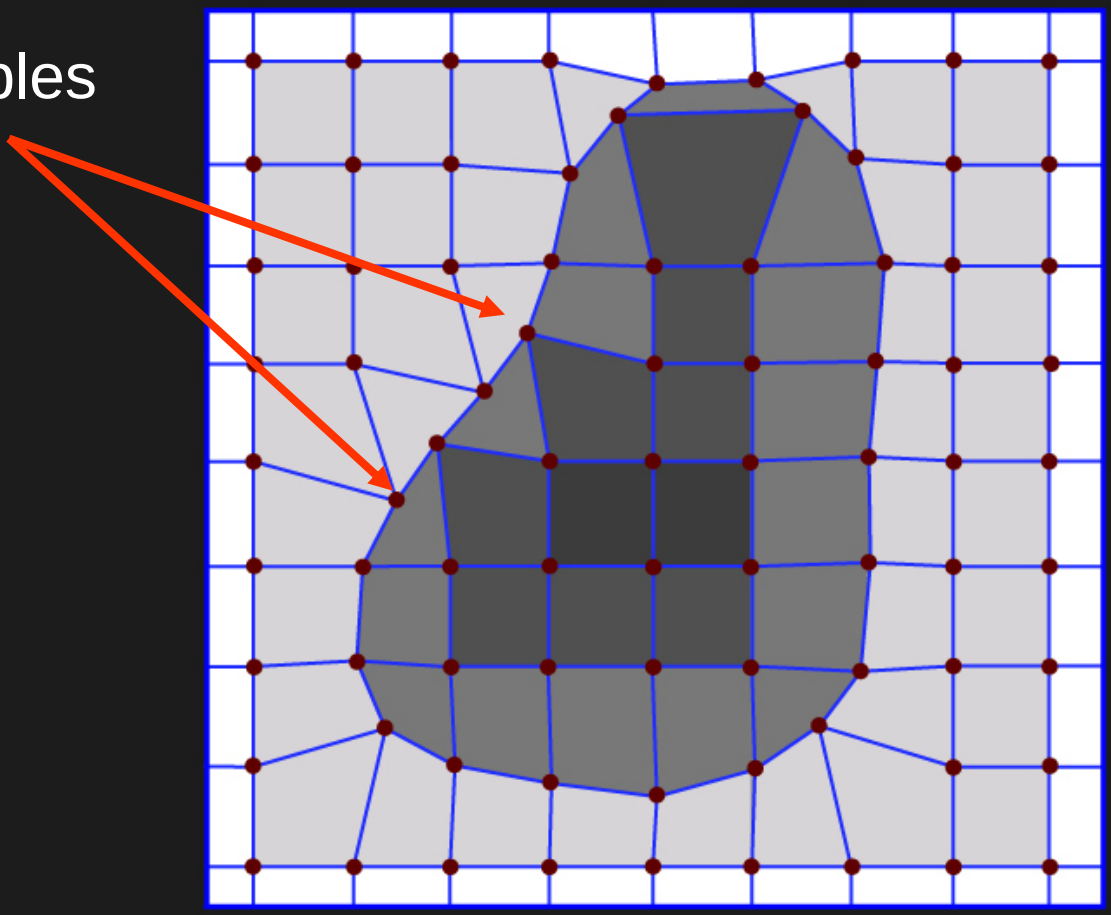
adjusted depth samples



deformed depth mesh

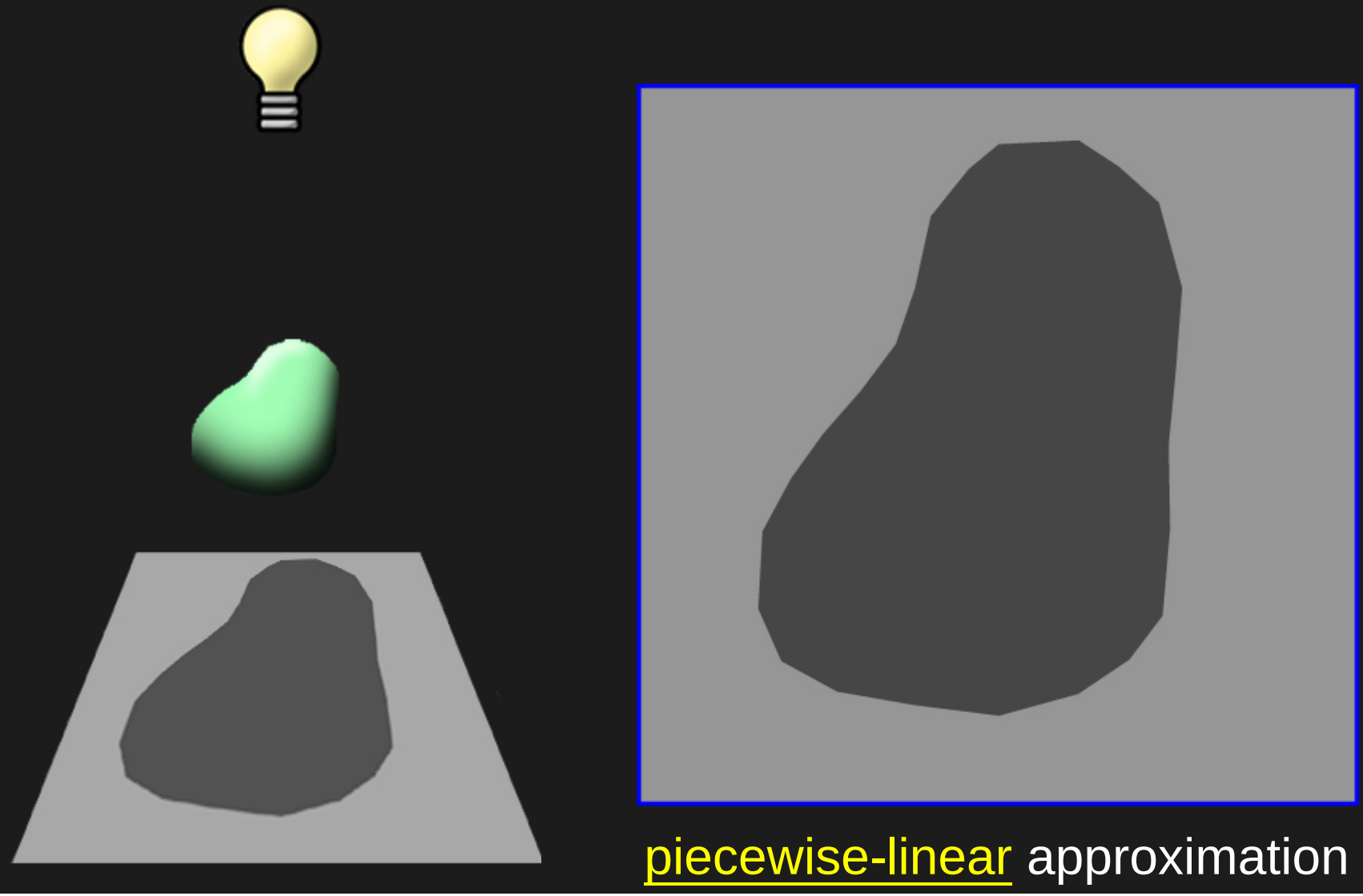
Depth Mesh Deformation

adjusted depth samples



deformed depth mesh

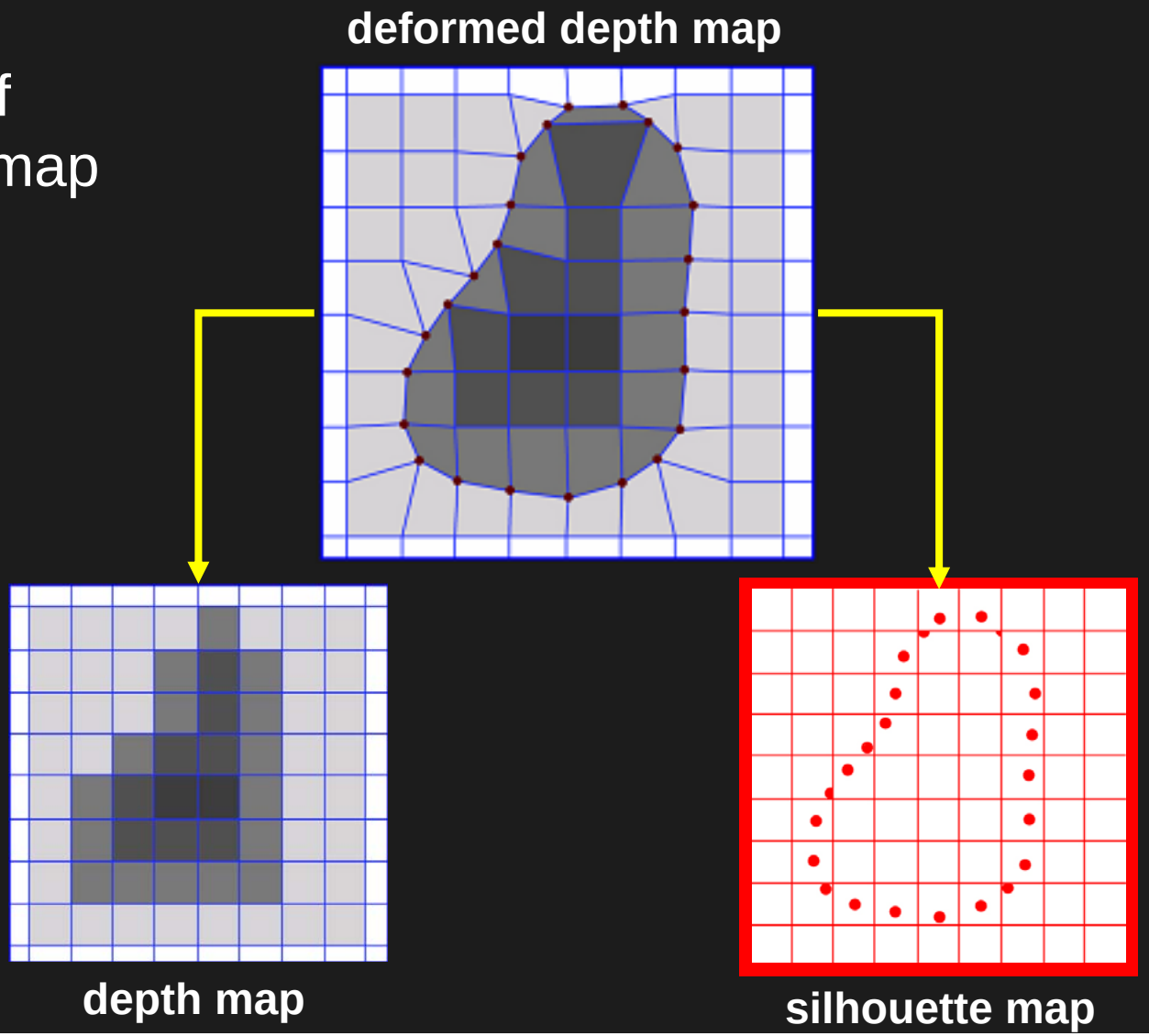
Better Approximation



piecewise-linear approximation

Silhouette Map

Decomposition of deformed depth map



What is a Silhouette Map?

Many ways to think about it:

- Edge representation
- 2D image, same resolution as depth map
- Offset from depth map by ½ pixel in x, y
- Stores xy-coordinates of silhouette points
- Stores only one silhouette point per texel
- Piecewise-linear approximation

Algorithm

Algorithm Properties

- Scalable
- Treats perspective and projection aliasing
- Supports dynamic scenes
- Maps to graphics hardware

Algorithm Overview

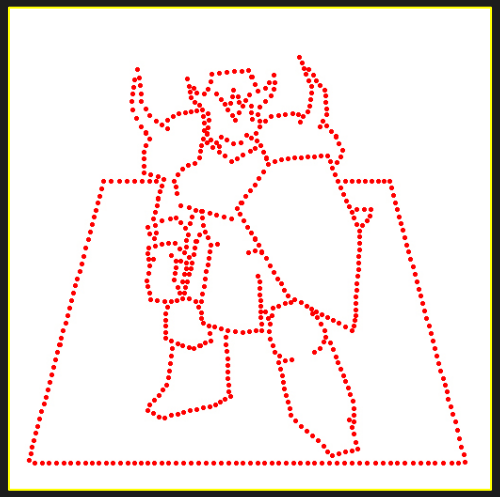
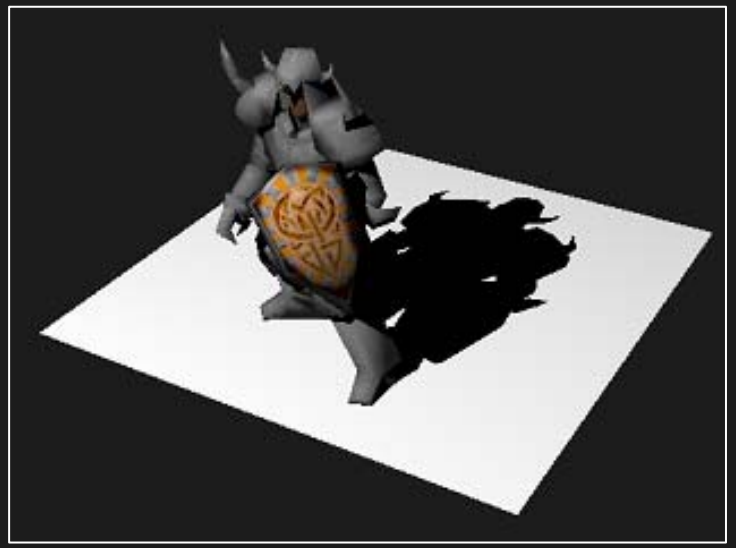
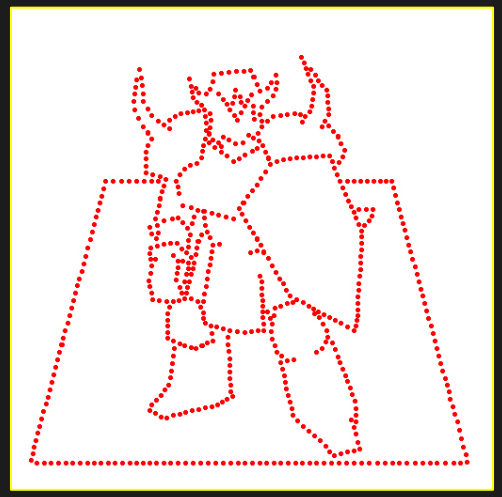
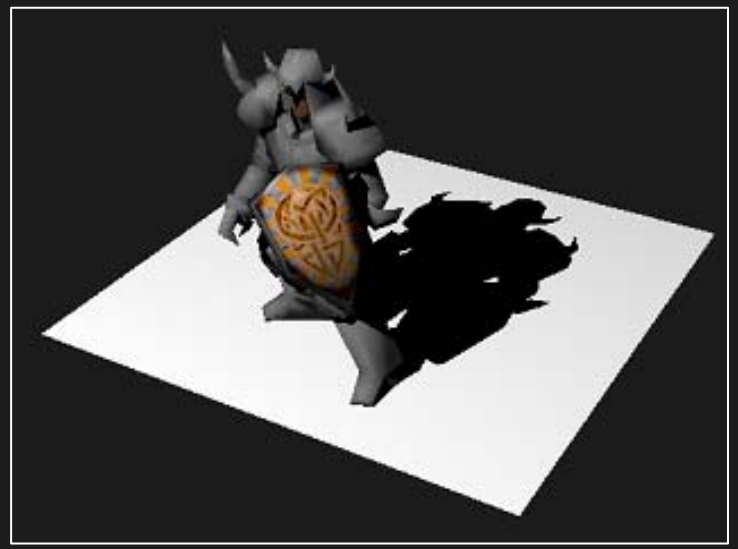


Image-space algorithm



Algorithm Overview

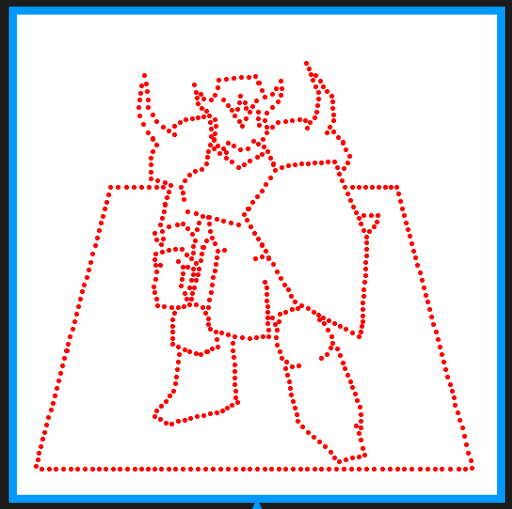


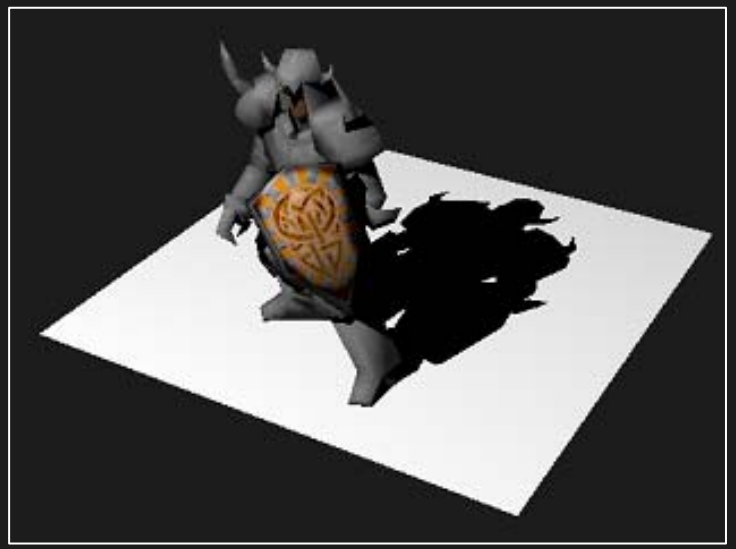


Step 1

Create depth map

Algorithm Overview

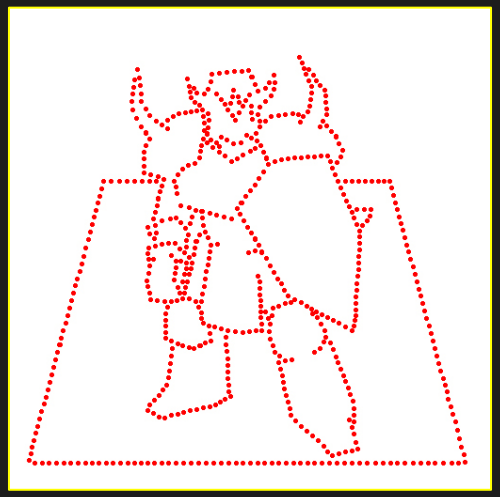


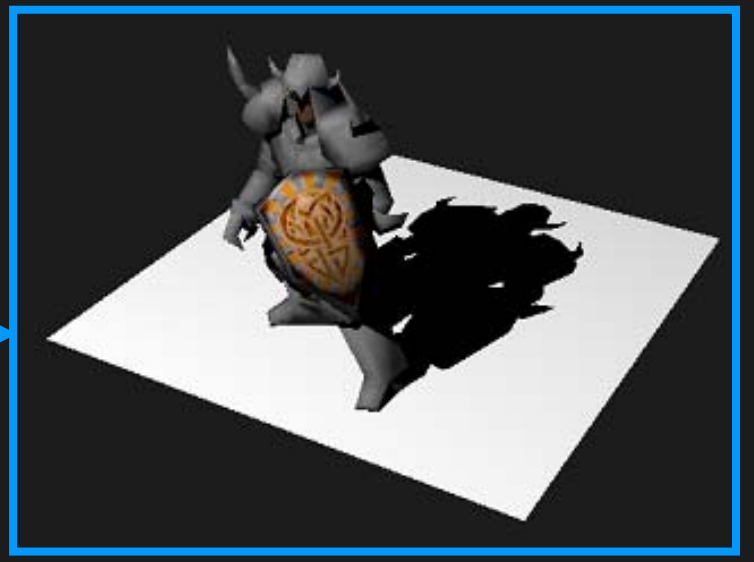


Step 2

Create silhouette map

Algorithm Overview





Step 3

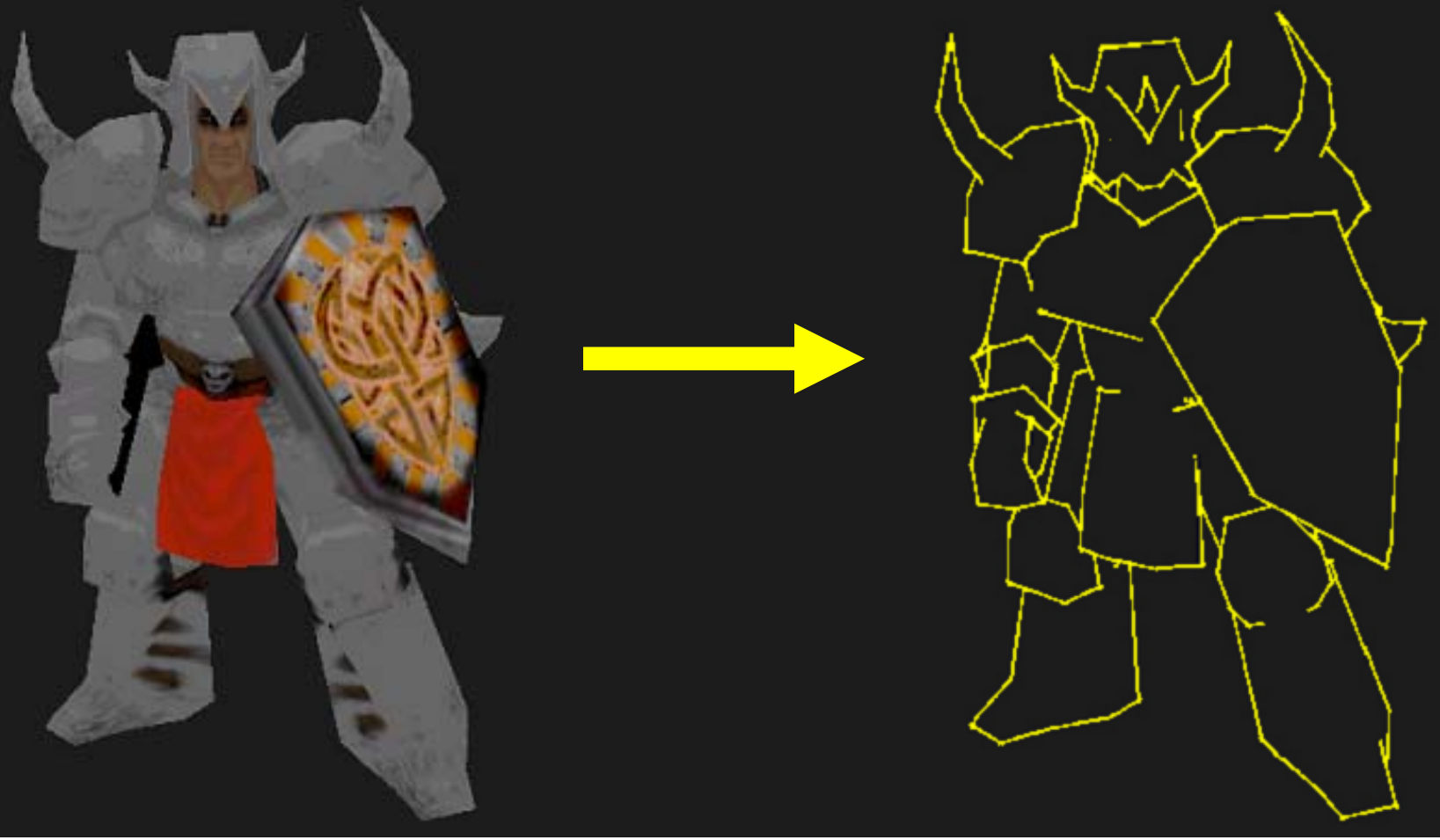
Render scene and shadows

Create Depth Map

Same as in regular shadow maps

Identify Silhouette Edges

Find object-space silhouettes (light's view)

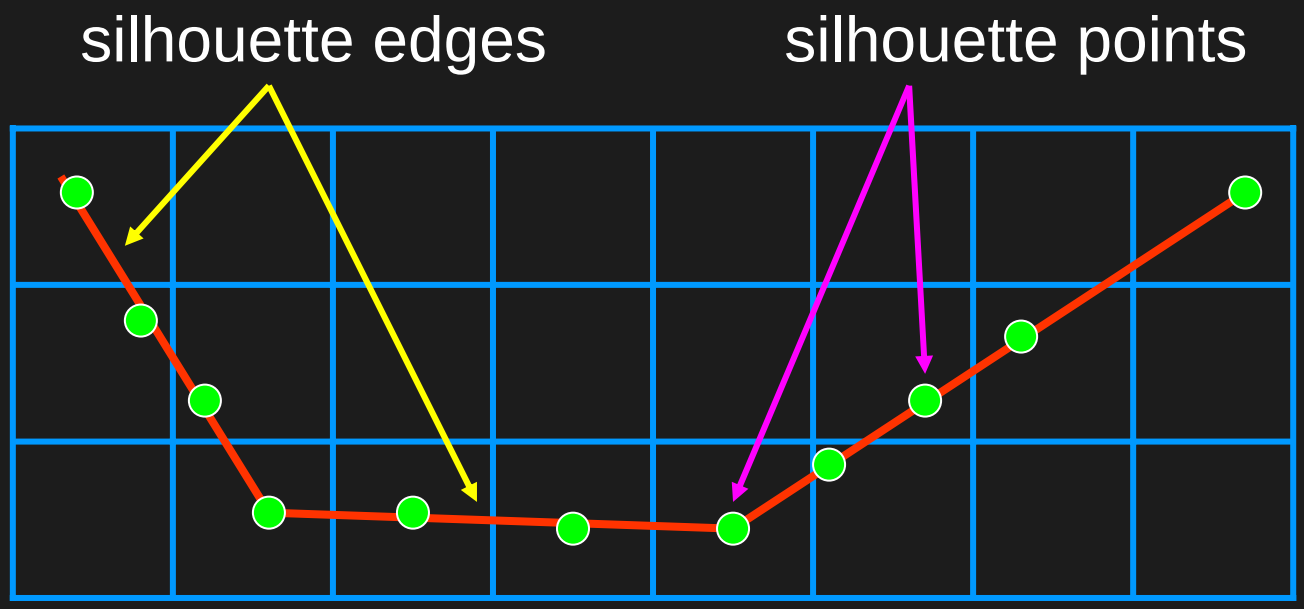


Create Silhouette Map

Rasterize silhouette edges (light's view)

Find points that lie on silhouette edges

Store one such point per texel

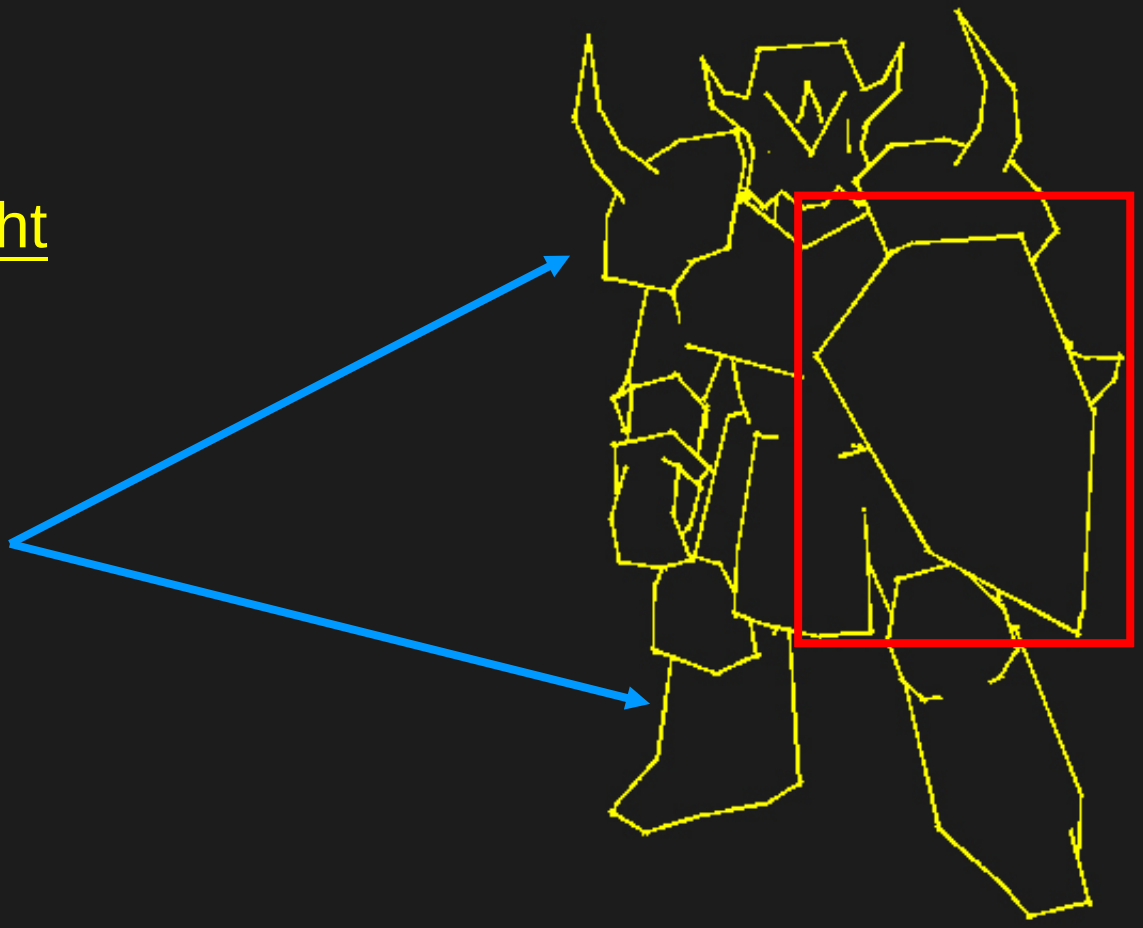


Compute Silhouette Points

Example:

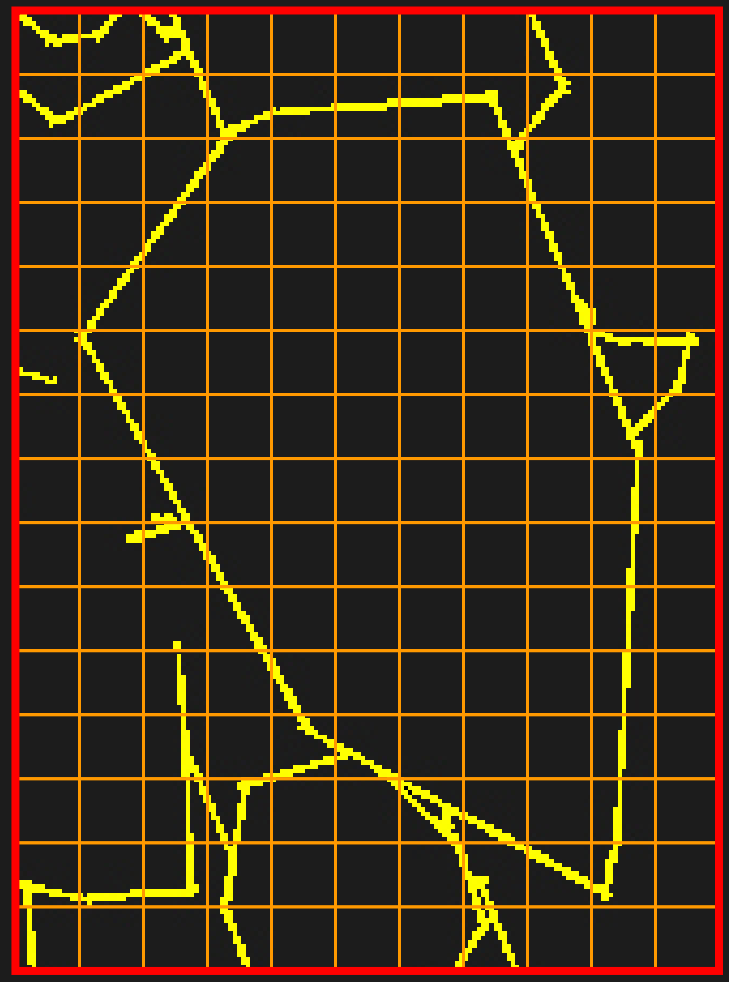
point of view of light

silhouette edges



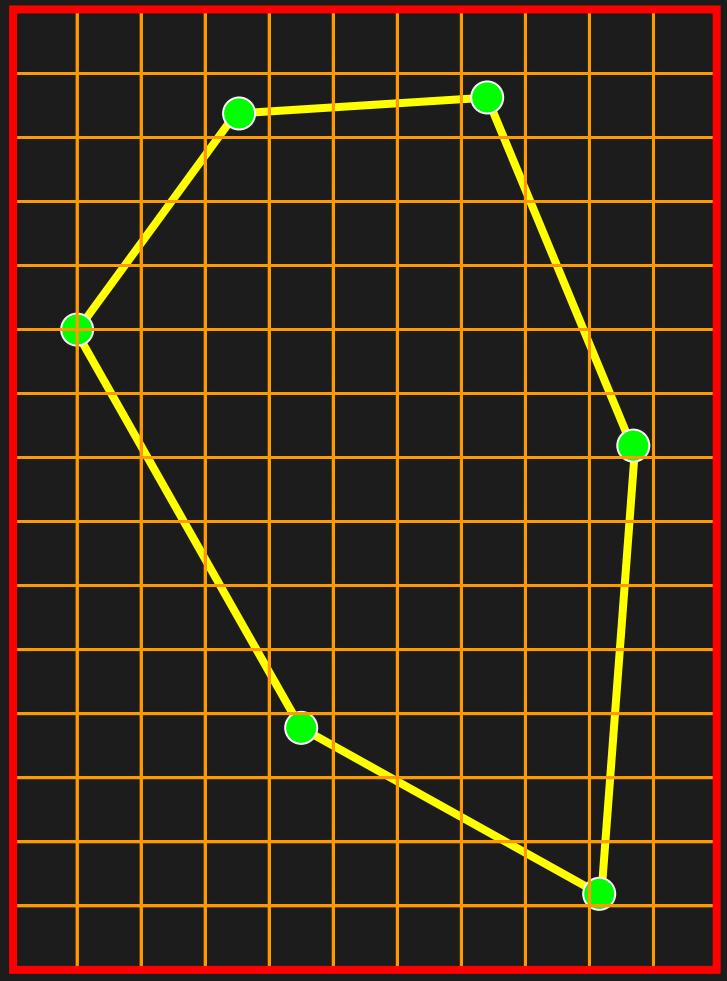
Compute Silhouette Points

silhouette map (dual grid)



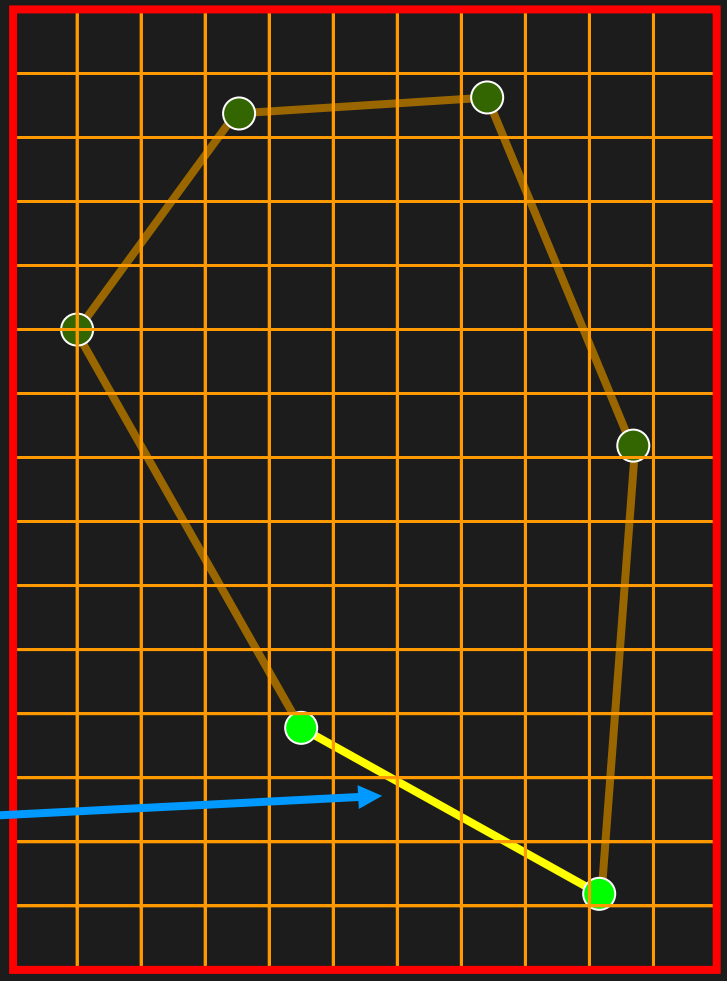
Compute Silhouette Points

rasterization of silhouettes



Compute Silhouette Points

rasterization of silhouettes

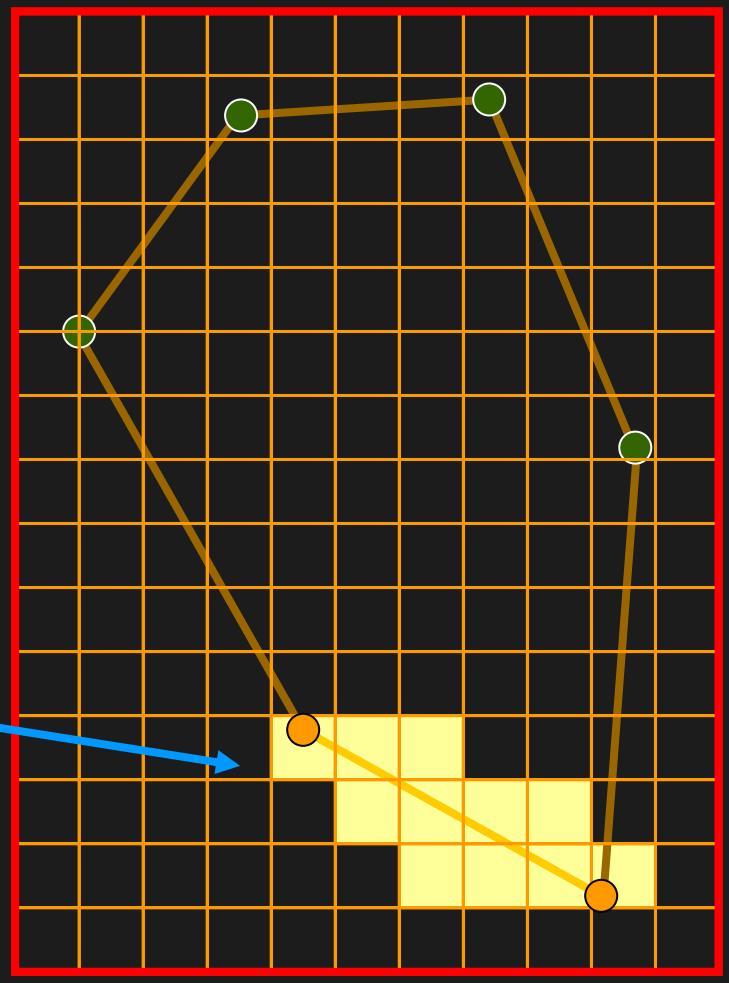


pick an edge

Compute Silhouette Points

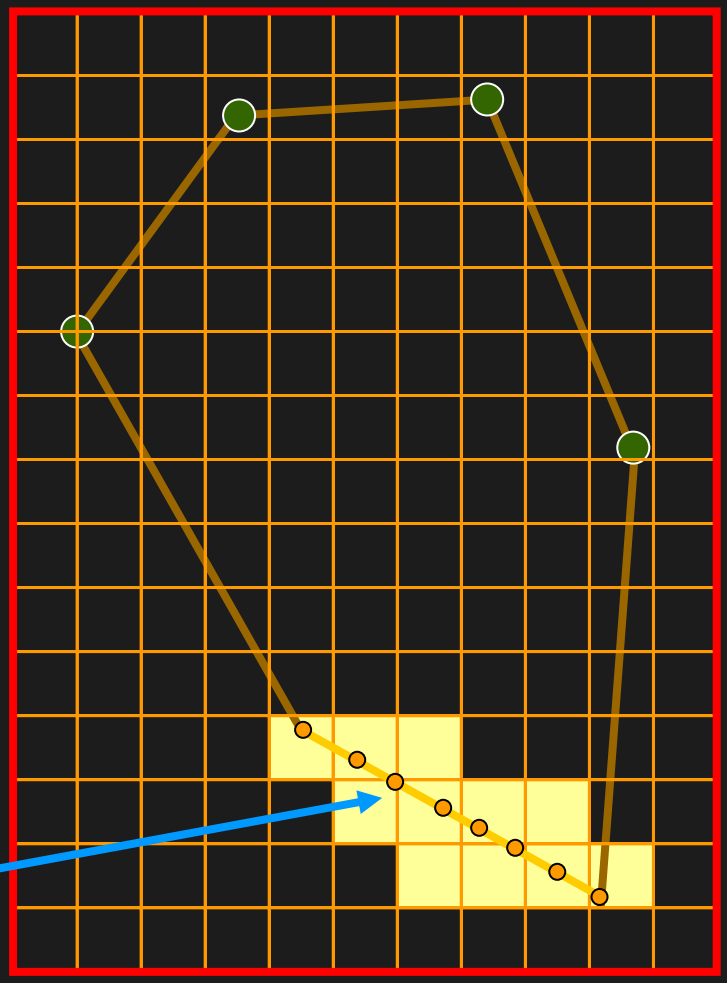
rasterization of silhouettes

rasterize edge conservatively:
be sure to generate fragments
for silhouette pixels



Compute Silhouette Points

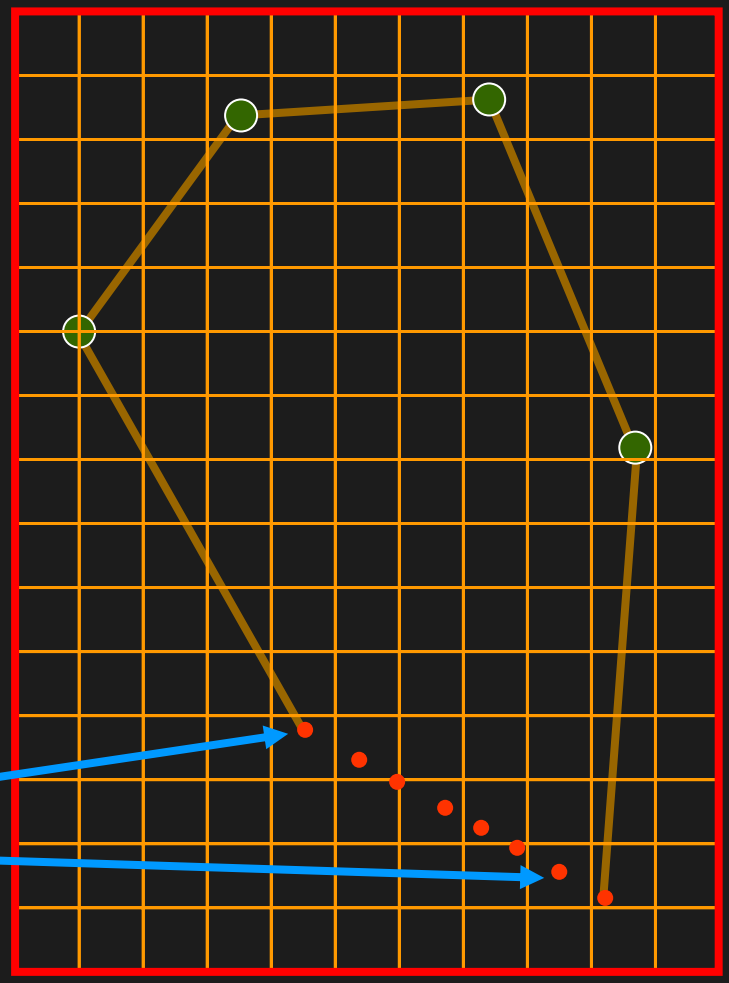
rasterization of silhouettes



for each fragment:
pick a point on the edge

Compute Silhouette Points

rasterization of silhouettes

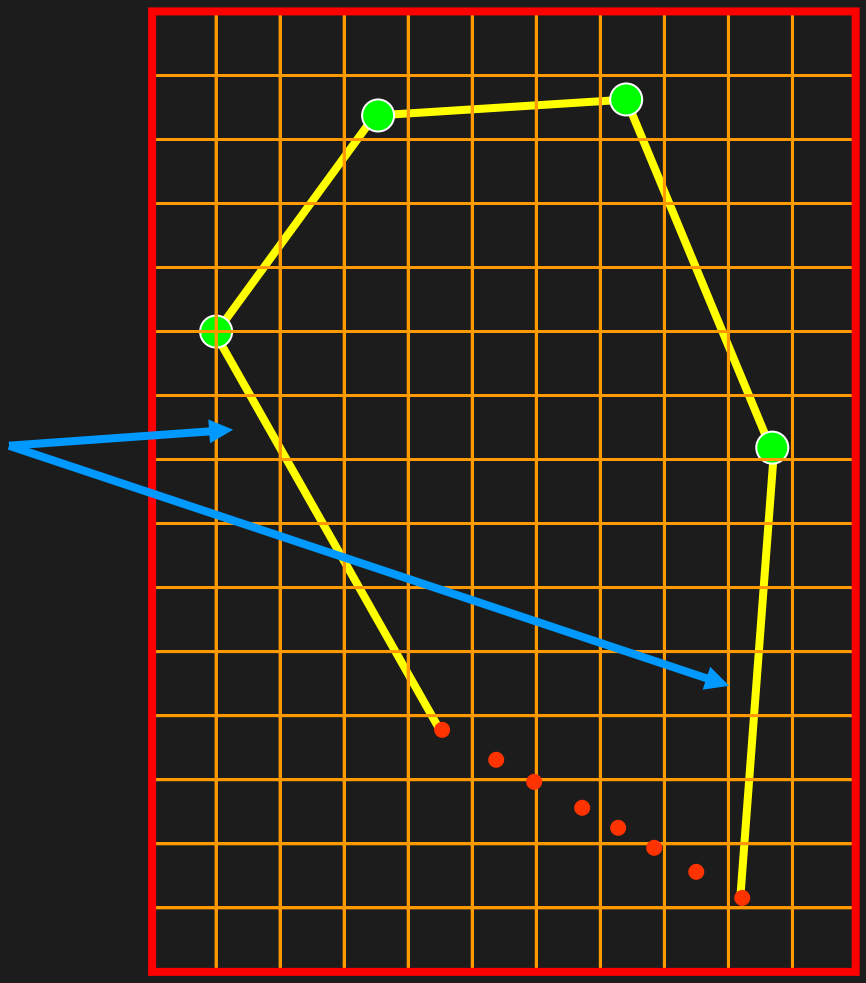


silhouette points

Compute Silhouette Points

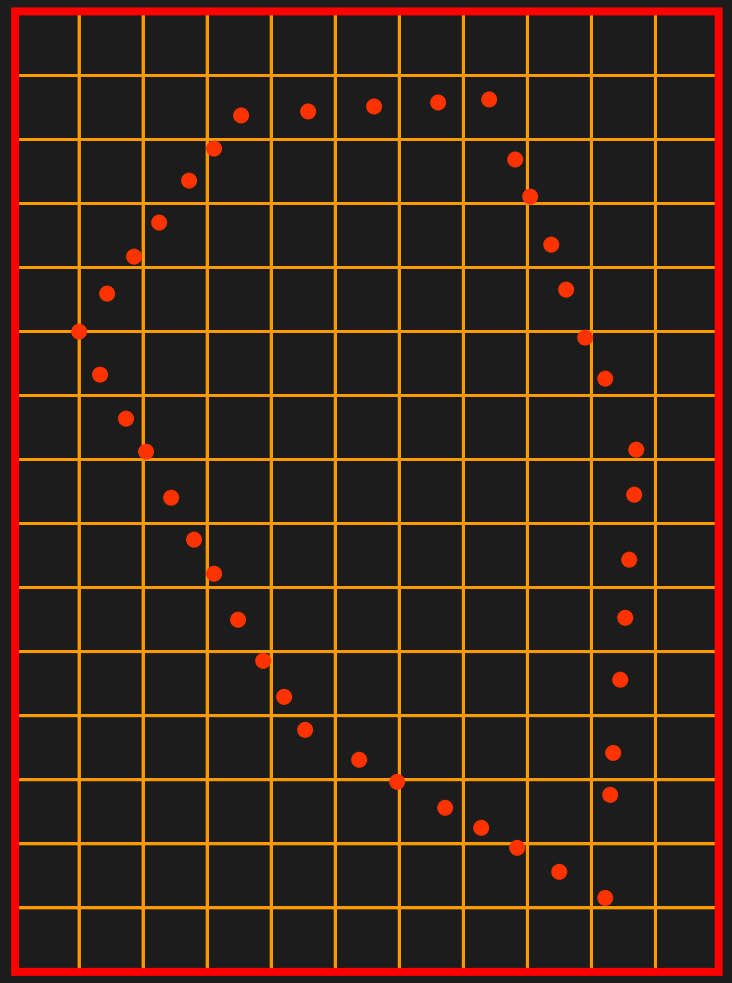
rasterization of silhouettes

do the same for other edges



Compute Silhouette Points

rasterization of silhouettes

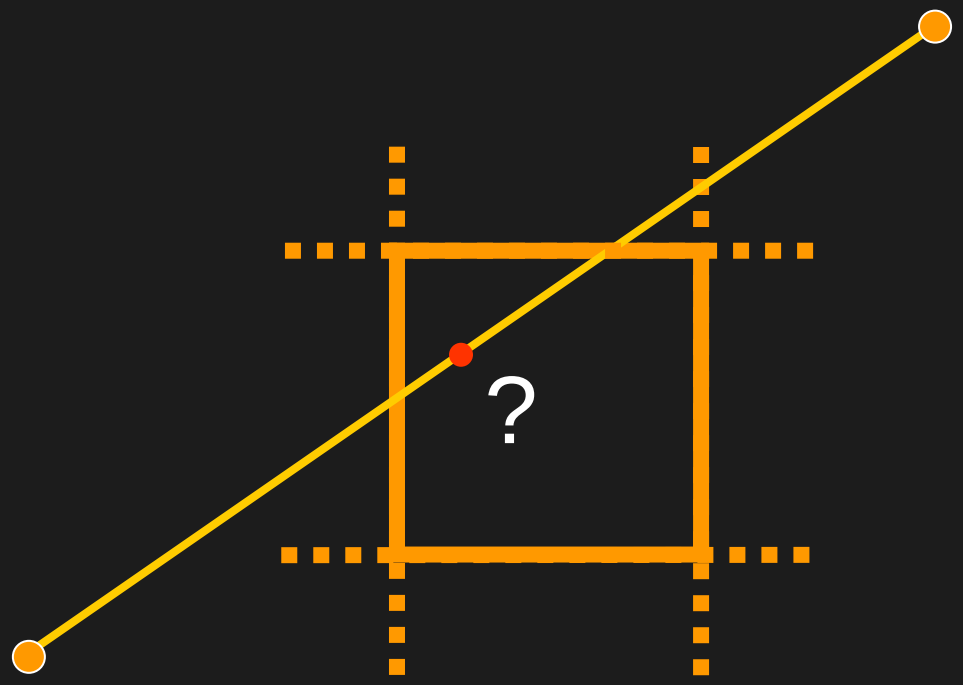
completed silhouette map 

subtle issues:
- only one point per texel
- new values overwrite old ones

how to pick silhouette points?

Picking Silhouette Points

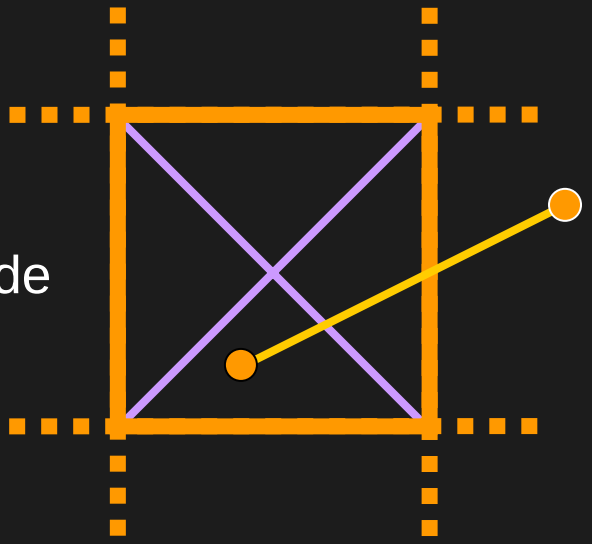
Pick a point on the line that lies inside the texel



Silhouette Point Algorithm

Case 1:

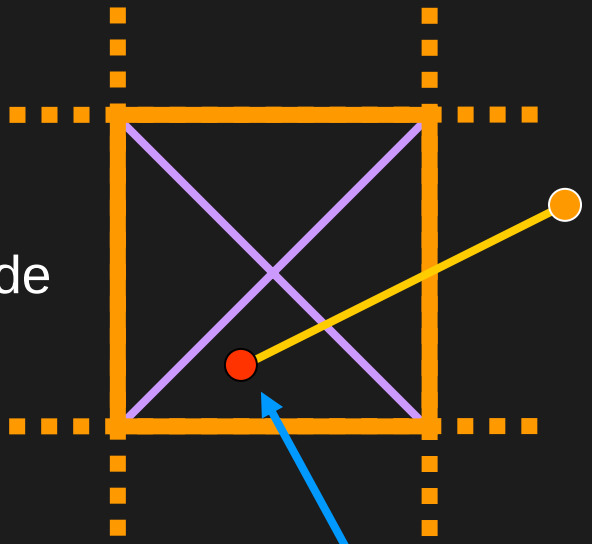
vertex inside



Silhouette Point Algorithm

Case 1:

vertex inside

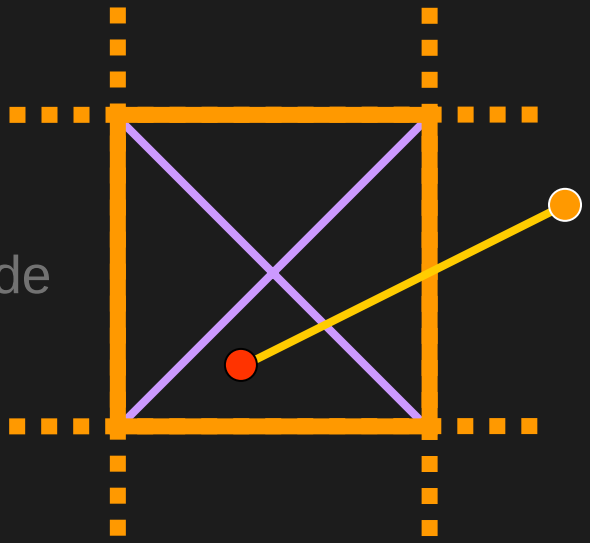


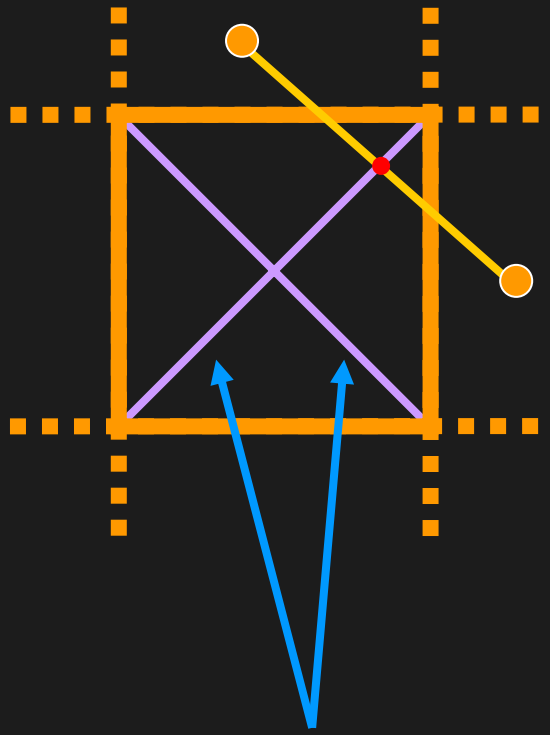
pick the vertex itself

Silhouette Point Algorithm

Case 1:

vertex inside





Case 2:

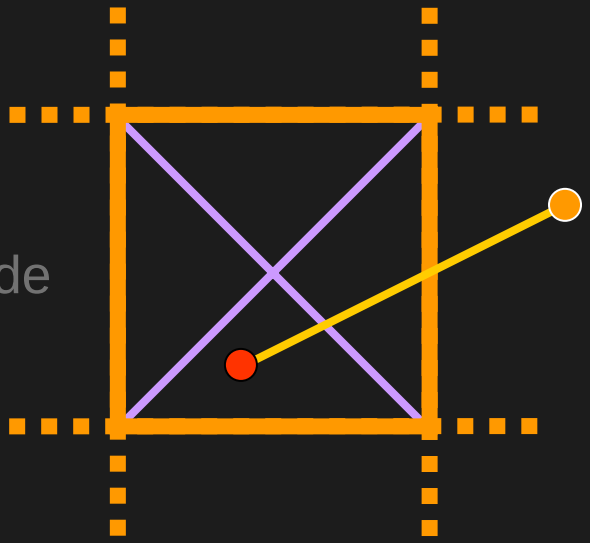
one intersection

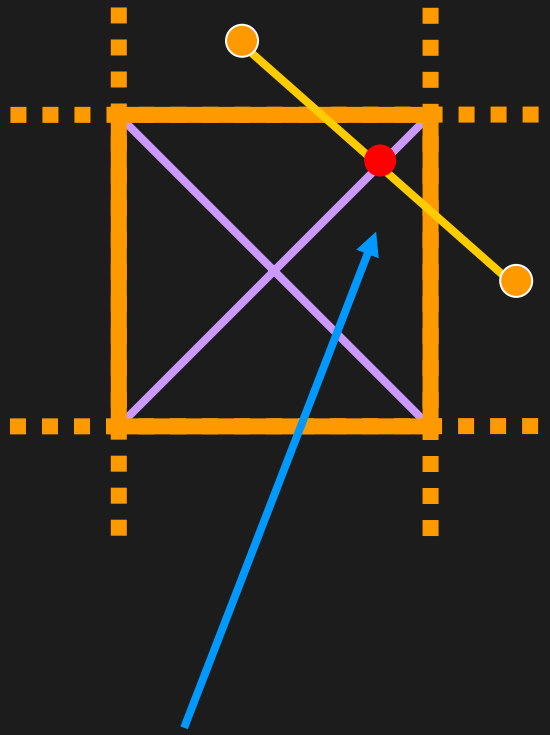
test for intersection against two diagonals

Silhouette Point Algorithm

Case 1:

vertex inside





Case 2:

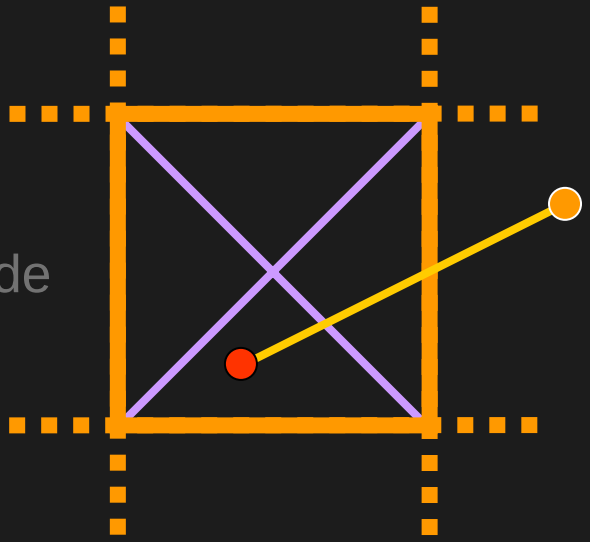
one intersection

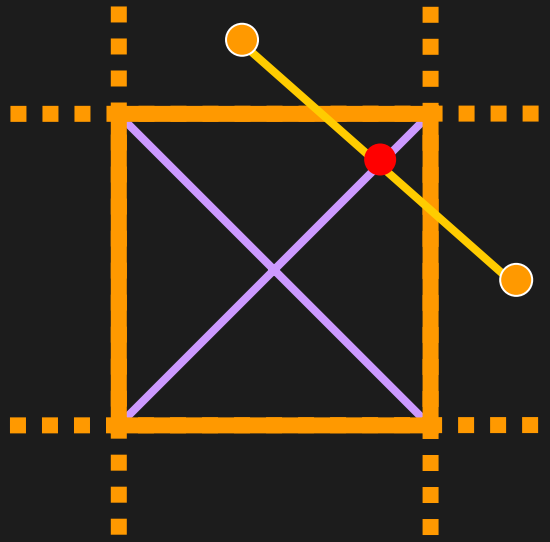
pick the intersection point itself

Silhouette Point Algorithm

Case 1:

vertex inside



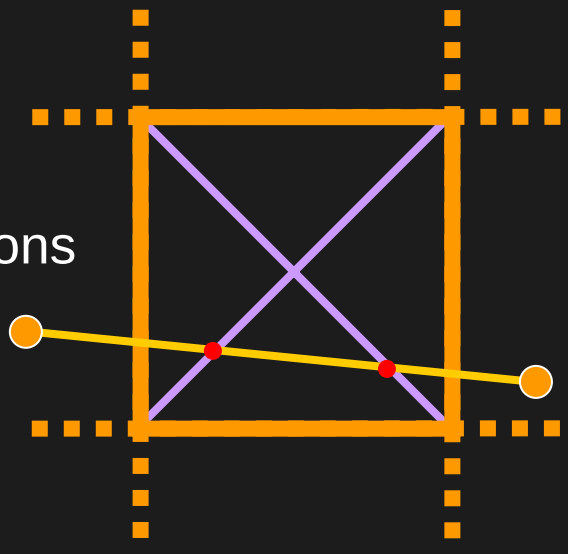


Case 2:

one
intersection

Case 3:

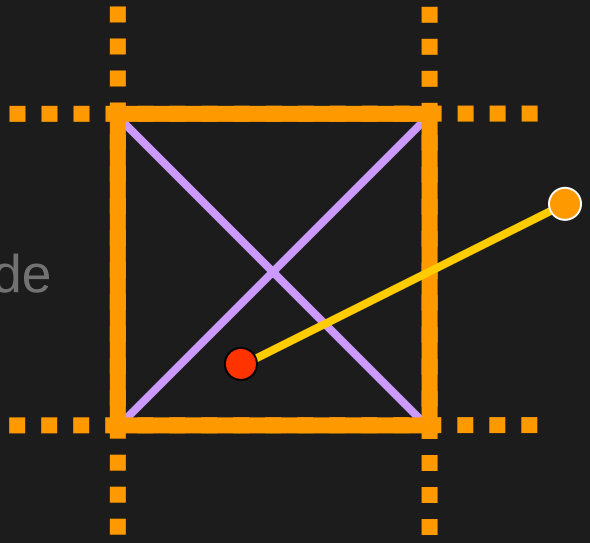
two
intersections

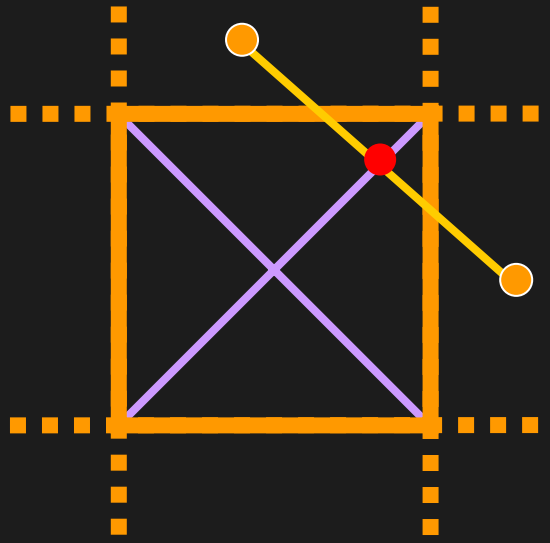


Silhouette Point Algorithm

Case 1:

vertex inside



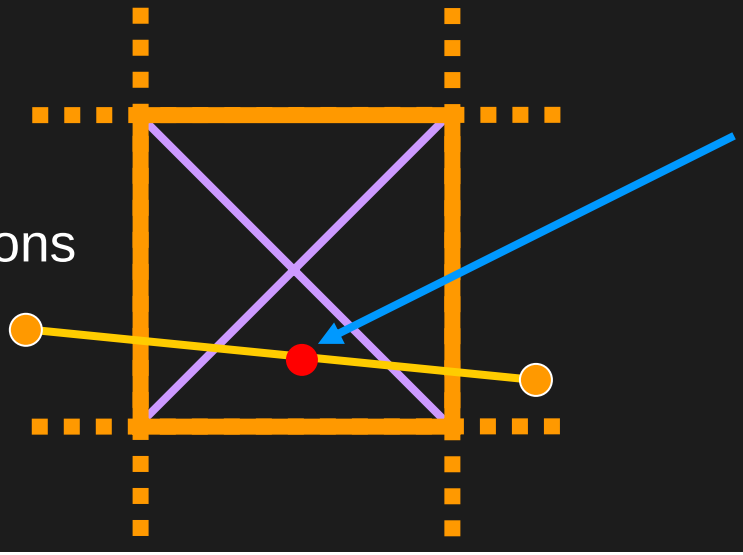


Case 2:

one
intersection

Case 3:

two
intersections

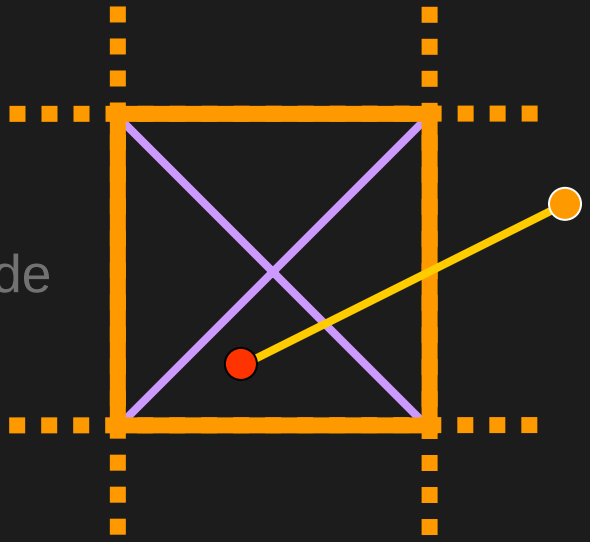


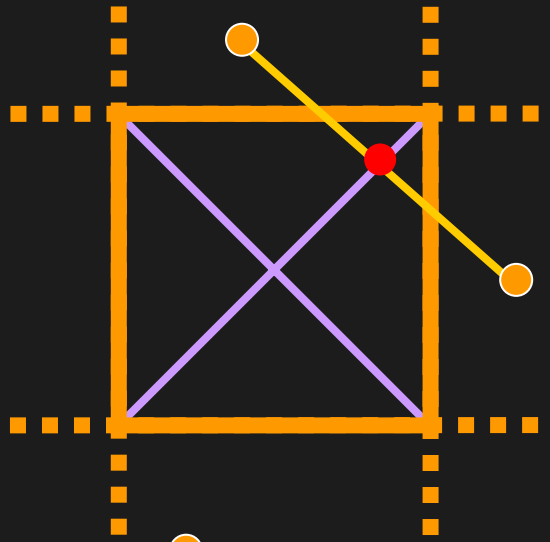
use midpoint

Silhouette Point Algorithm

Case 1:

vertex inside



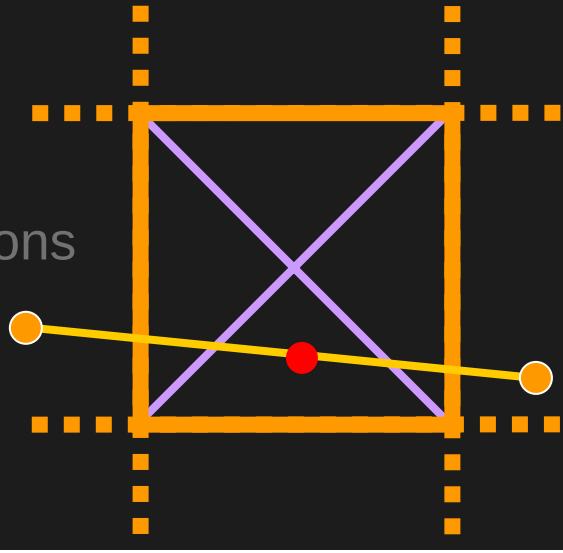


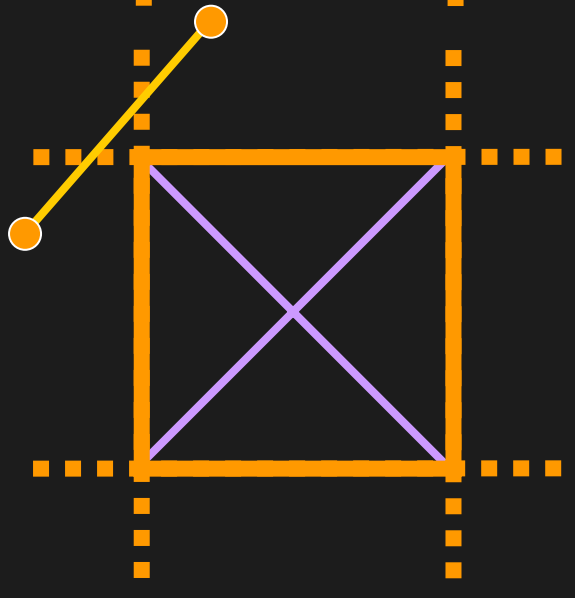
Case 2:

one intersection

Case 3:

two intersections





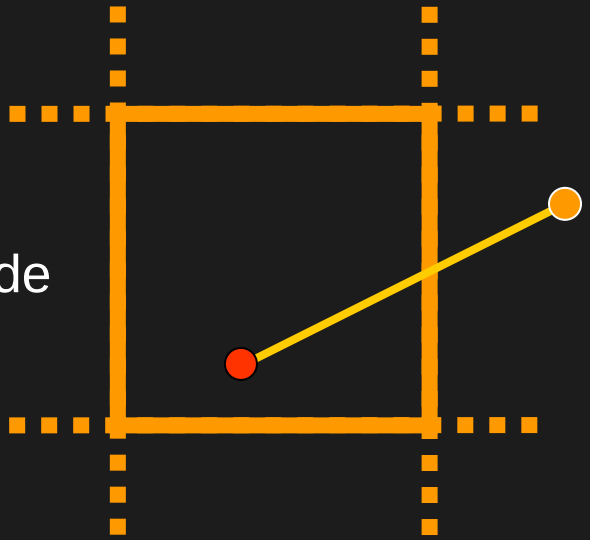
Case 4:

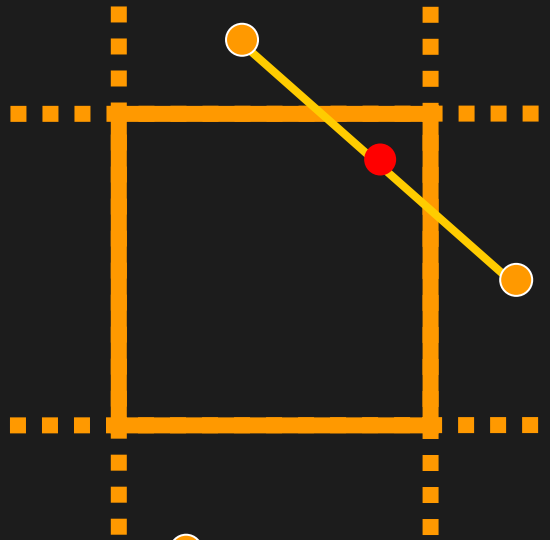
no intersections

Silhouette Point Algorithm

Case 1:

vertex inside



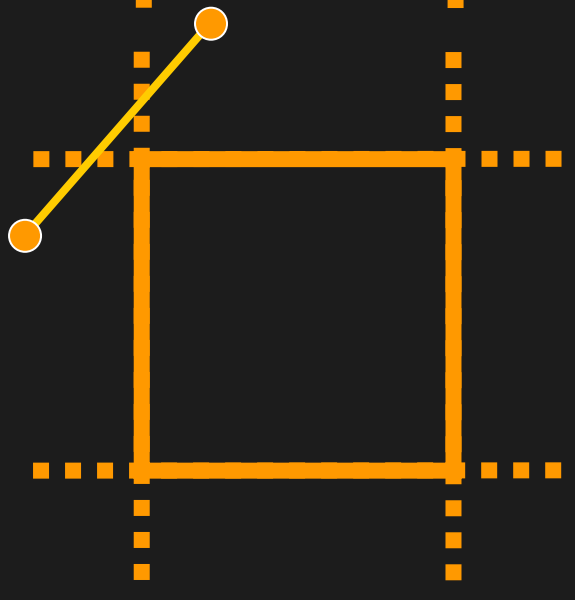


Case 2:

one
intersection

Case 3:

two
intersections



Case 4:

no
intersections

Render scene

How to compute shadows?

Split problem into two parts:
non-silhouette pixels: use shadow map
silhouette pixels: use silhouette map

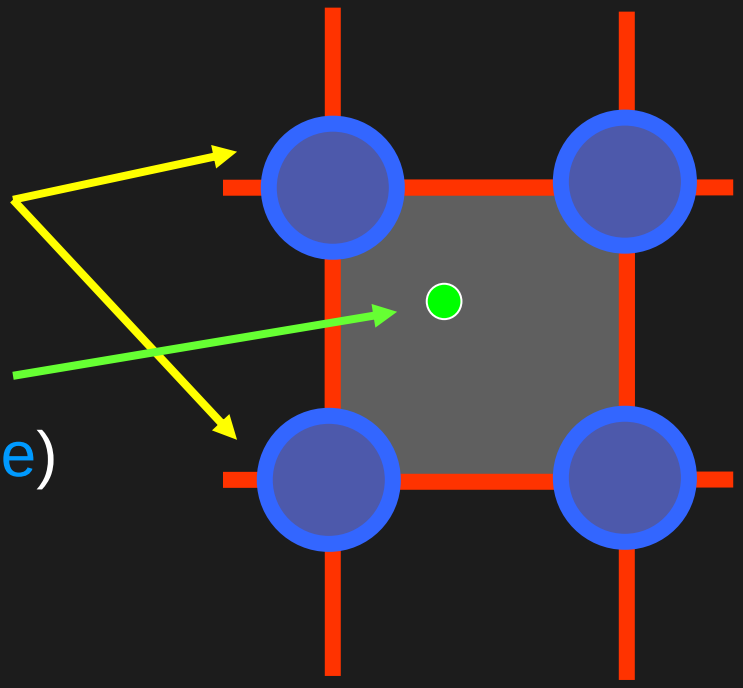
Find Silhouette Pixels

Project sample into light space

Compare depth against 4 nearest samples in shadow map

shadow map samples

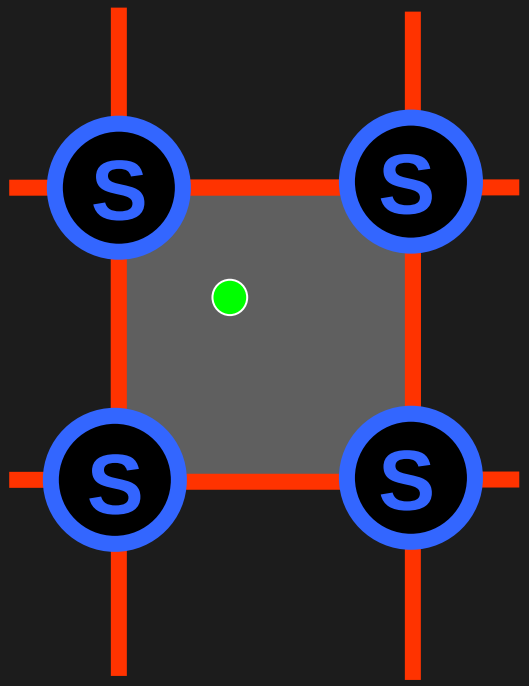
sample to be shaded
(projected to light space)



Find Silhouette Pixels

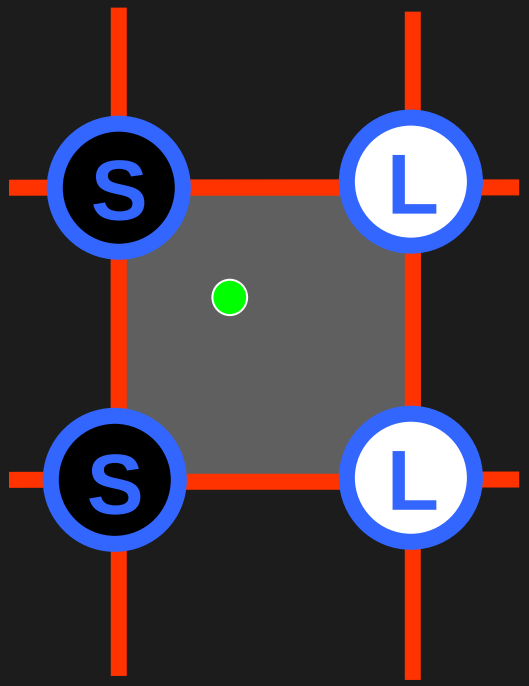
Case #1

results agree:
non-silhouette pixel



Case #2

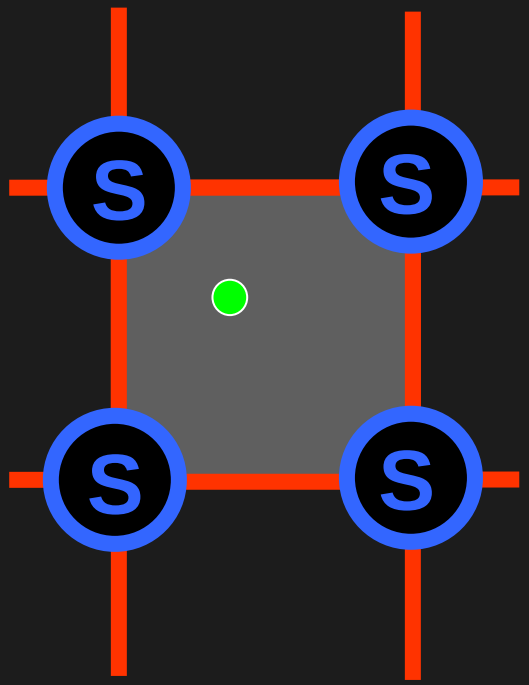
results disagree:
silhouette pixel



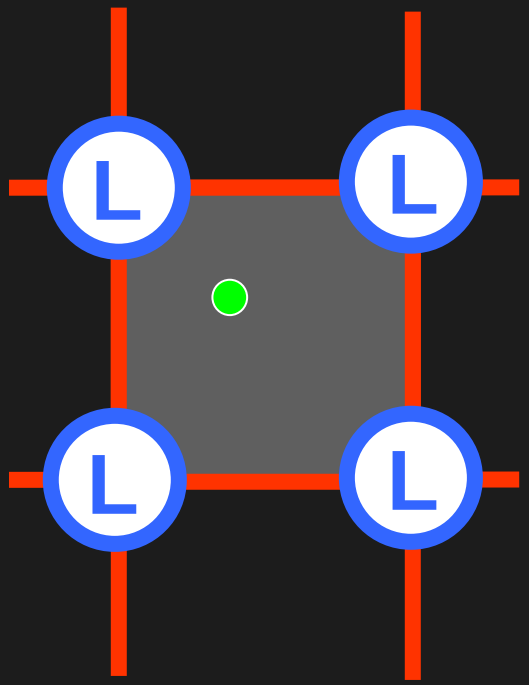
Treat Non-Silhouette Pixels

Easy: use depth comparison result

in shadow



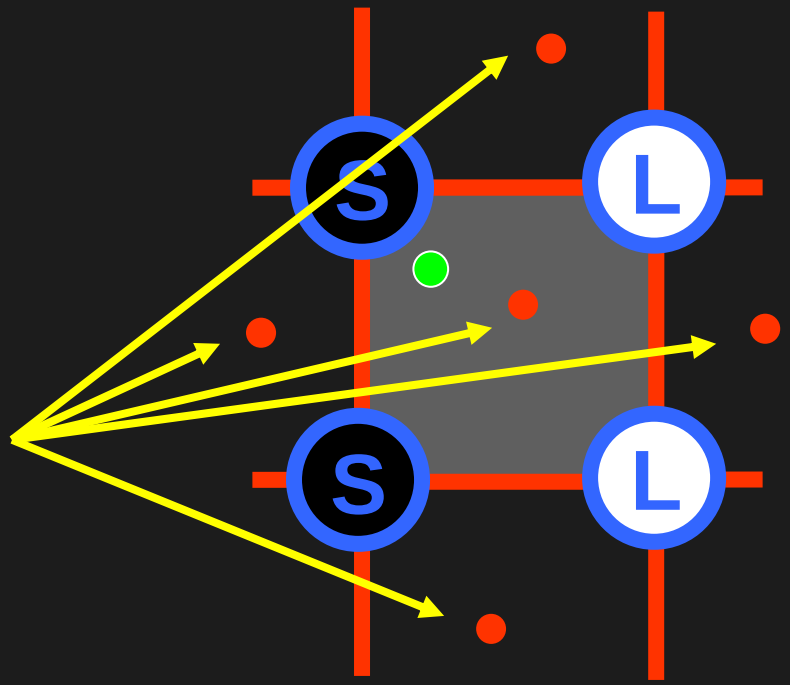
illuminated



Treat Silhouette Pixels

Reconstruct edge using silhouette map

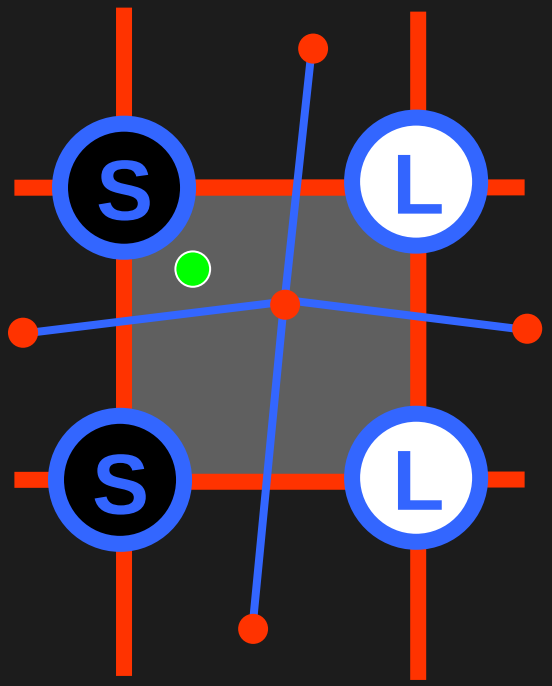
fetch five silhouette points



Treat Silhouette Pixels

Reconstruct edge using silhouette map

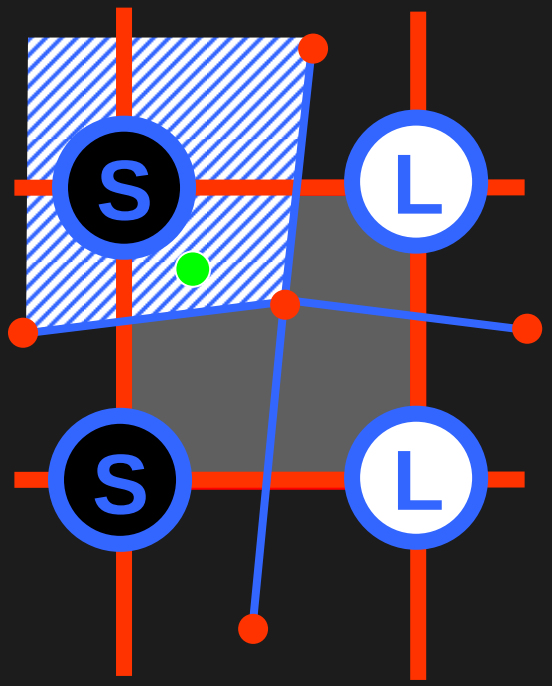
splits cell into four quadrants



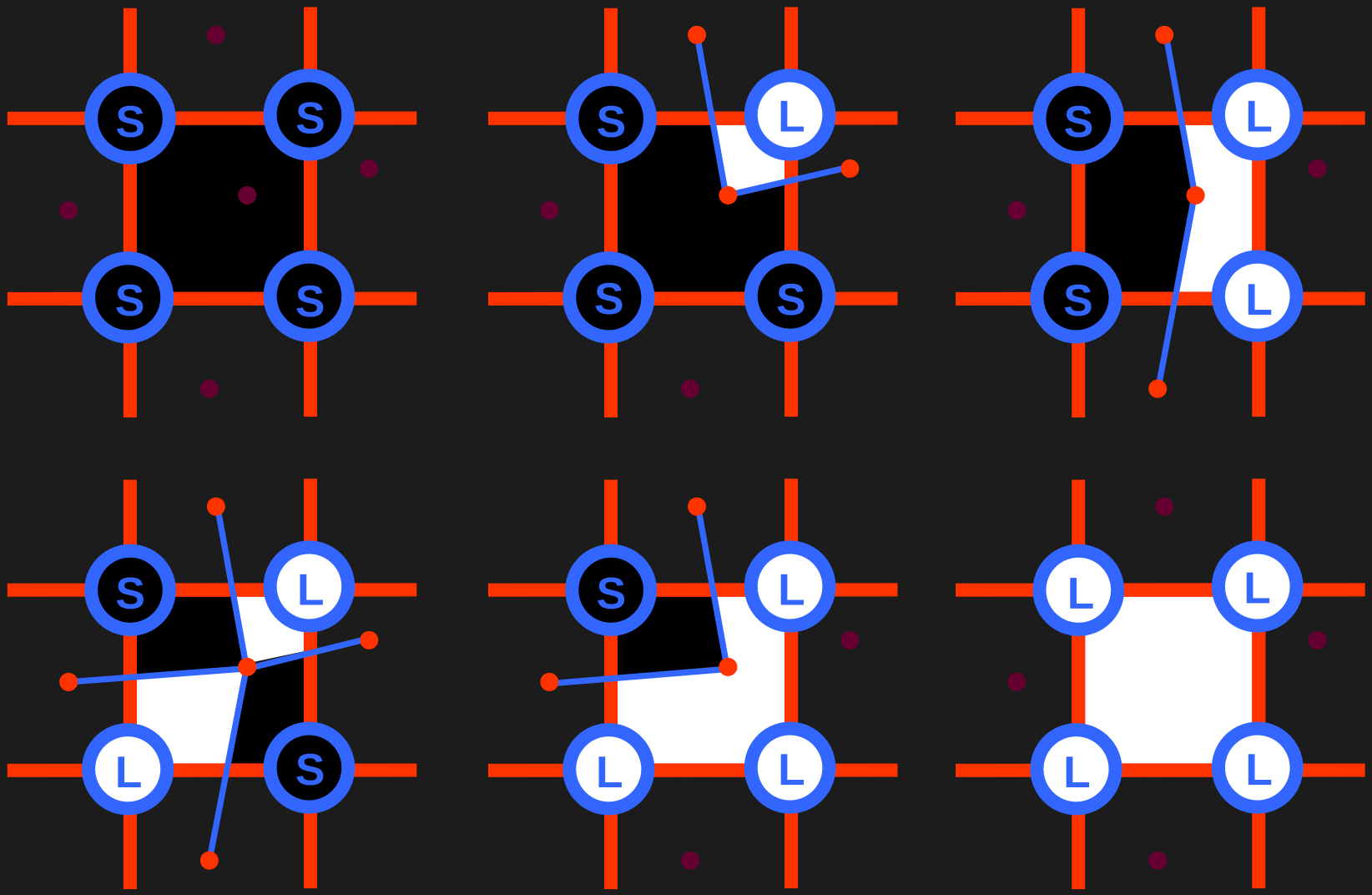
Treat Silhouette Pixels

Shade sample according to quadrant

example: sample in shadow



Six Combinations



Algorithm Recap

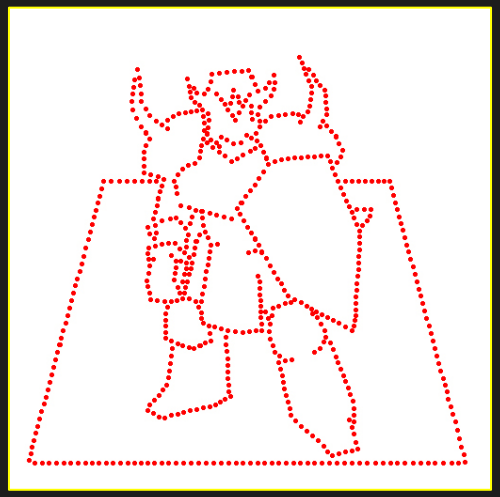
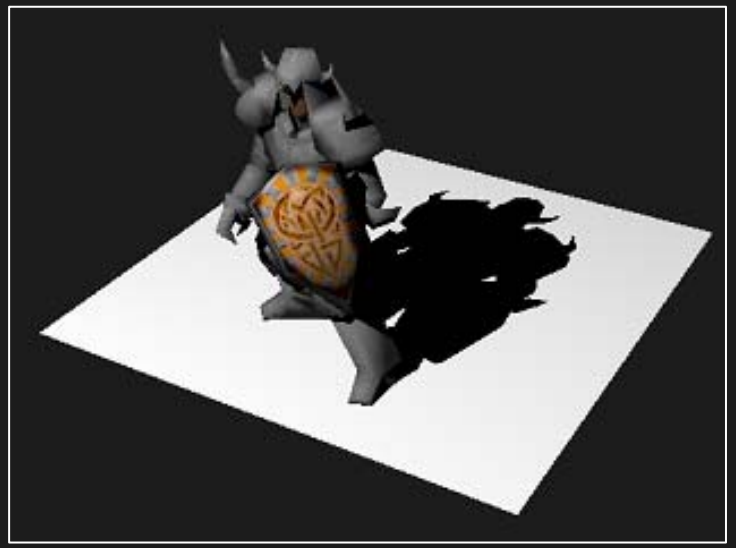
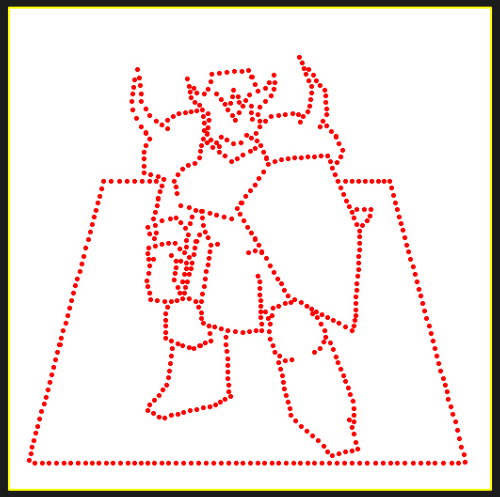


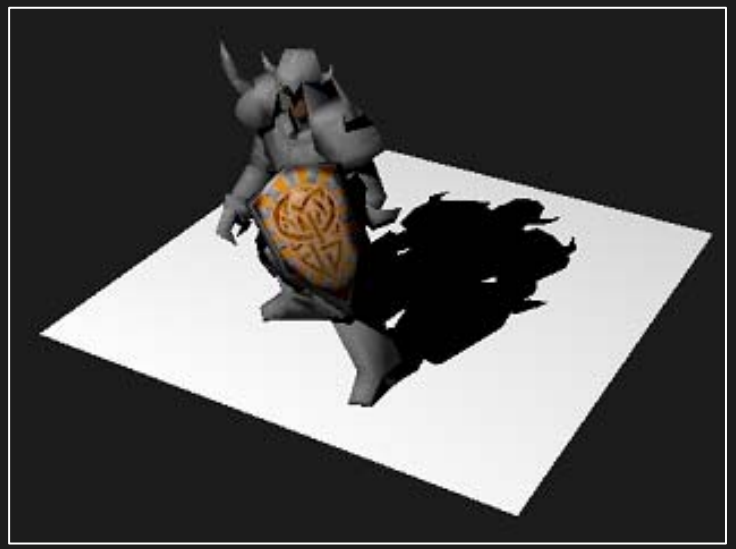
Image-space algorithm



Algorithm Recap (1 of 3)

Create depth map

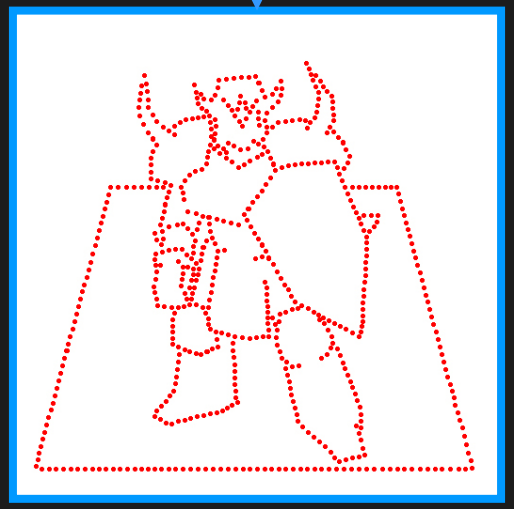


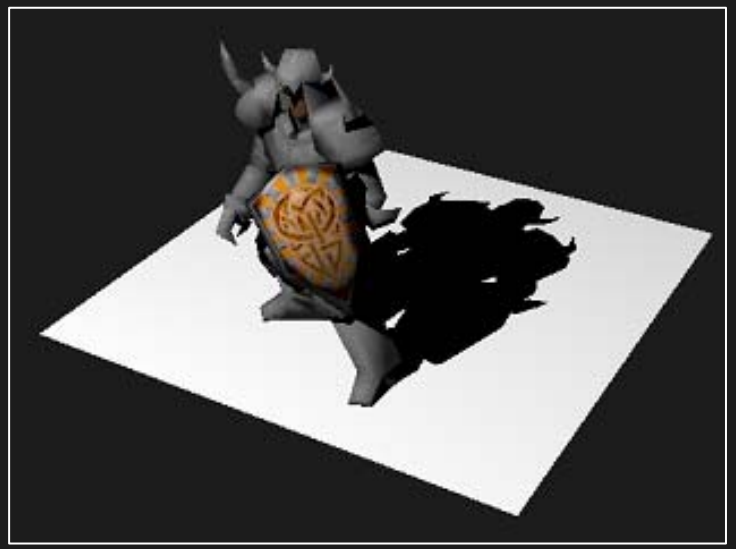


Easy: just like regular shadow map

Algorithm Recap (2 of 3)

Create silhouette map

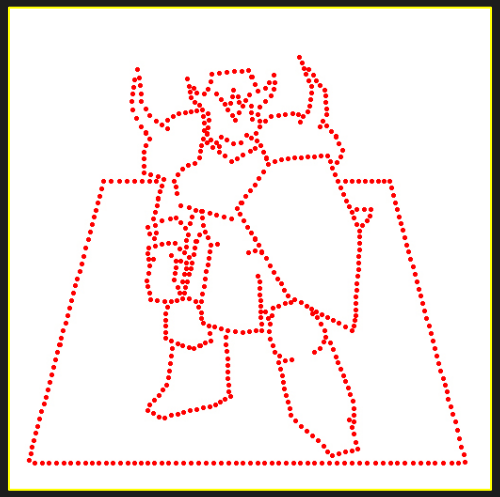




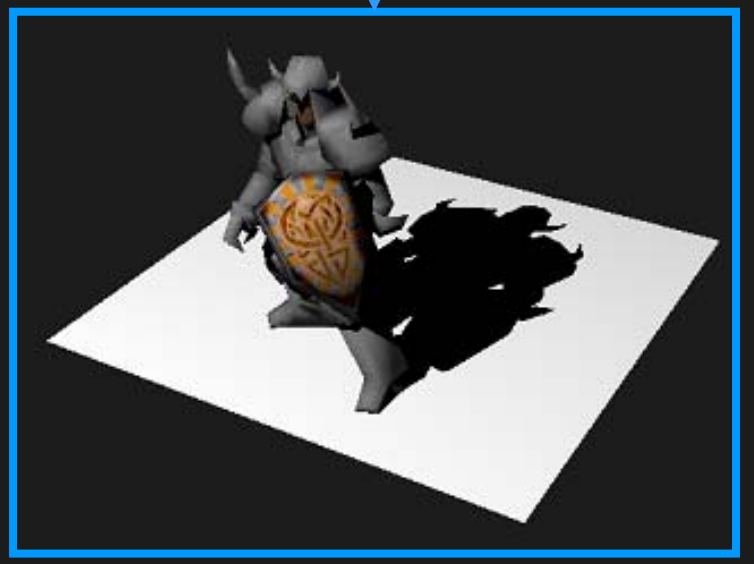
Rasterize silhouette edges

Pick silhouette points, 1 per texel

Algorithm Recap (3 of 3)



Render scene and shadows



Fetch local silhouette points

Reconstruct shadow edge

Examples and Analysis

Example 1

shadow maps

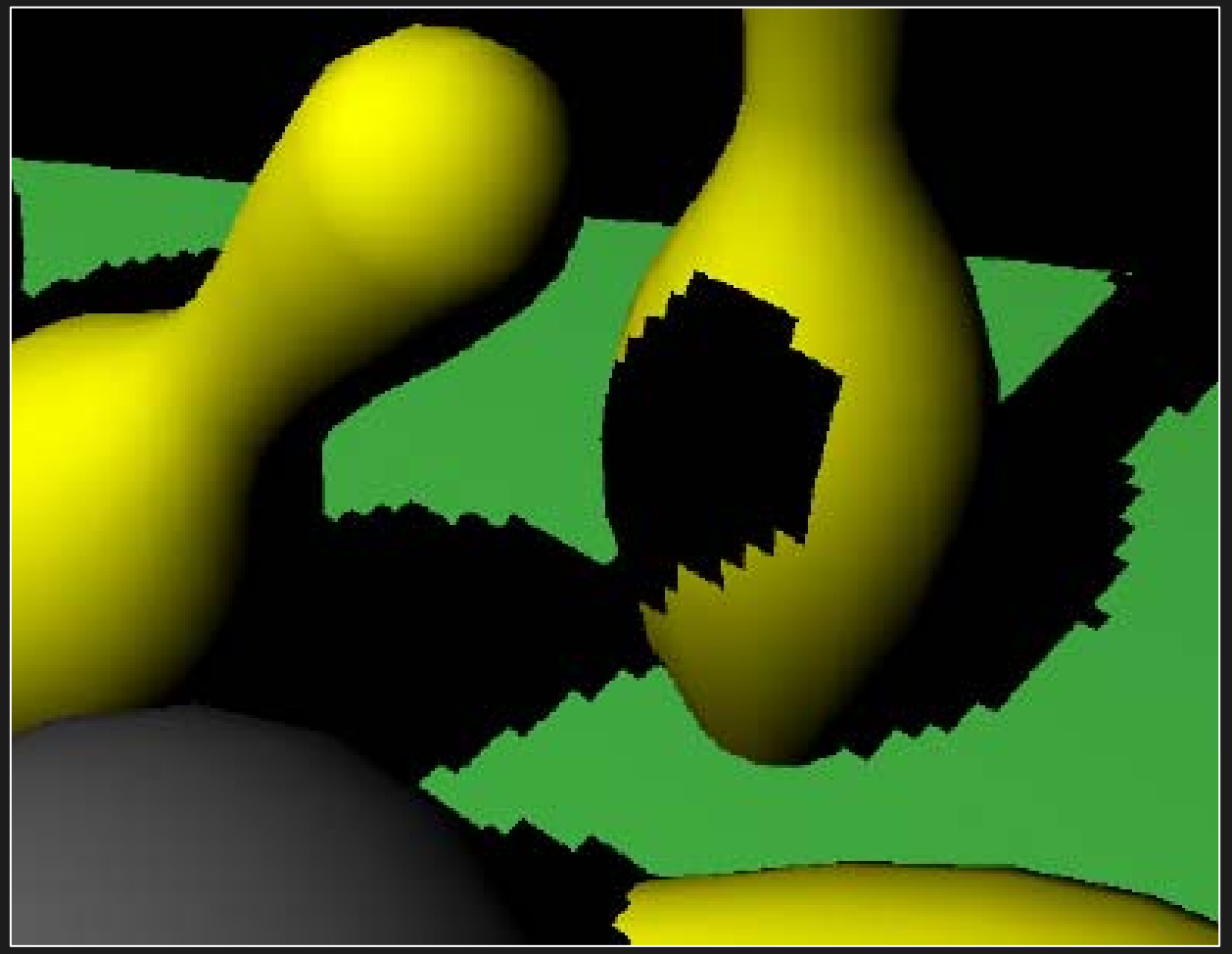
shadow volumes

silhouette maps

Example 1 (closeup)

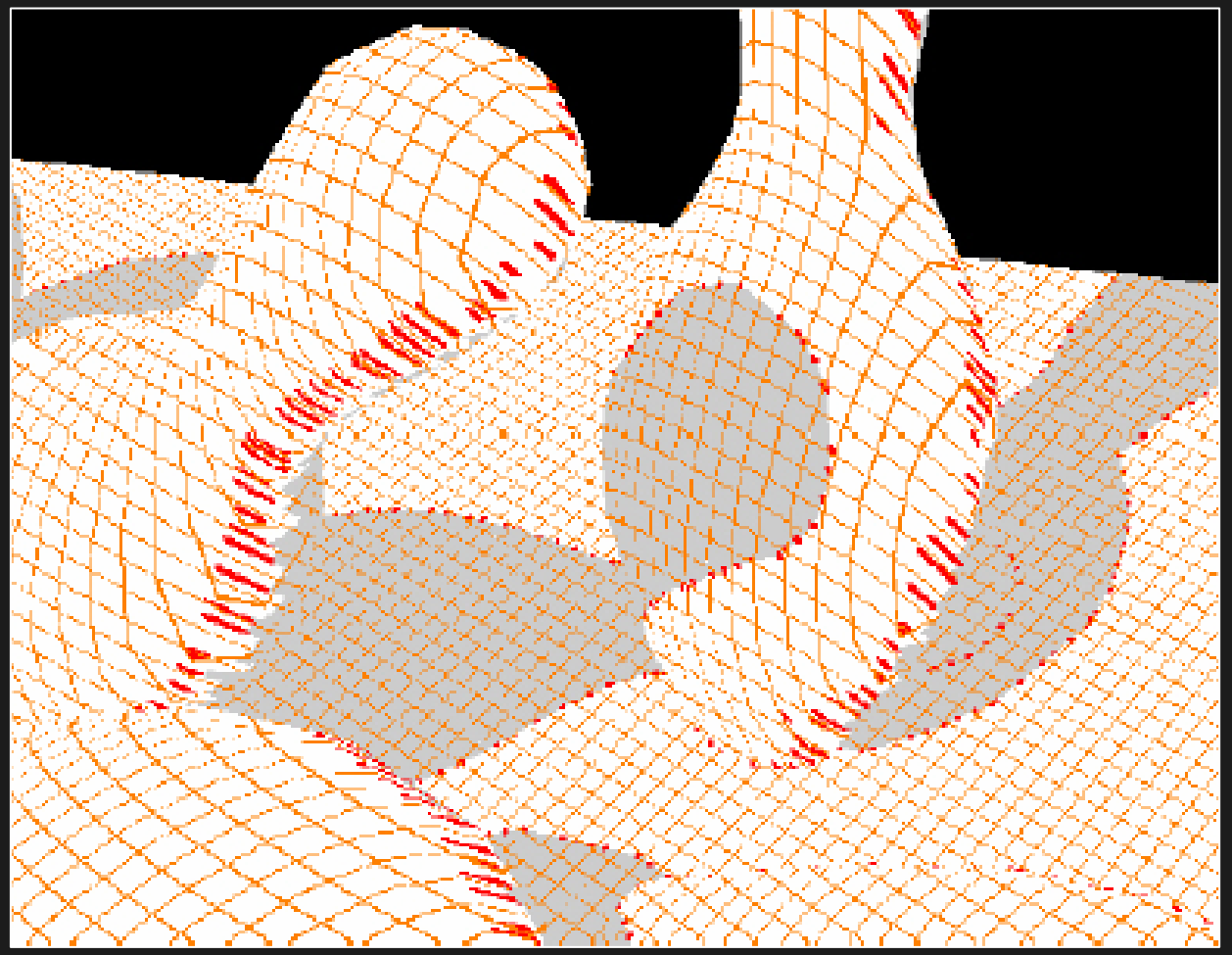
shadow maps shadow volumes **silhouette maps**

Example 2



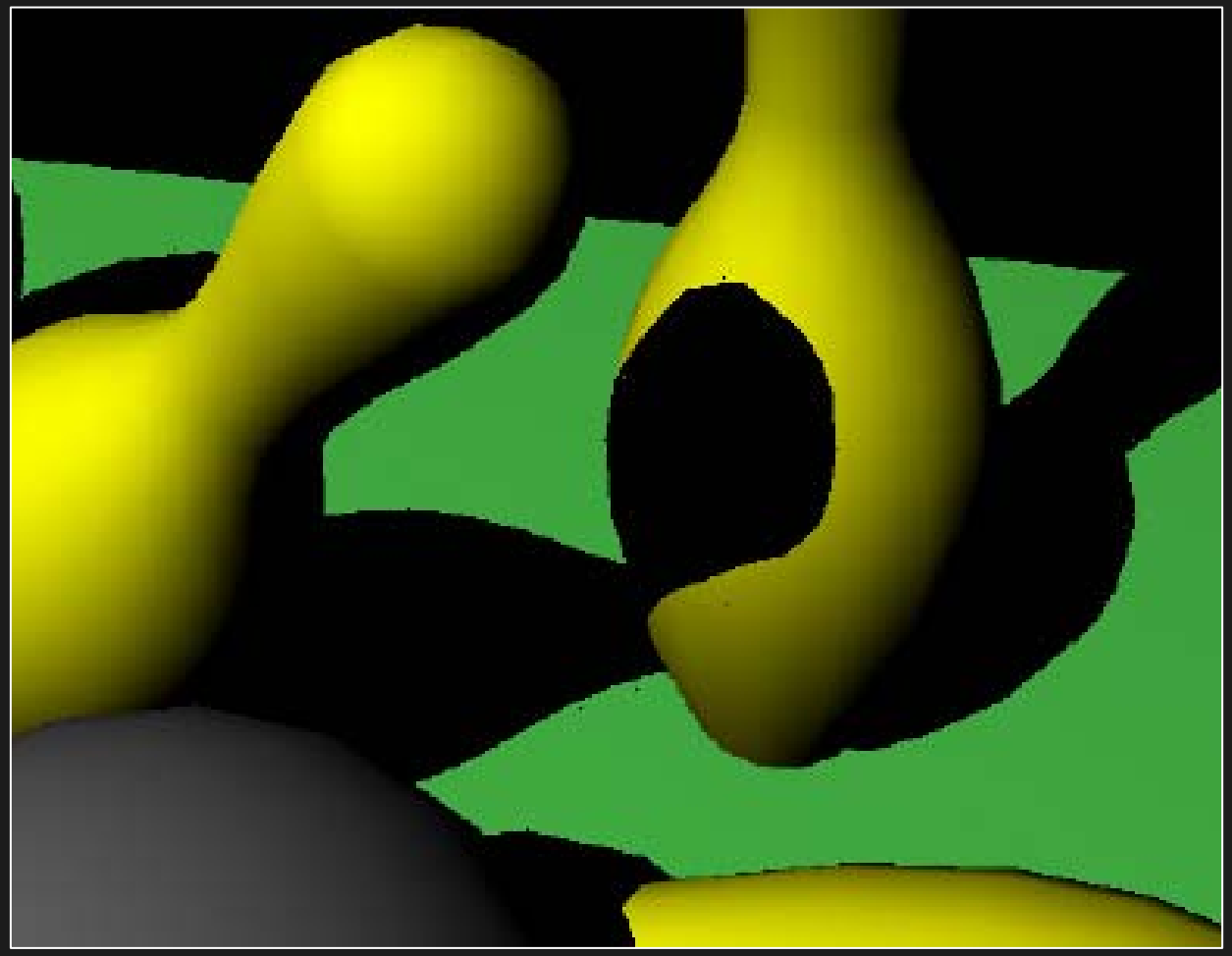
shadow maps

Example 2



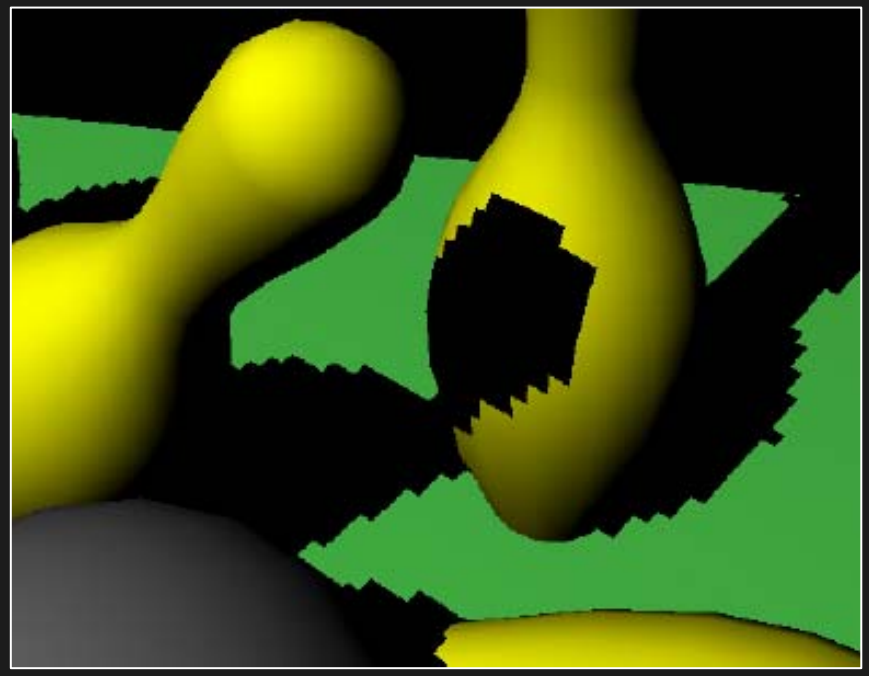
projected silhouette map

Example 2

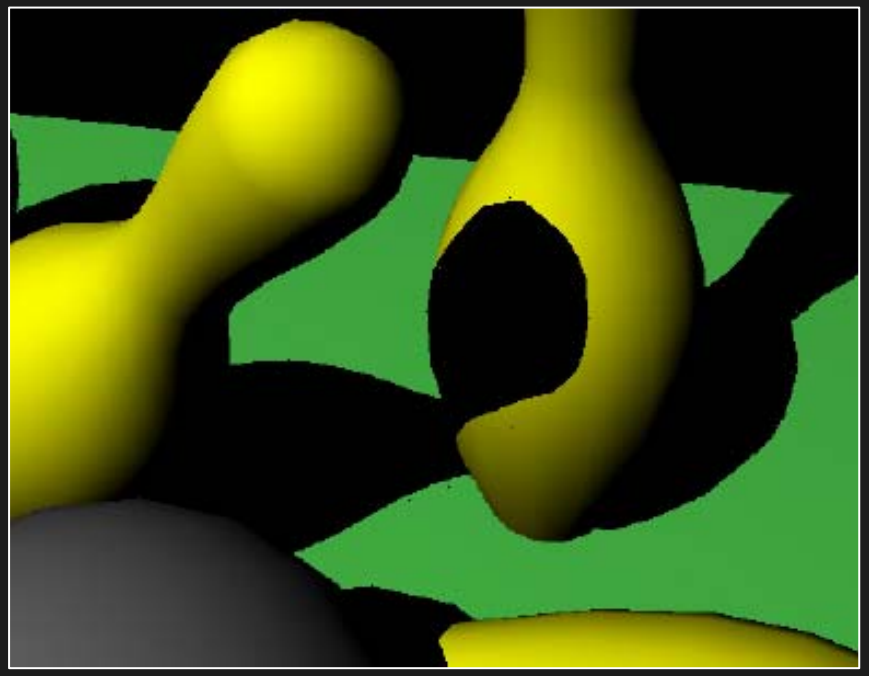


shadows using silhouette map

Quality Comparison



shadow map

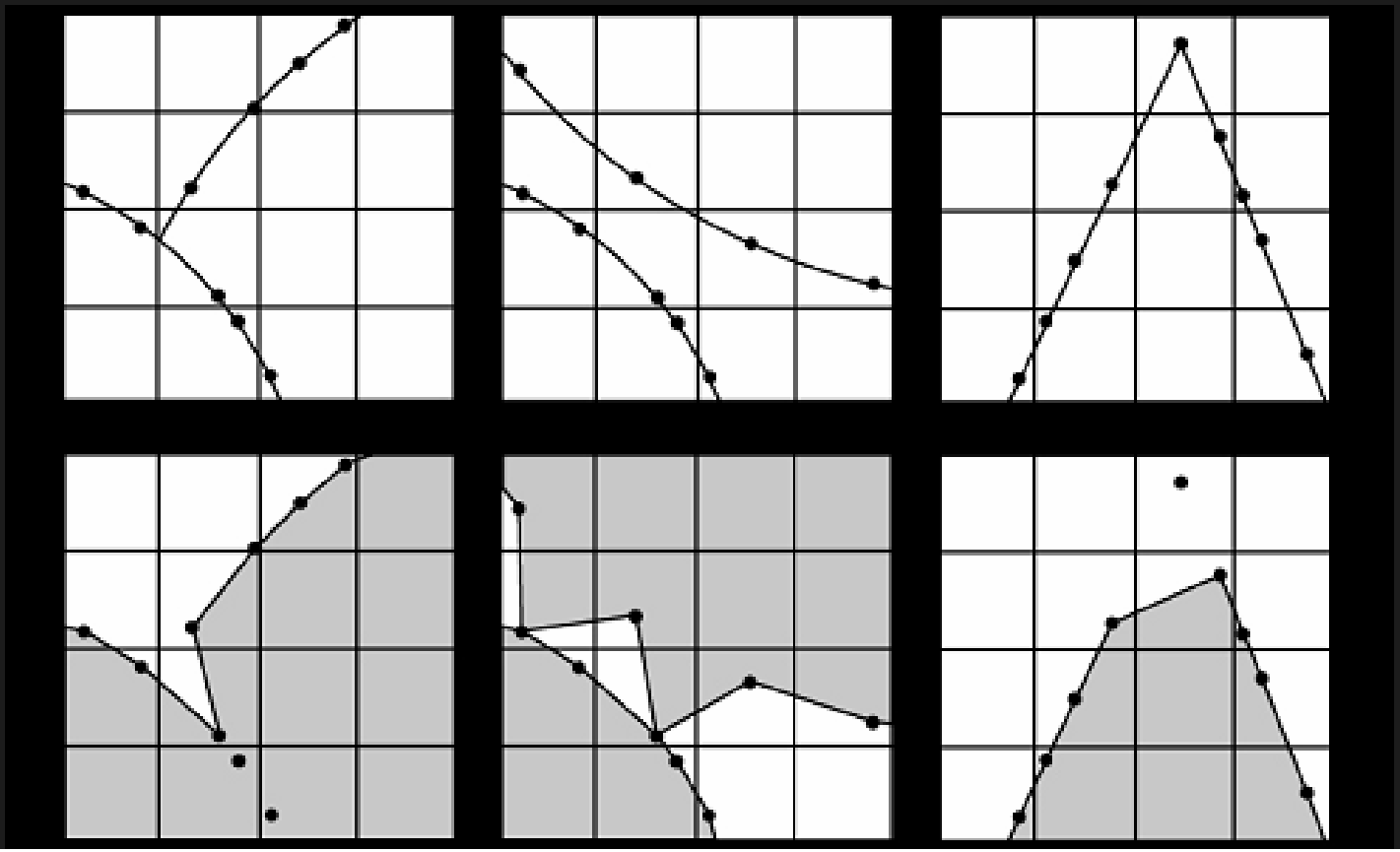


silhouette map

Artifacts

Silhouette map: one point per texel

Multiple edges inside a texel



Artifacts

shadow maps

shadow volumes

silhouette maps

Artifacts (closeup)

Artifacts due to multiple edges

More noticeable when animated

shadow maps

shadow volumes

silhouette maps

Algorithm Comparison

Perspective Shadow Maps:

- same generality as shadow maps
- minimal overhead (2 passes)
- doesn’t address aliasing in all cases

Shadow Silhouette Maps:

- addresses aliasing more generally
- more overhead (3 passes + big shaders)
- less general than shadow maps

Combination of Algorithms

Why not combine techniques?

Perspective shadow map:
Optimizes depth sample distribution
More samples closer to viewer

Shadow silhouette map:
Optimizes depth sample information
Exact silhouette edge locations

Summary

Image-space algorithm
Silhouette map: deformed depth map
Piecewise-linear approximation
Scalable

Compared to (perspective) shadow maps:
Removes aliasing in more cases
Additional overhead and requirements

An Efficient Hybrid Shadow Rendering Algorithm

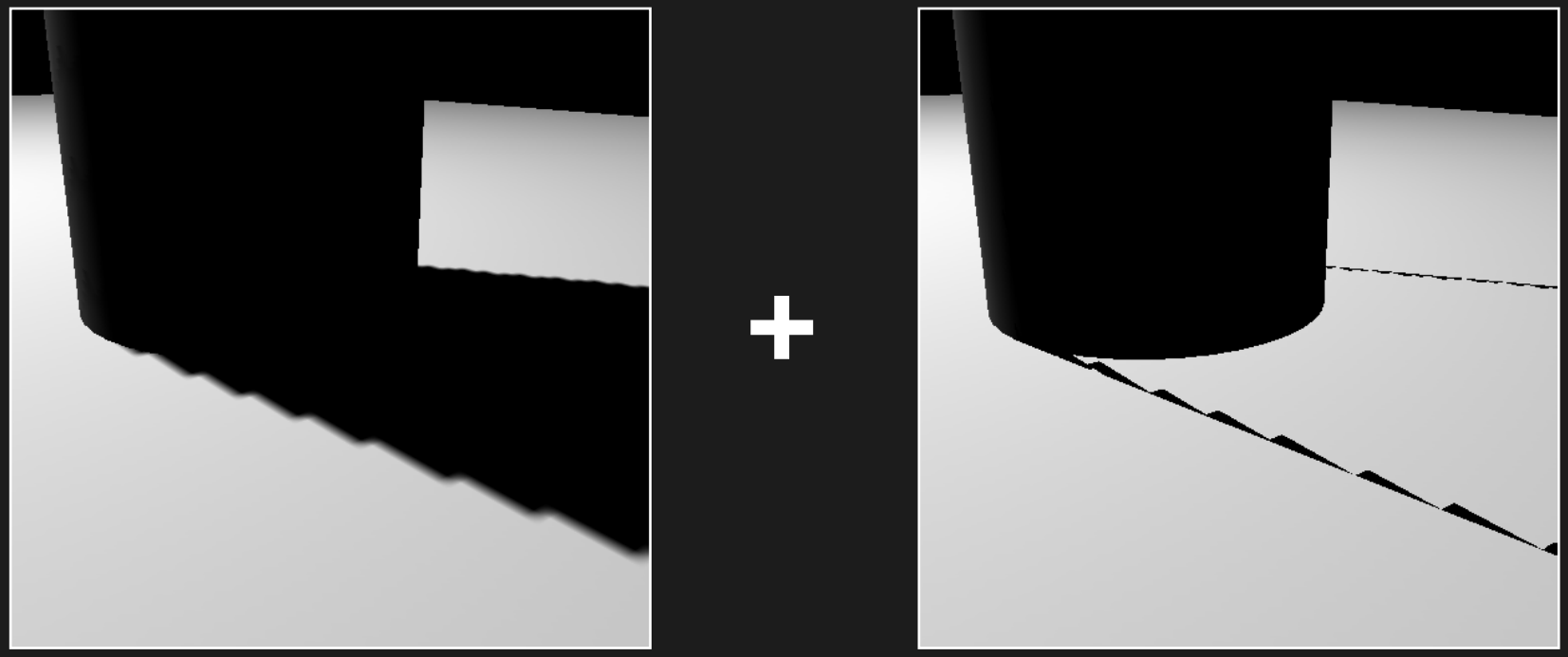
Eric Chan
Fedro Durand

EGSR 2004

Not Another Talk on Shadows?!

Main ideas:

- combination of shadow maps + shadow volumes
- computation masks



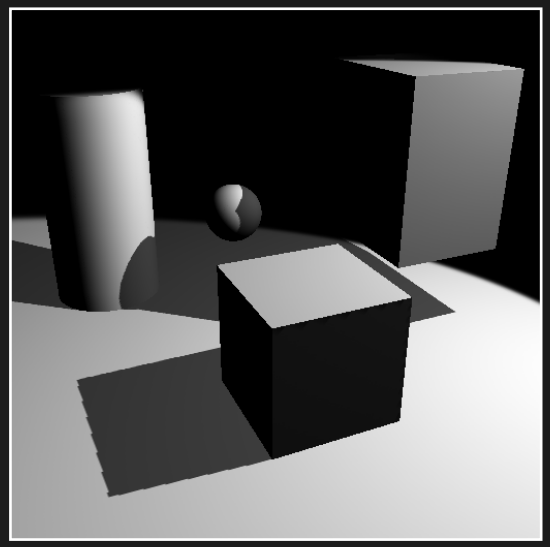
Fillrate Problem

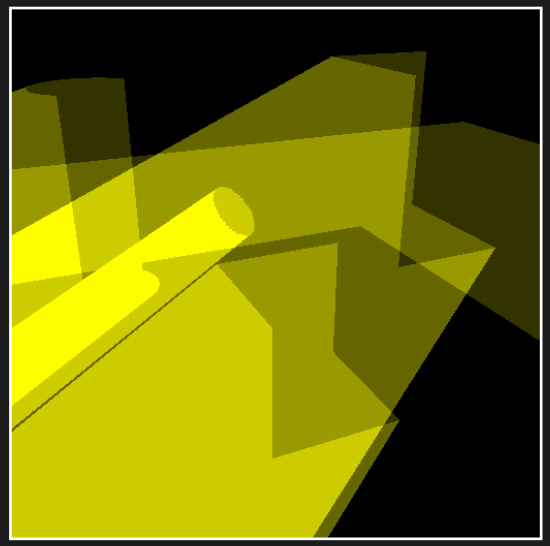
Lots and lots of fillrate!

- rasterization
- stencil updates

Why?

- polygons have large screen area
- polygons overlap





Fillrate Problem

Lots and lots of fillrate!

- rasterization
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Why?

- polygons have large screen area
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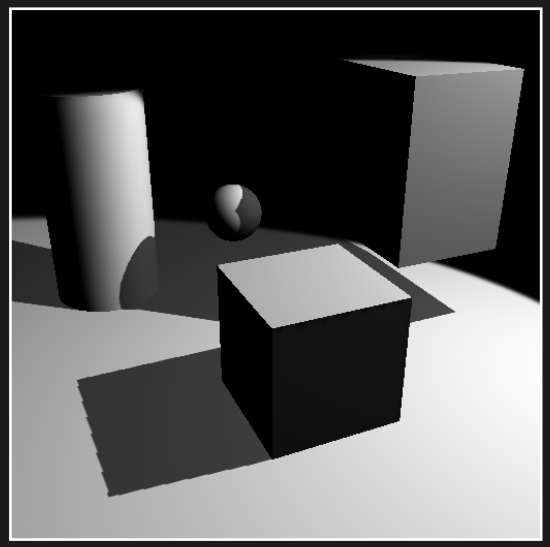
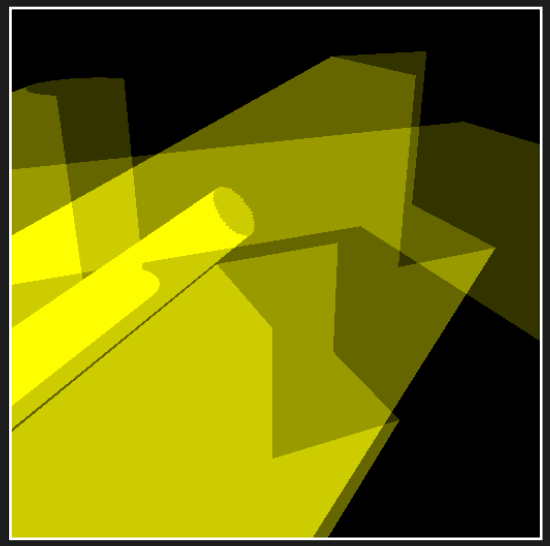
But is this really a problem?





But Is This *Really* A Problem?

Case study: Doom 3 engine (id Software)

- bump mapping
- per-pixel surface shading
- dynamic and projected lights
- atmospheric effects
- particle effects

} **50%**

- shadow volumes

} **50%**

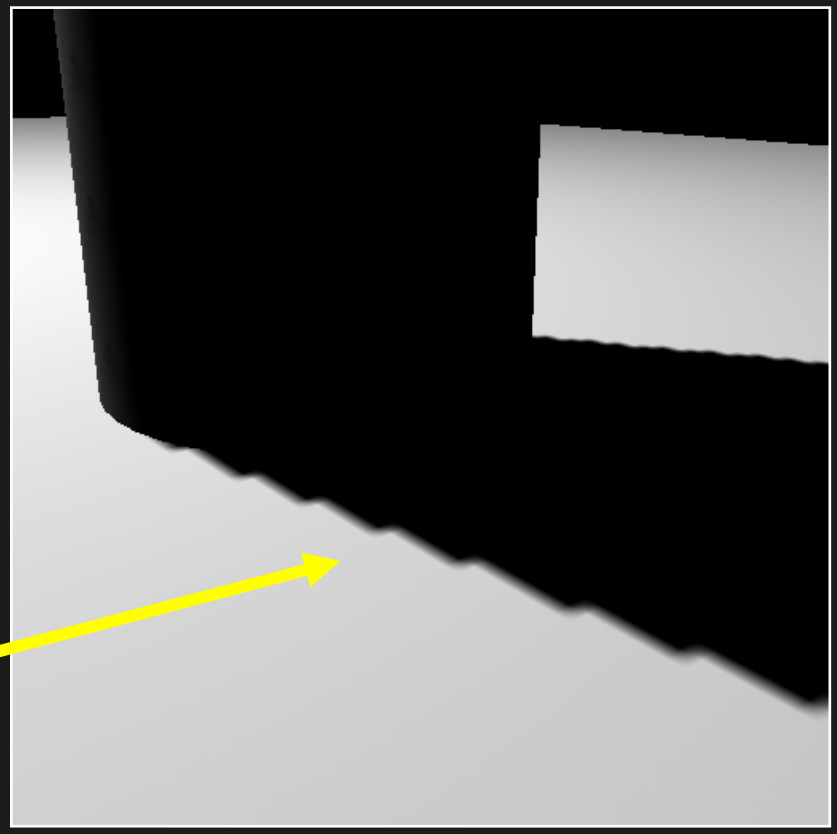
"Shadowing accounts for about half of the game's rendering time."

— John Carmack

Two Observations (shadow maps)

Shadow-map aliasing is ugly

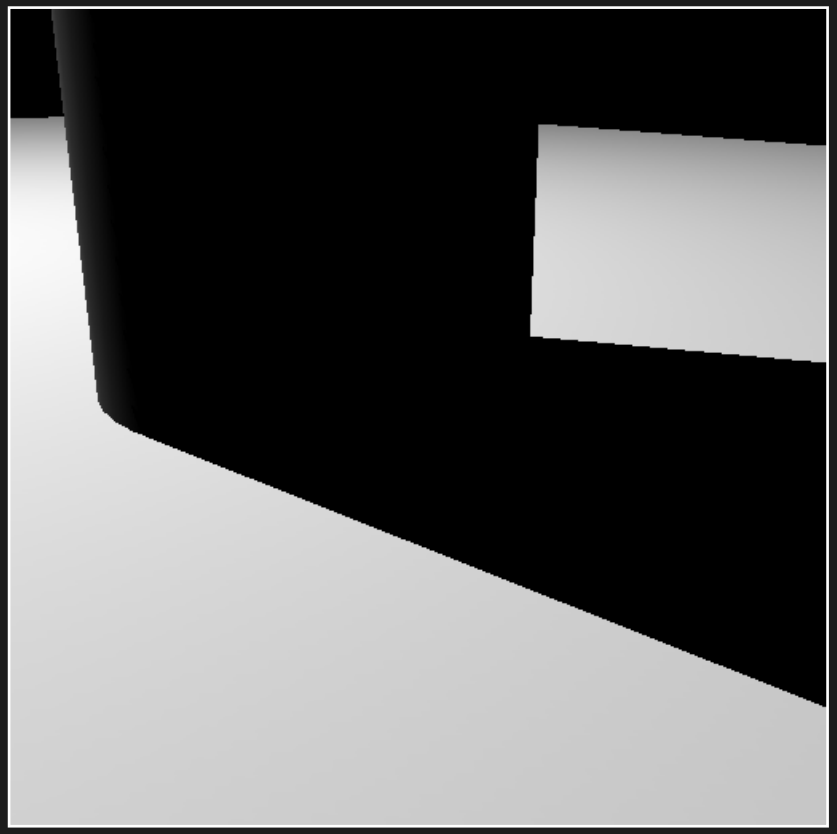
But — only noticeable at shadow silhouettes

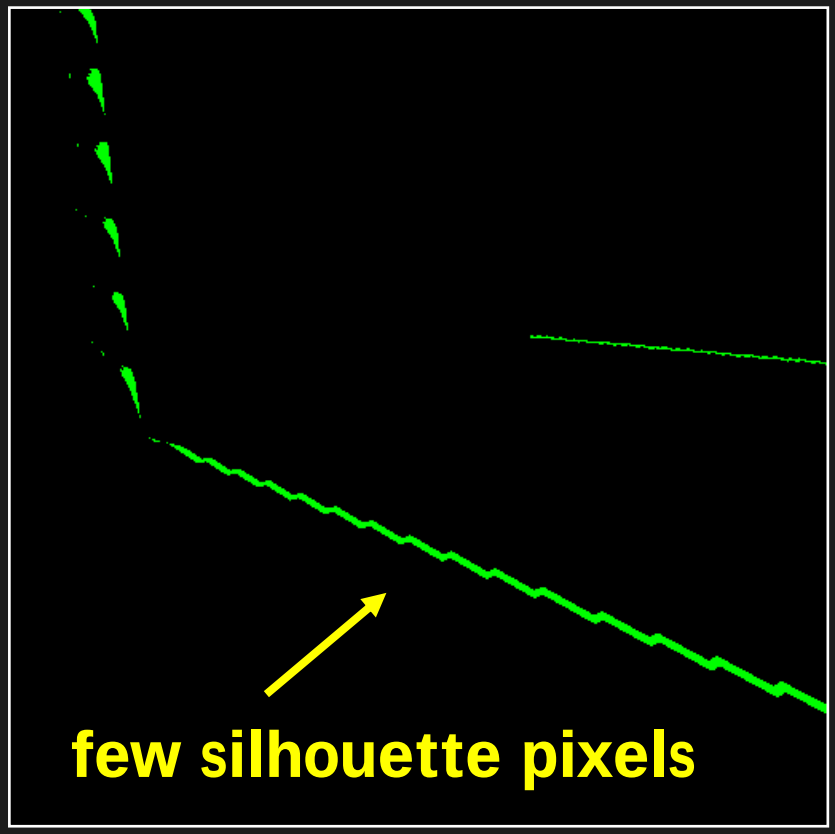


Two Observations (shadow volumes)

Shadow volumes are accurate everywhere

But — accuracy is only needed at silhouettes

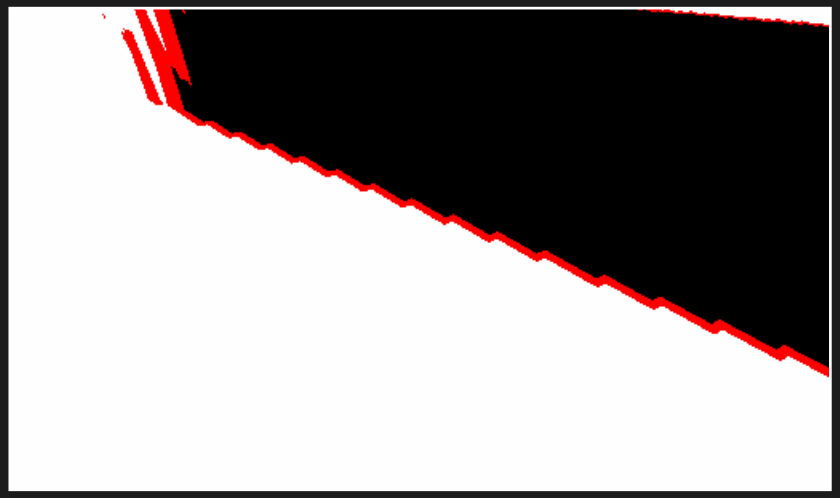




Hybrid Approach

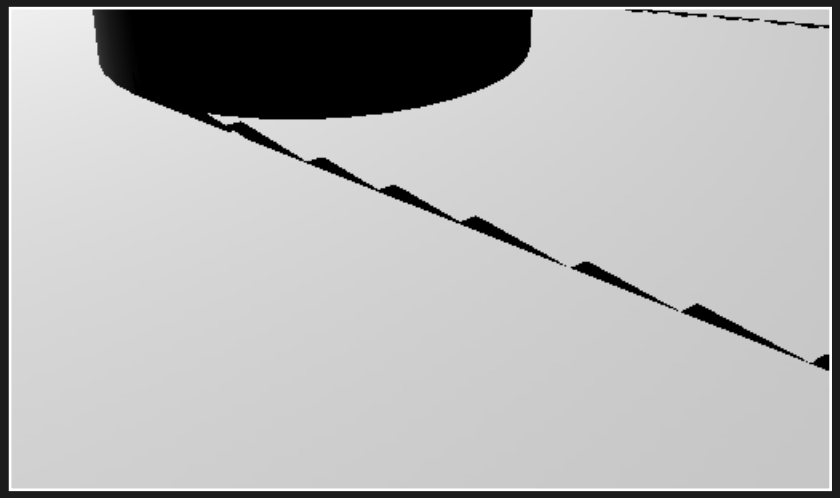
Decompose the problem:

- use shadow volumes at silhouettes
- use shadow maps everywhere else



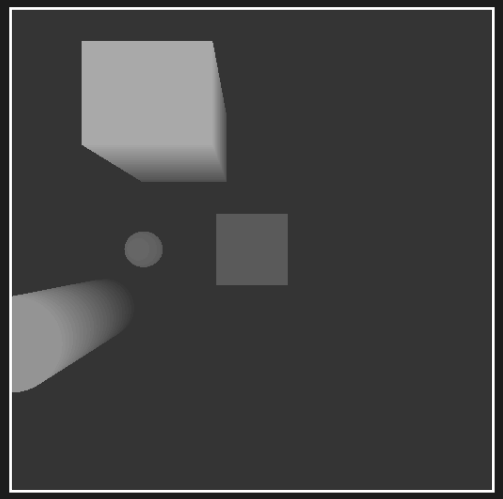
shadow map

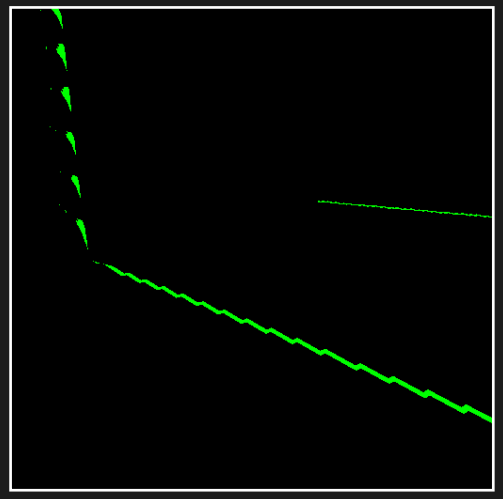
+

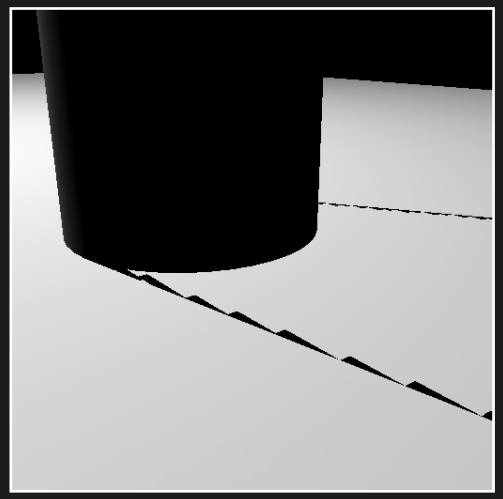


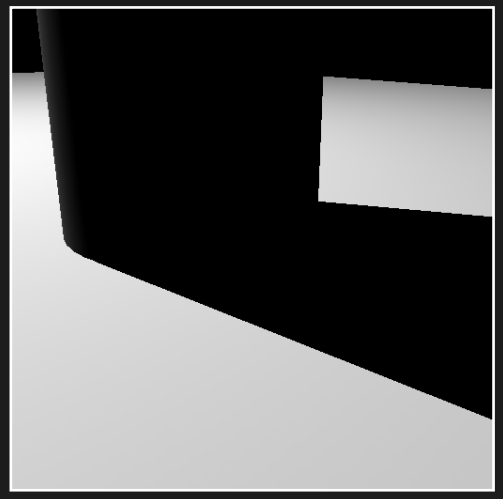
shadow volume

Algorithm

1. 

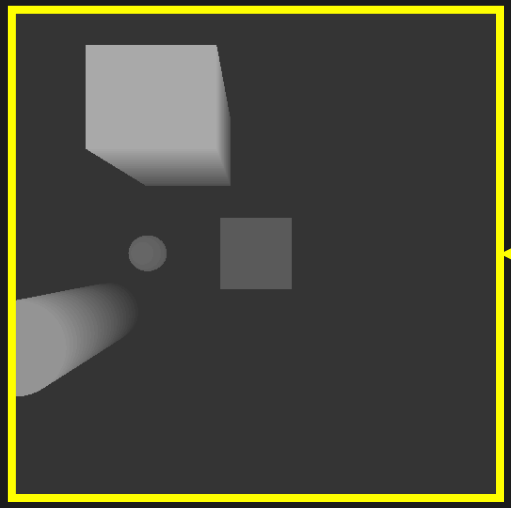
2. 

3. 

4. 

Algorithm

1.



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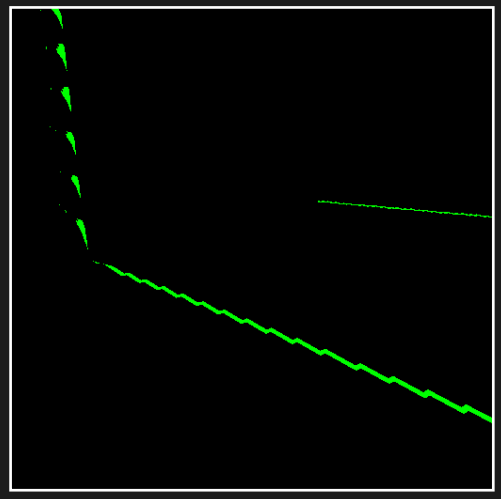

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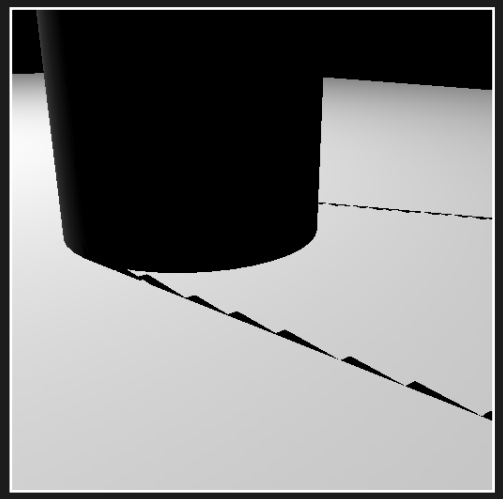

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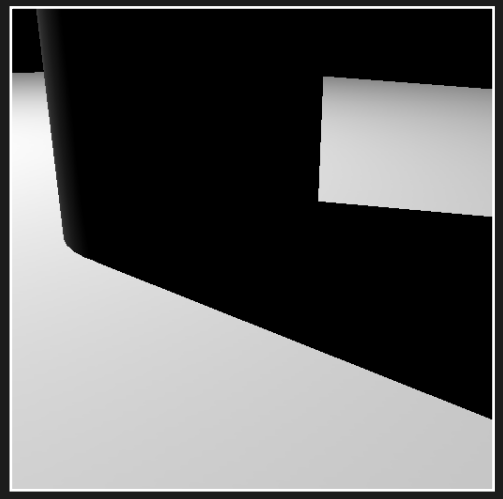
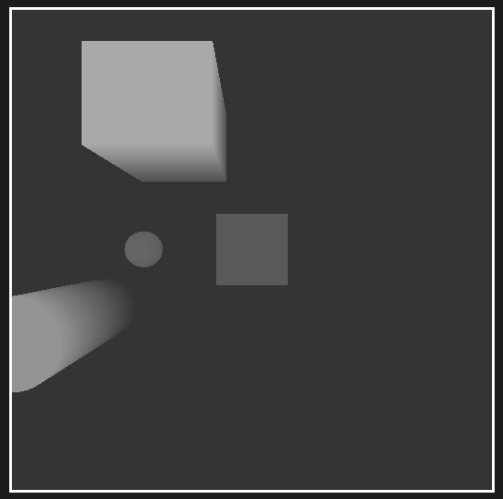


create a shadow map

Algorithm

1.



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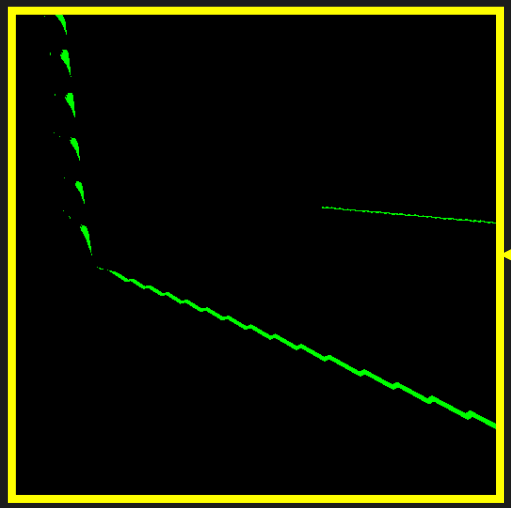

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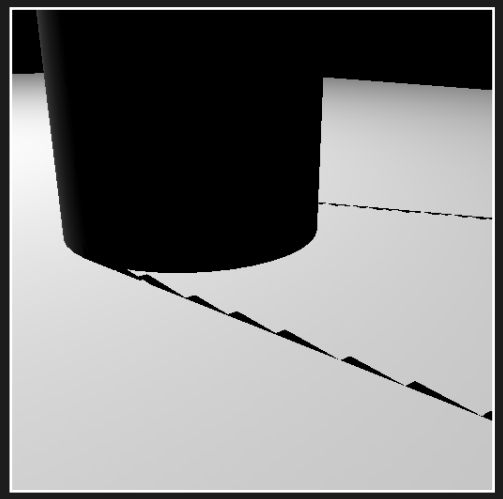

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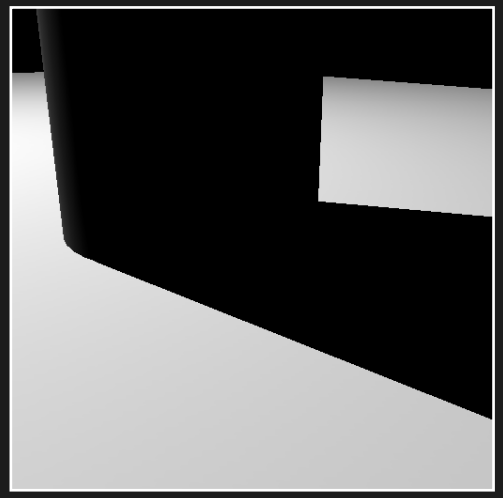
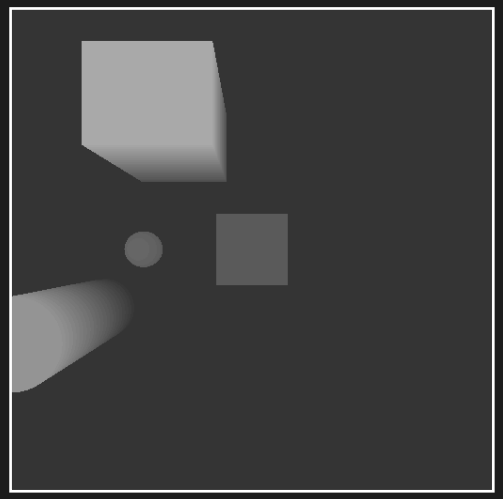


find silhouette pixels

Algorithm

1.



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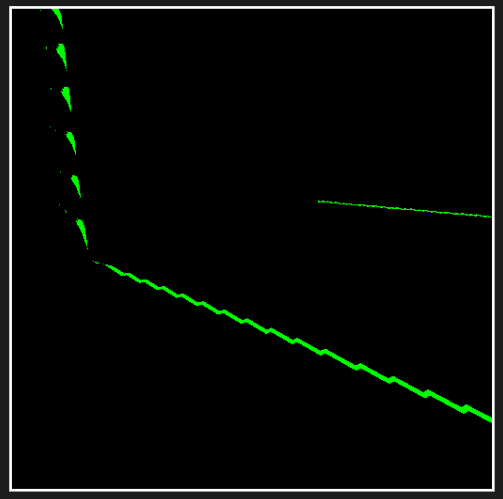

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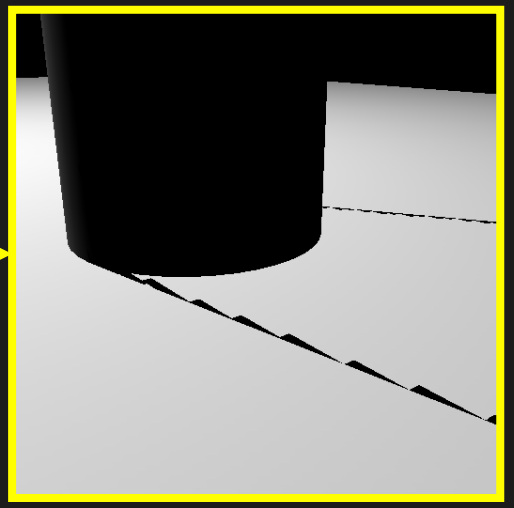
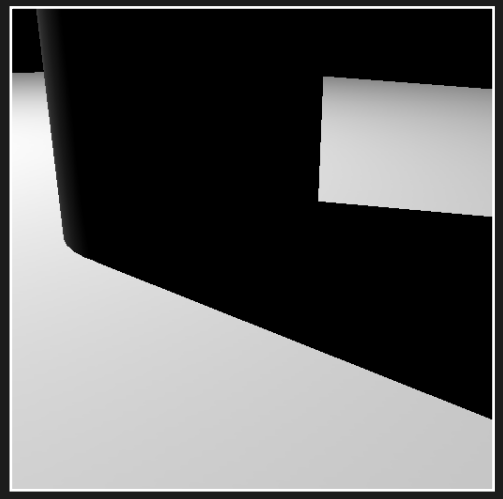
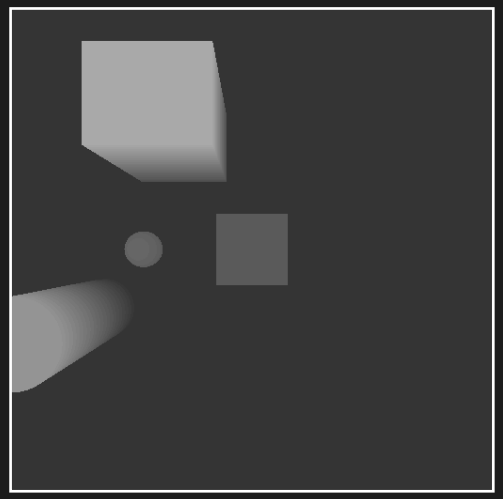


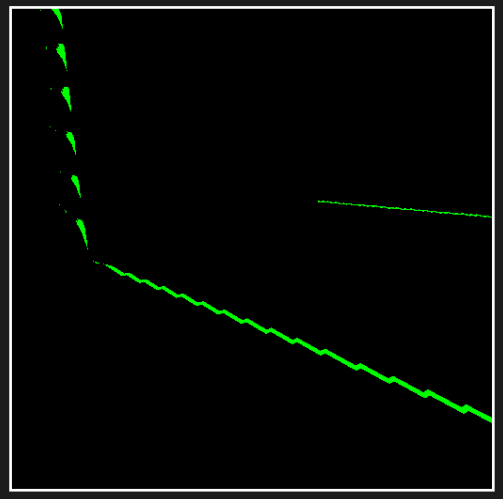
4.

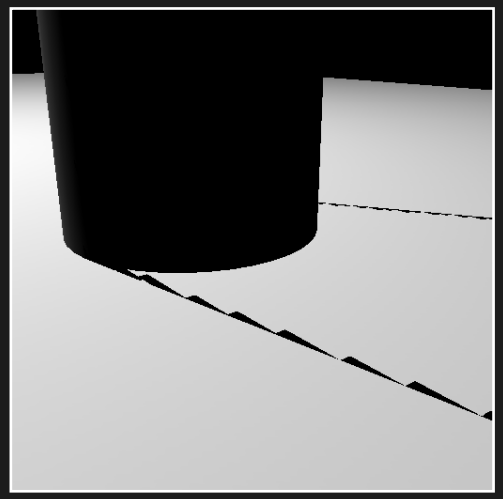


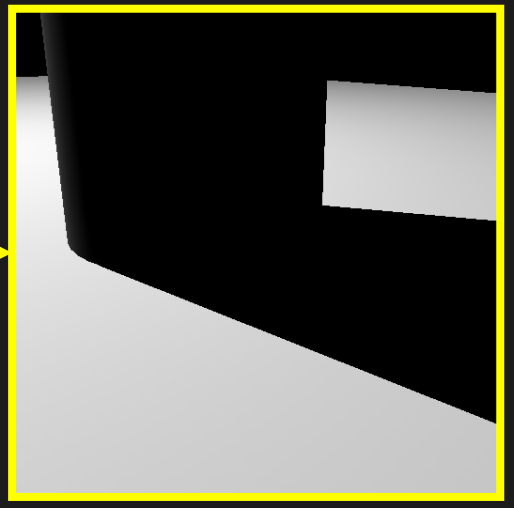
apply shadow volumes only at silhouette pixels

Algorithm

1. 

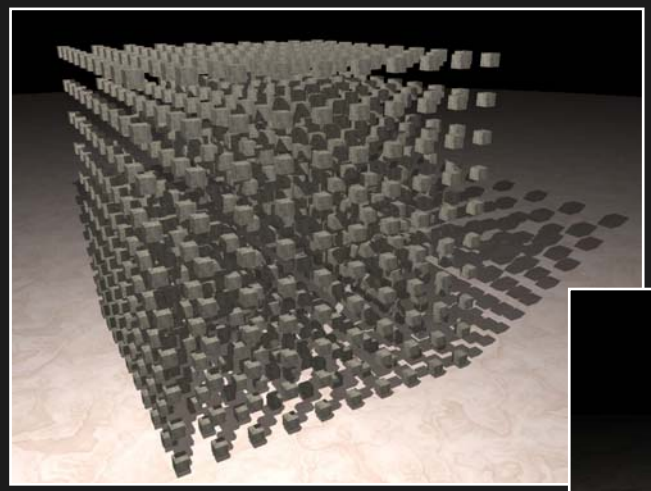
2. 

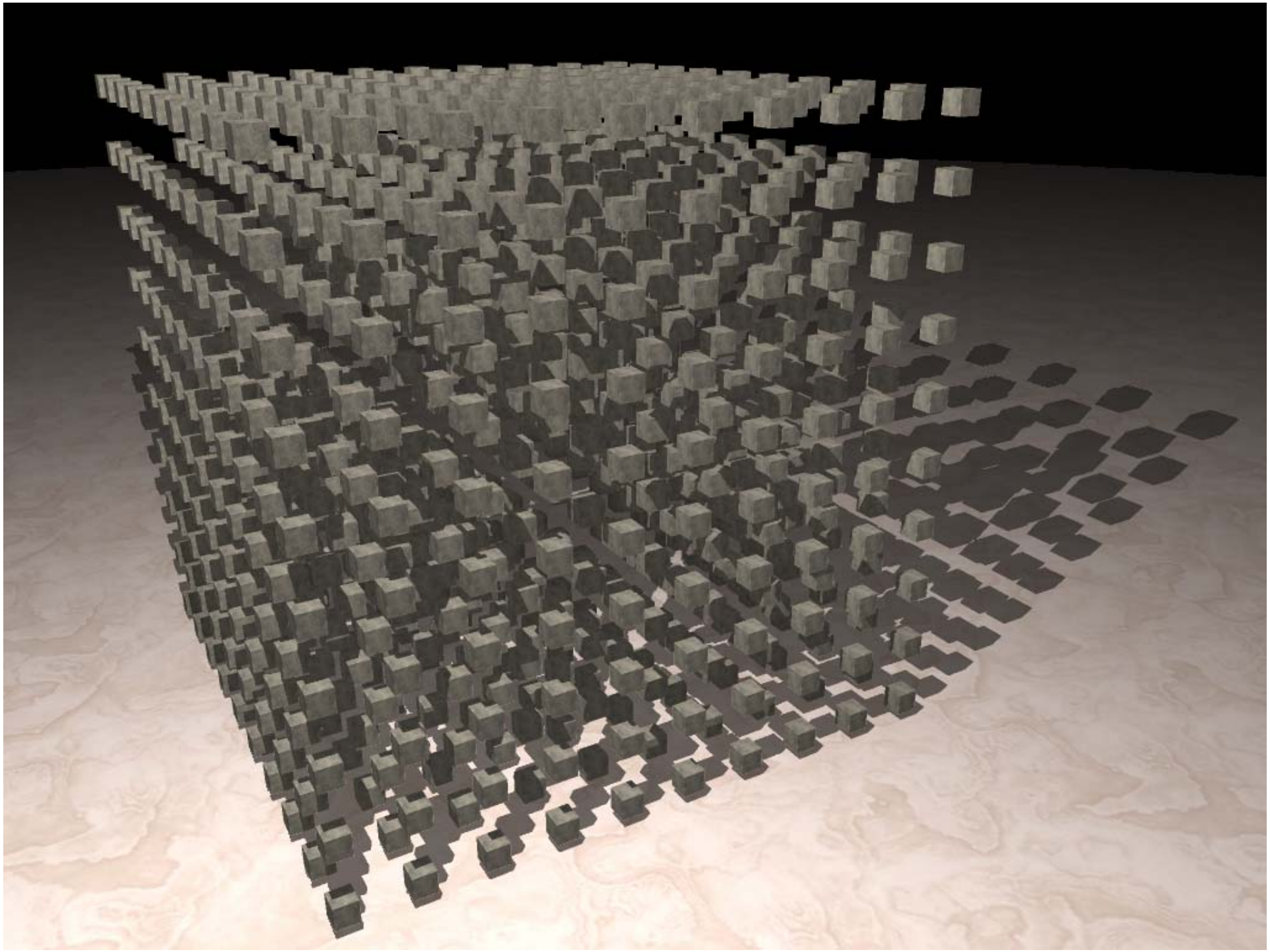
3. 

4. 

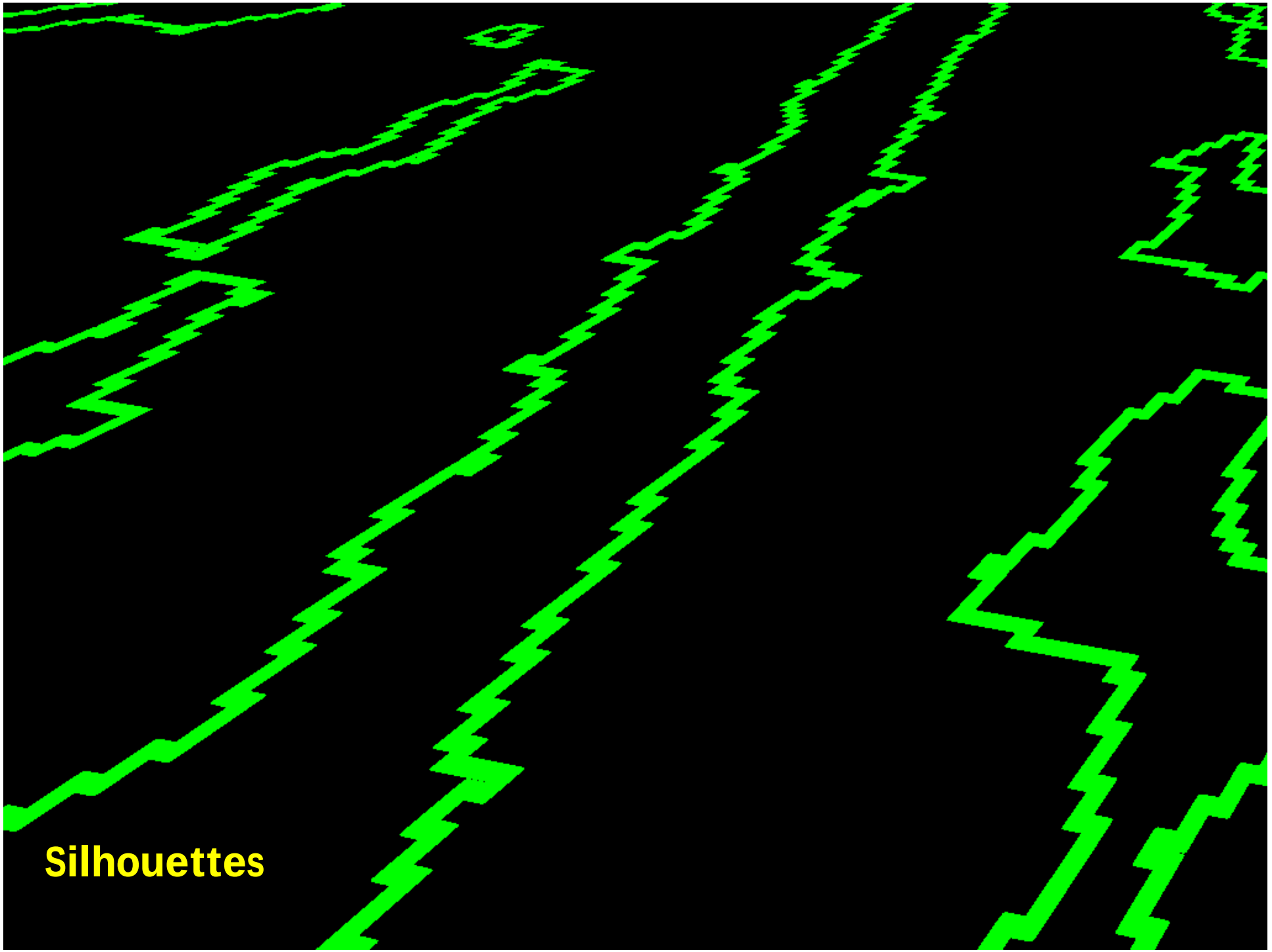
apply shadow maps everywhere else

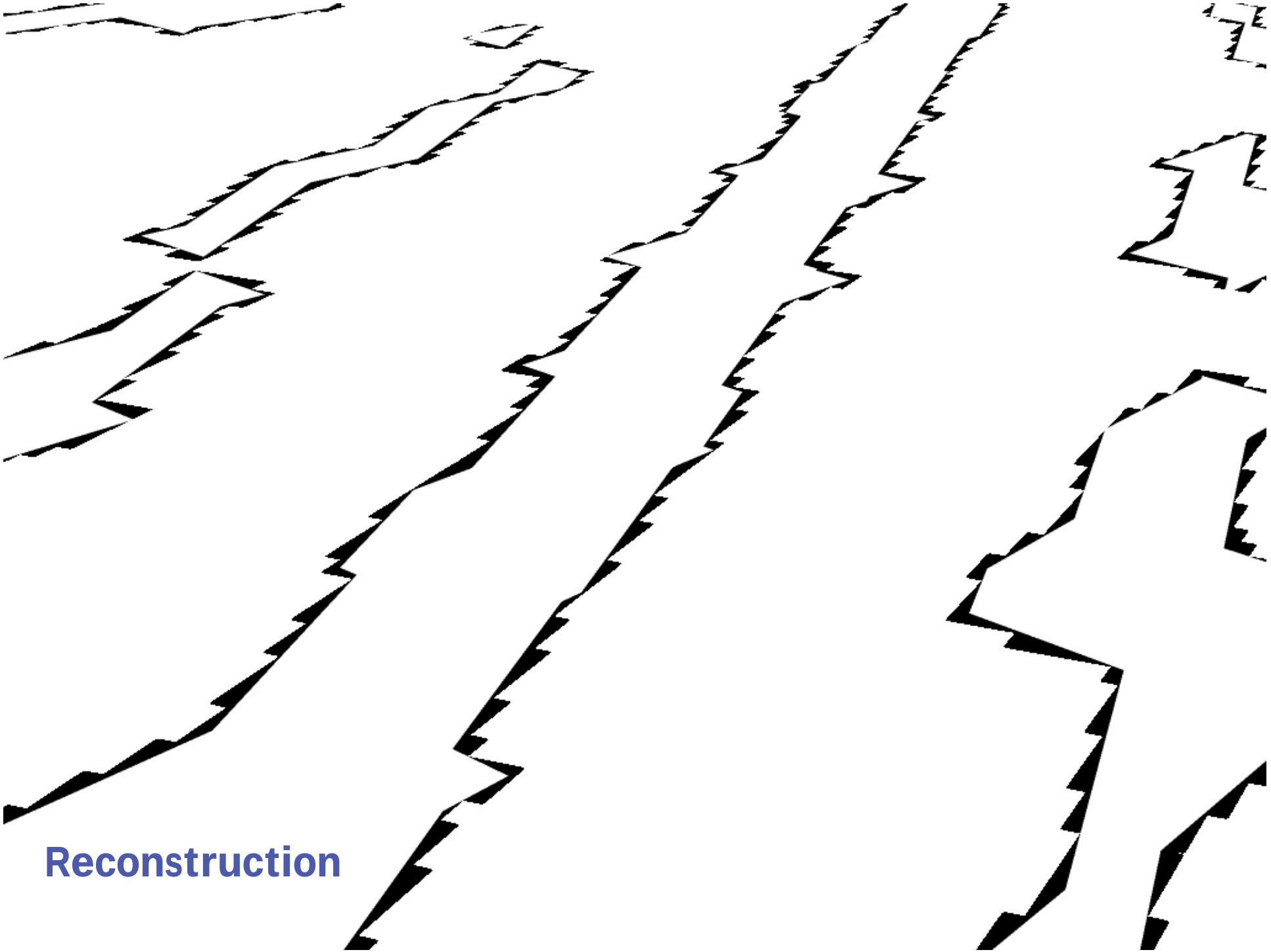
Test Scenes

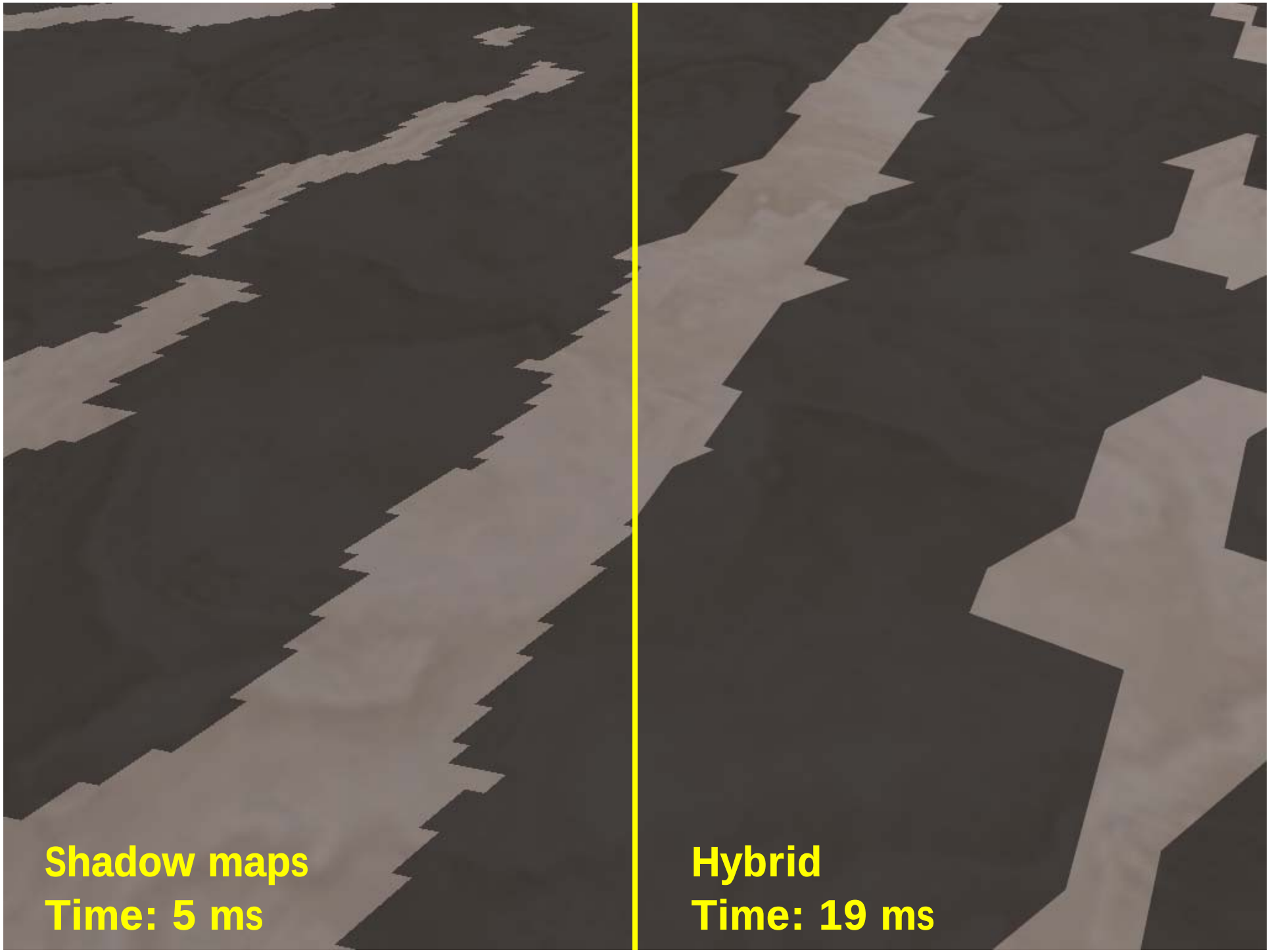


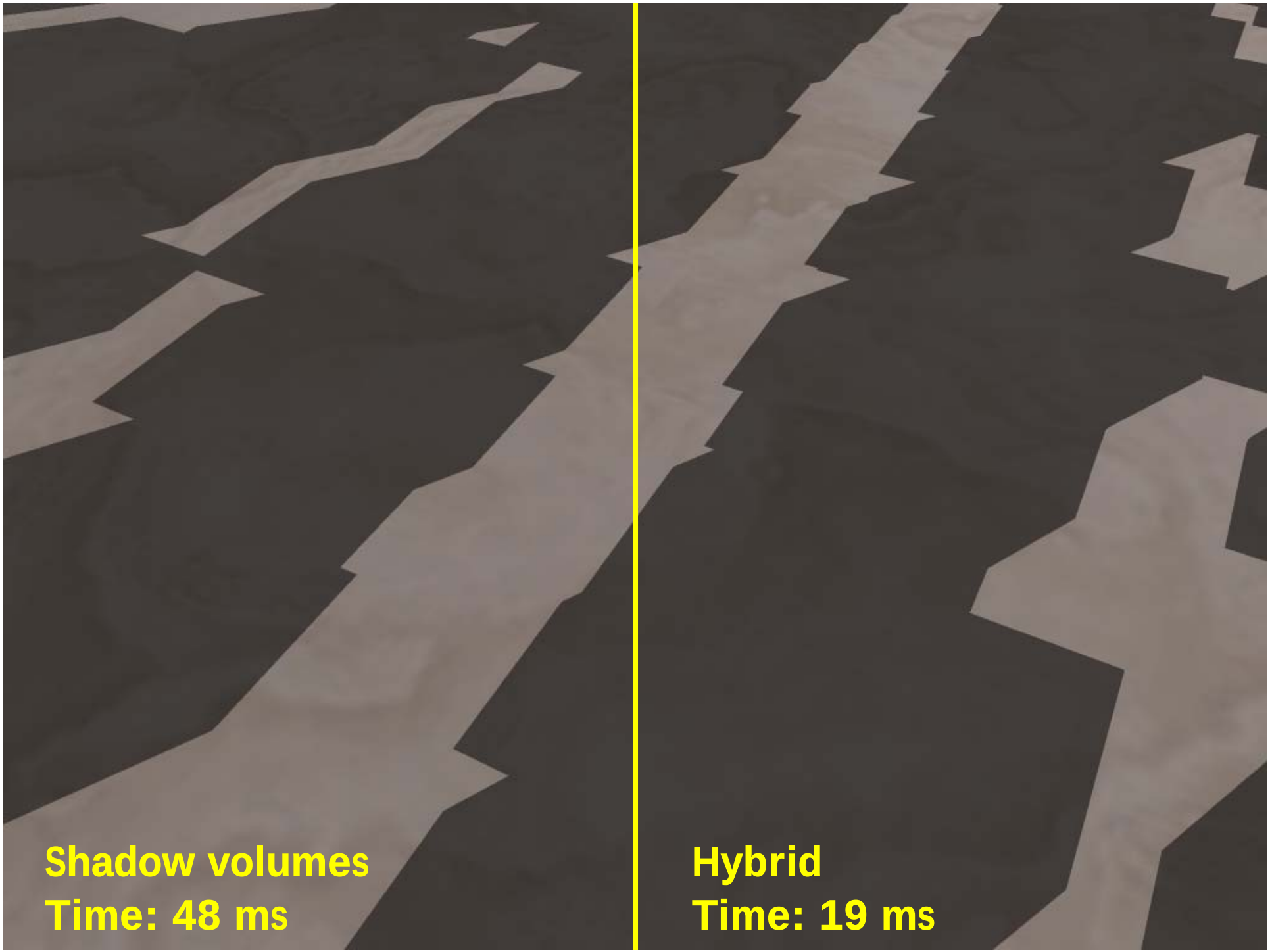



Shadow maps


Silhouettes


Reconstruction


Shadow maps
Time: 5 ms
Hybrid
Time: 19 ms


Shadow volumes
Time: 48 ms
Hybrid
Time: 19 ms