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NVIDIA

PRACTICAL REAL-TIME VOXEL-BASED GLOBAL ILLUMINATION FOR CURRENT GPUS

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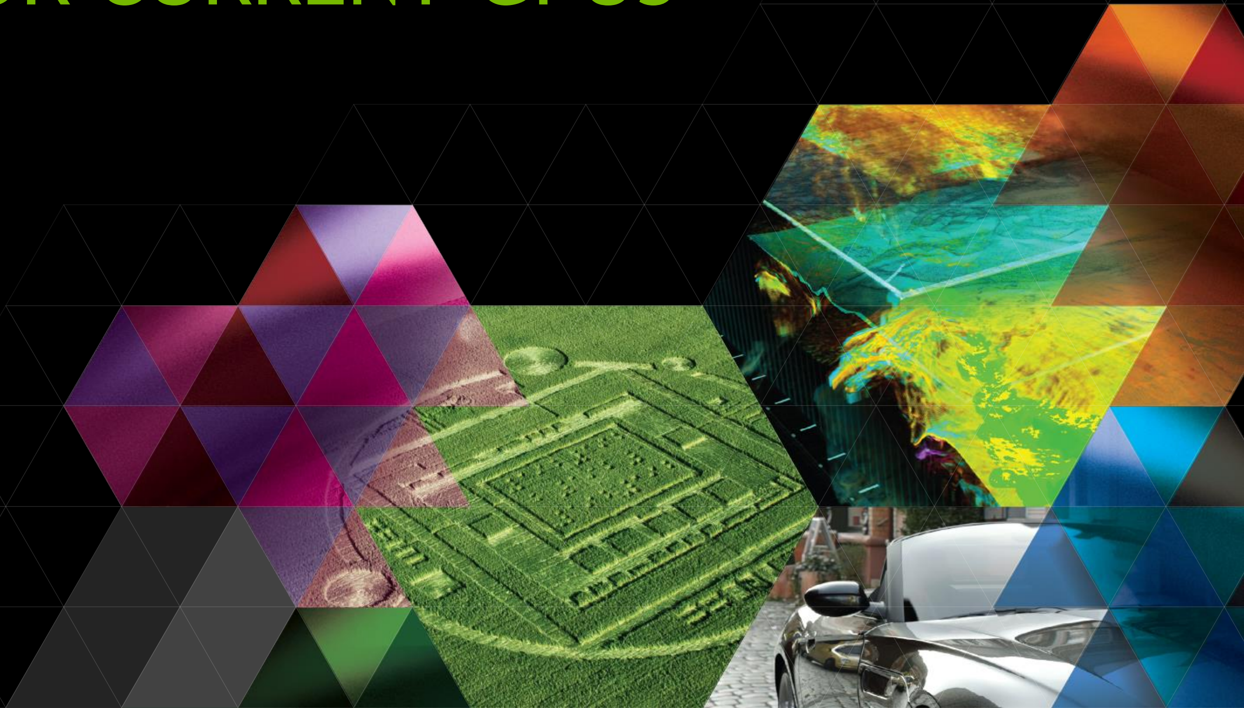
NVIDIA



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OUTLINE

- Introduction: what is Global Illumination?
- Screenshots
- Overview of Voxel Cone Tracing

- Our main innovation: 3D clipmap
- Implementation details
- Performance

WHAT IS GLOBAL ILLUMINATION?

Here is a flashlight that lights the floor.

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Light bounces off the floor
and hits the surrounding objects.

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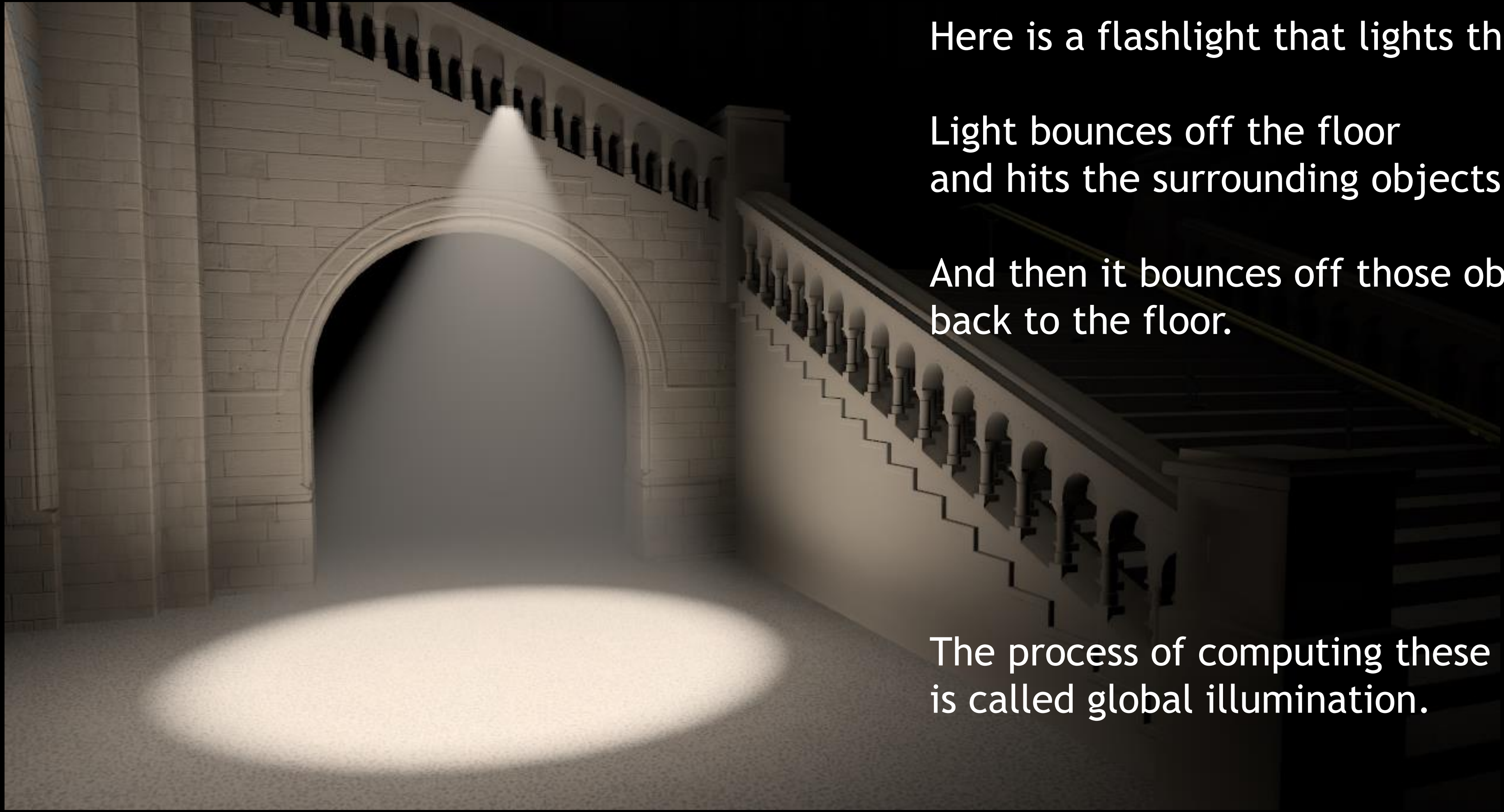


Here is a flashlight that lights the floor.

Light bounces off the floor
and hits the surrounding objects.

And then it bounces off those objects
back to the floor.

The process of computing these bounces
is called global illumination.

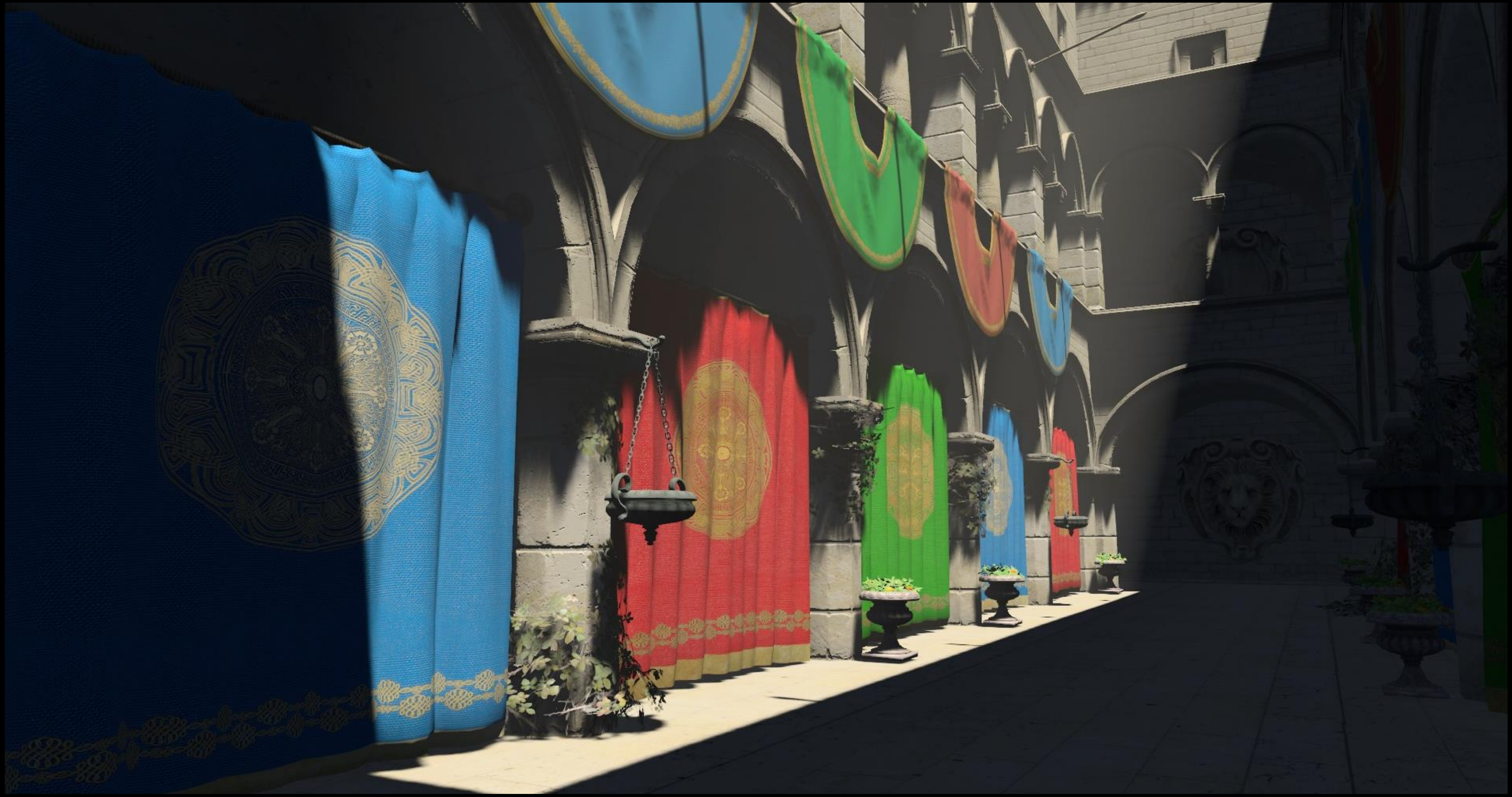
HOW IT IS USUALLY SOLVED

- Accurate physics-based GI computation is extremely expensive
- Static approximations
  - Flat ambient
  - Light maps
- Dynamic approximations
  - Manually placed lights simulating indirect illumination
  - Virtual Point Lights - expensive, no occlusion
  - SH irradiance volumes, Light propagation volumes - no specular
  - Image-space approaches - incomplete scene information
  - Sparse Voxel Octree Global Illumination (SVOGI) - doesn't handle dynamic or large scenes well

OUR SOLUTION

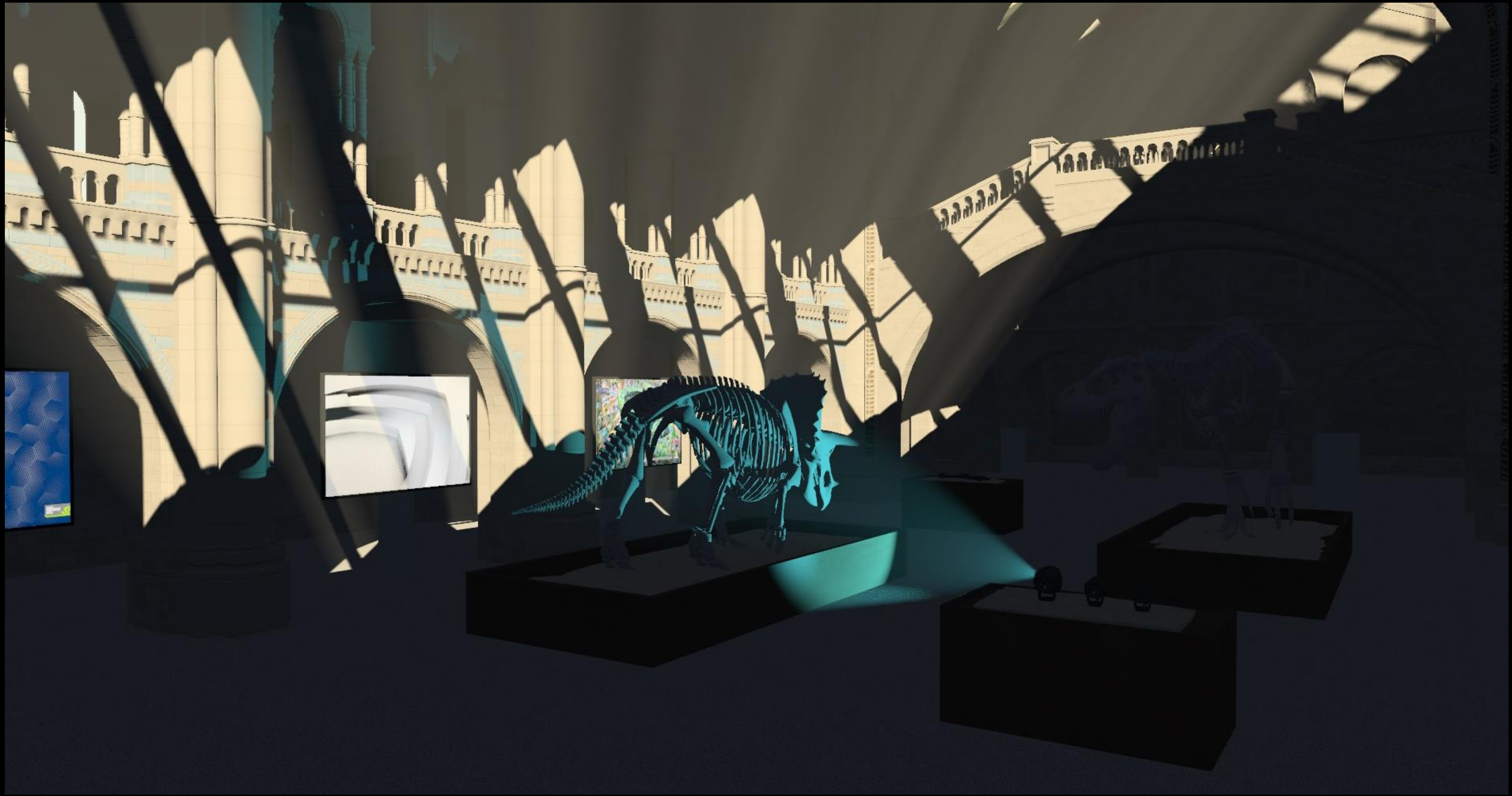
- Dynamic approximation
  - No offline pre-computations
  - Handles dynamic scenes easily
- Voxel Cone Tracing
  - “Interactive Indirect Illumination Using Voxel Cone Tracing” by Cyril Crassin, Fabrice Neyret, Miguel Sainz, Simon Green, Elmar Eisemann
- Gathering information from a multi-resolution voxel representation of the scene

SCREENSHOTS: DIRECT LIGHTING

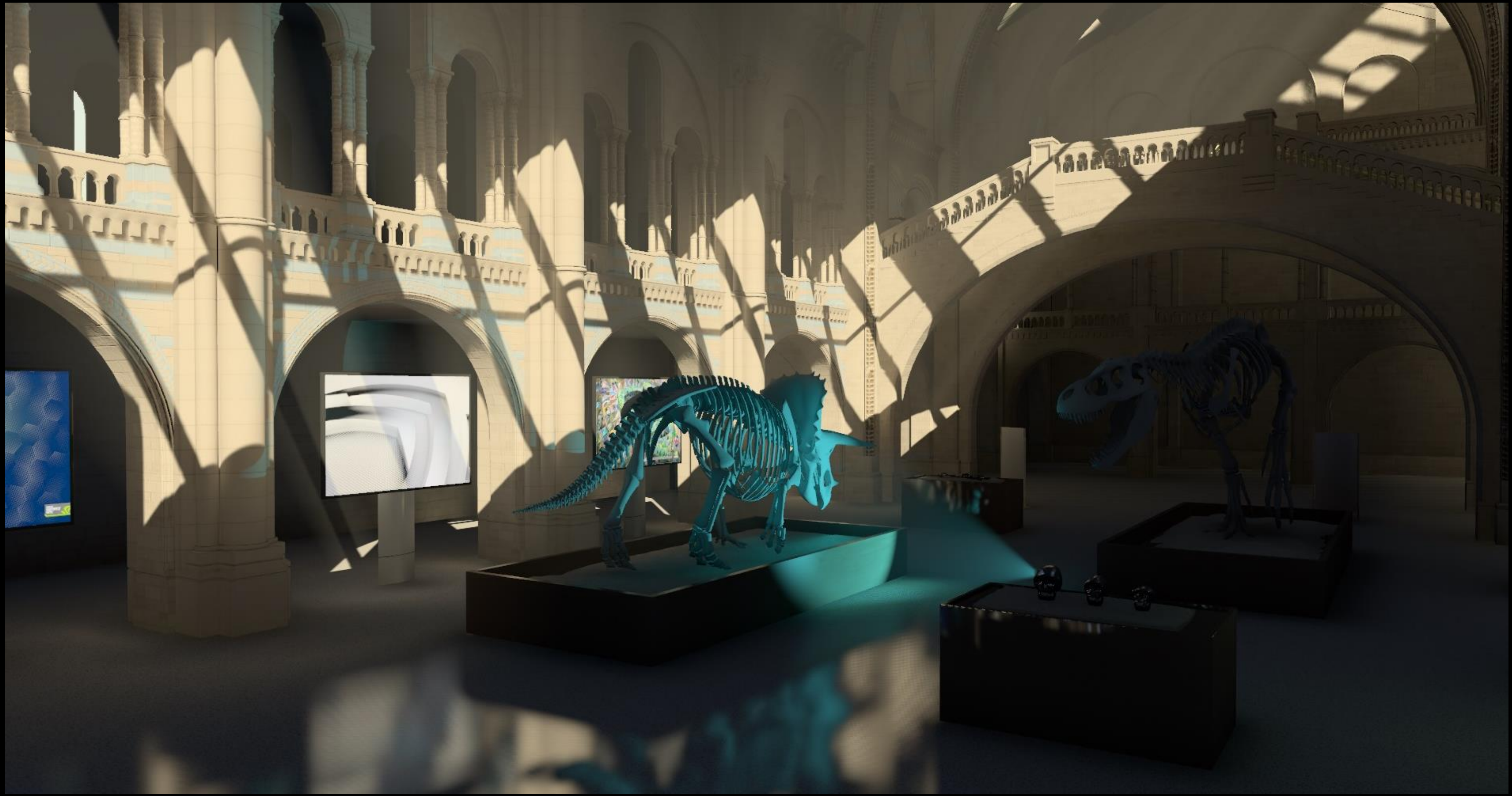


SCREENSHOTS: GI

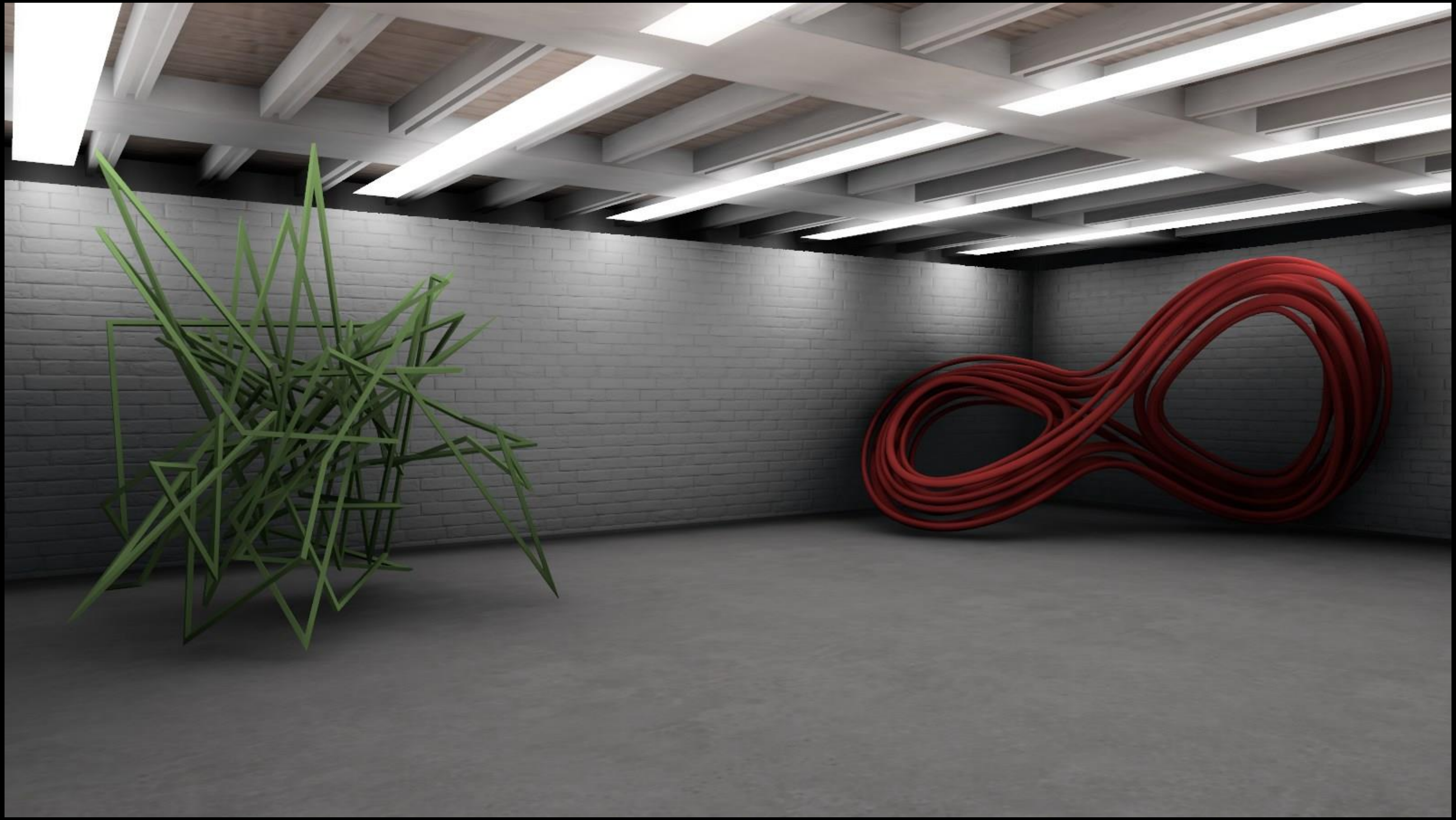
SCREENSHOTS: DIRECT LIGHTING



SCREENSHOTS: GI



SCREENSHOTS: AREA LIGHTS



SCREENSHOTS: FLAT AMBIENT

SCREENSHOTS: SSAO (HBAO+)

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SCREENSHOTS: VOXEL-BASED AMBIENT

The volumetric structure of the scene becomes obvious.

OVERVIEW OF VOXEL CONE TRACING

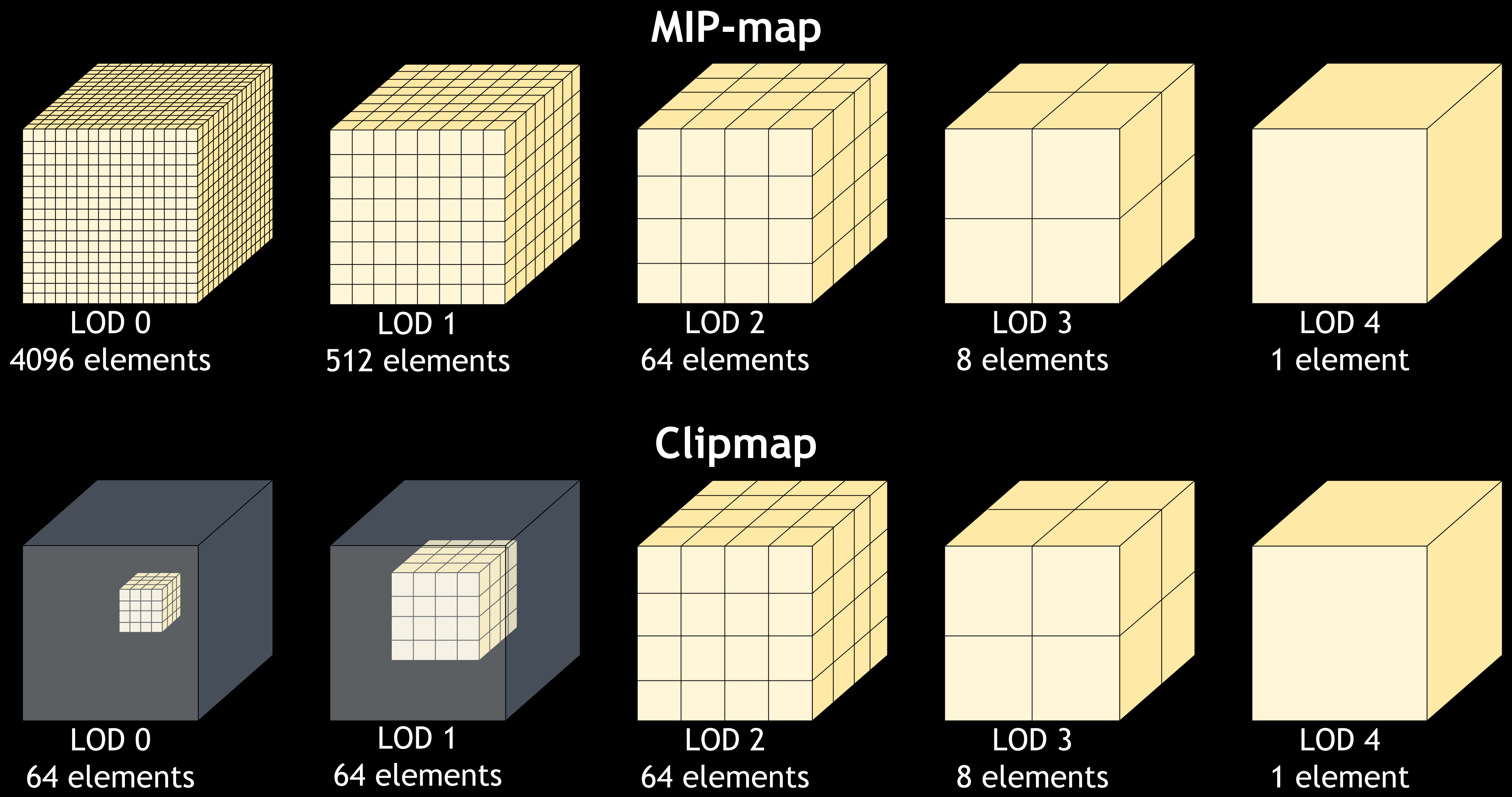
- Transform the scene into voxels that encode opacity
  - Then downsample the opacity map
- Render reflective shadow maps (RSMs)
- Translate RSMs into another voxel map encoding emittance
  - Then downsample the emittance map
- Gather light by tracing cones through the opacity and emittance maps

OUR INNOVATION: 3D CLIPMAP

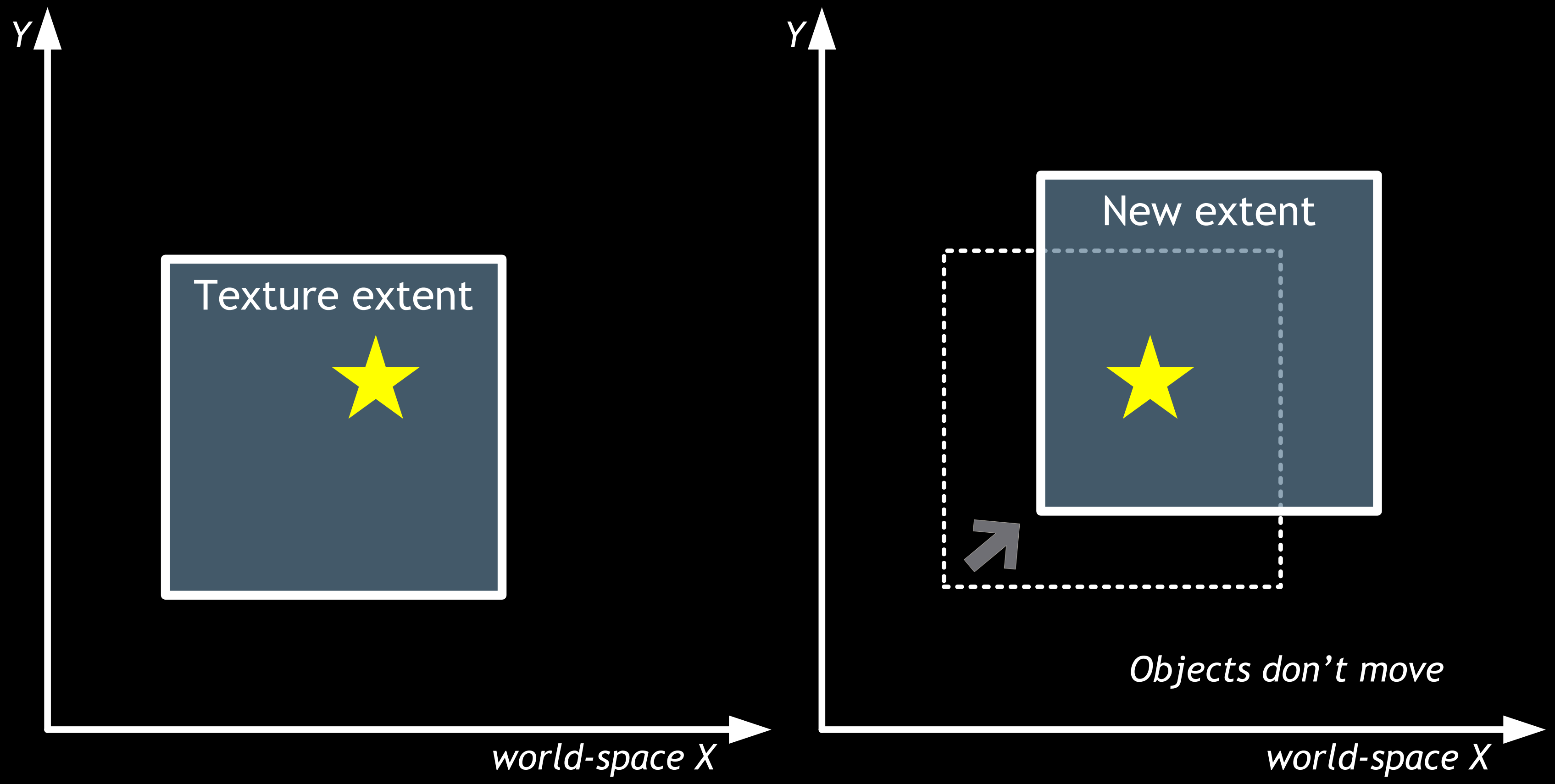
- We store the voxel data in clipmaps
  - Multi-resolution texture
  - Regions near the center have higher spatial resolution
  - Seems to map naturally to cone tracing needs
- A clipmap is easier to build than SVO
  - No nodes, pointers etc., handled by hardware
- A clipmap is easier to read from
  - Same reasons

- Clipmap size is (64…256)^3 with 3…5 levels of detail
  - 16…32 bytes per voxel => 12 MB … 2.5 GB of video memory required

CLIPMAP VS. MIPMAP

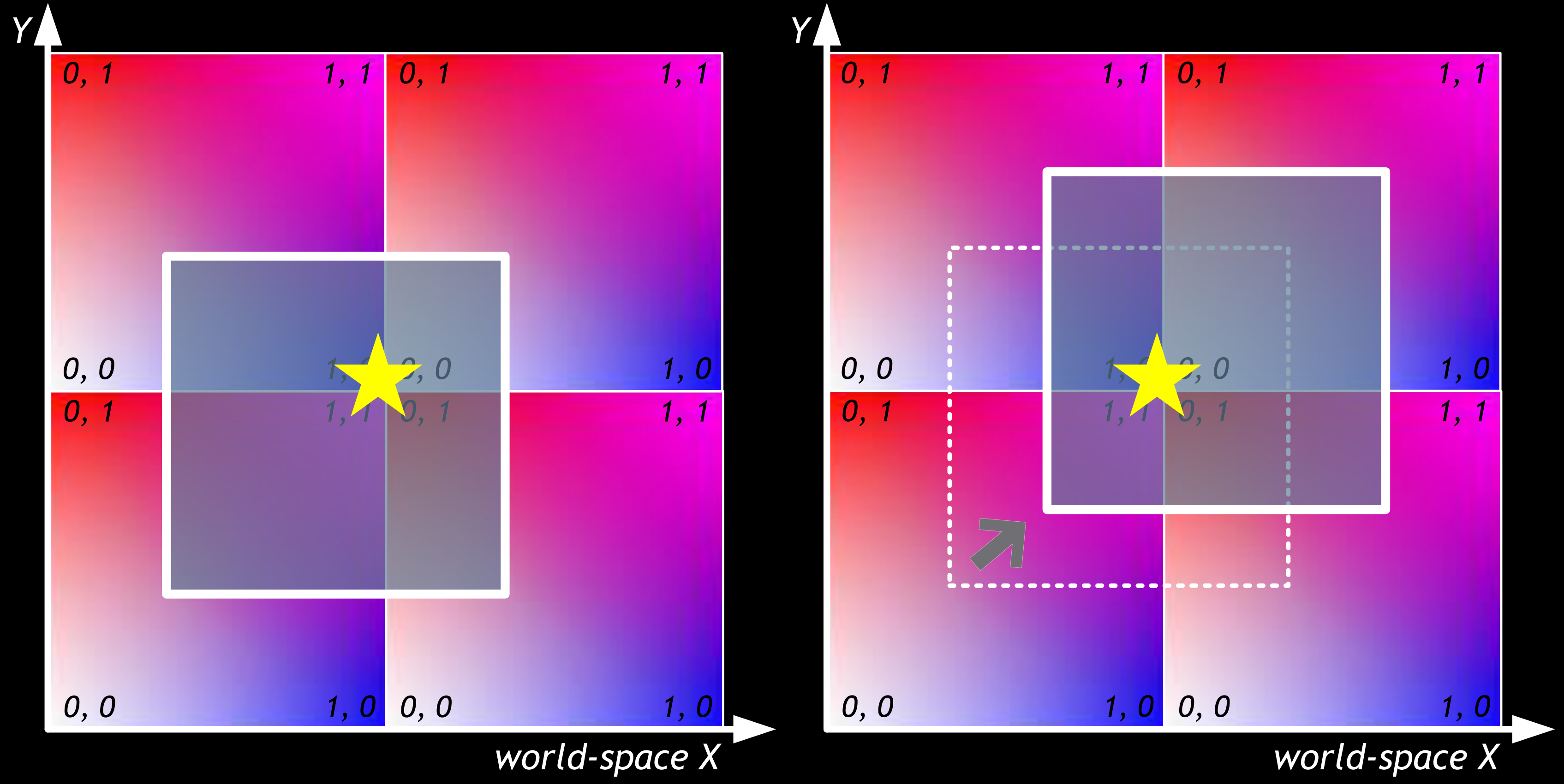


UPDATING THE CLIPMAP DATA



TOROIDAL ADDRESSING

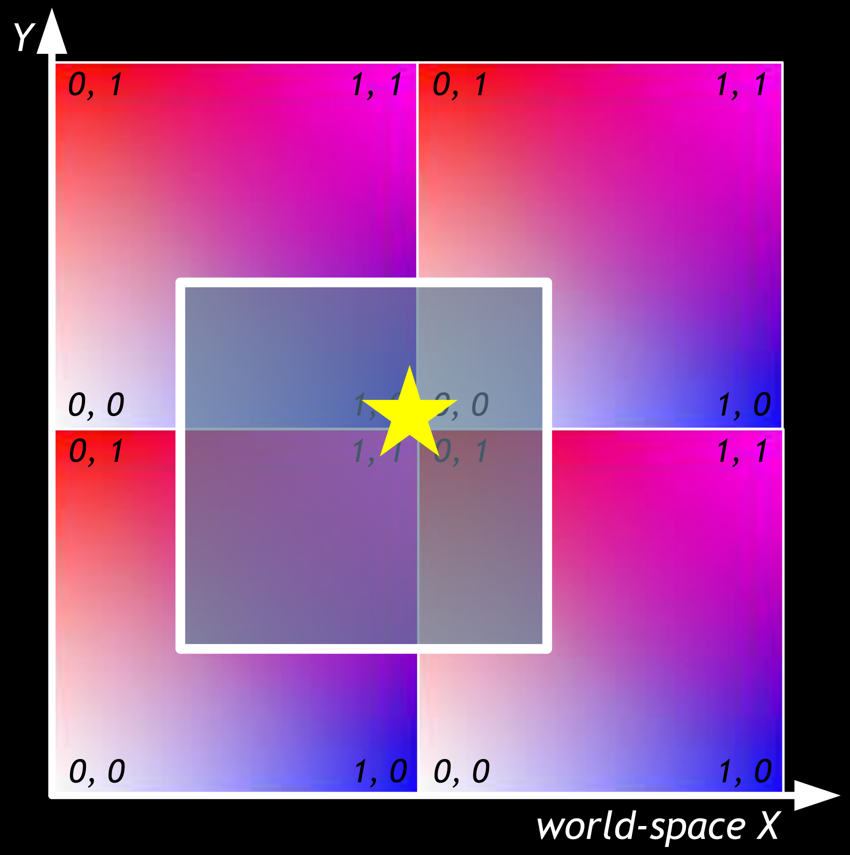
A fixed point in space always maps to the same address in the clipmap.

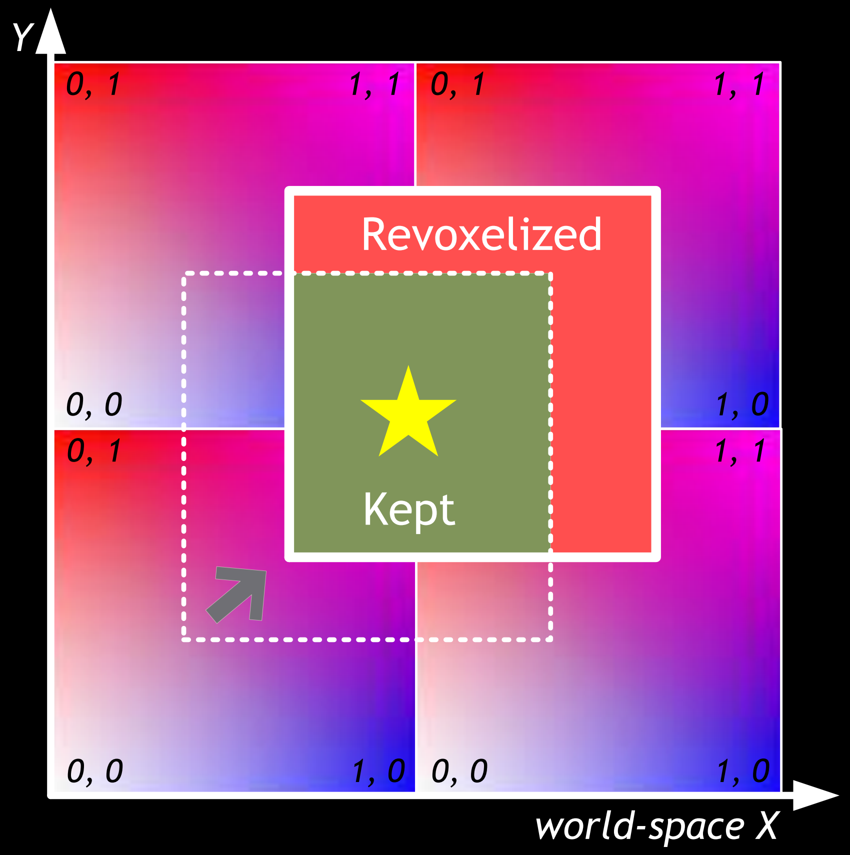


The background shows texture addresses: *frac(worldPos.xy / levelSize.xy)*

INCREMENTAL UPDATES: CLIPMAP MOVES

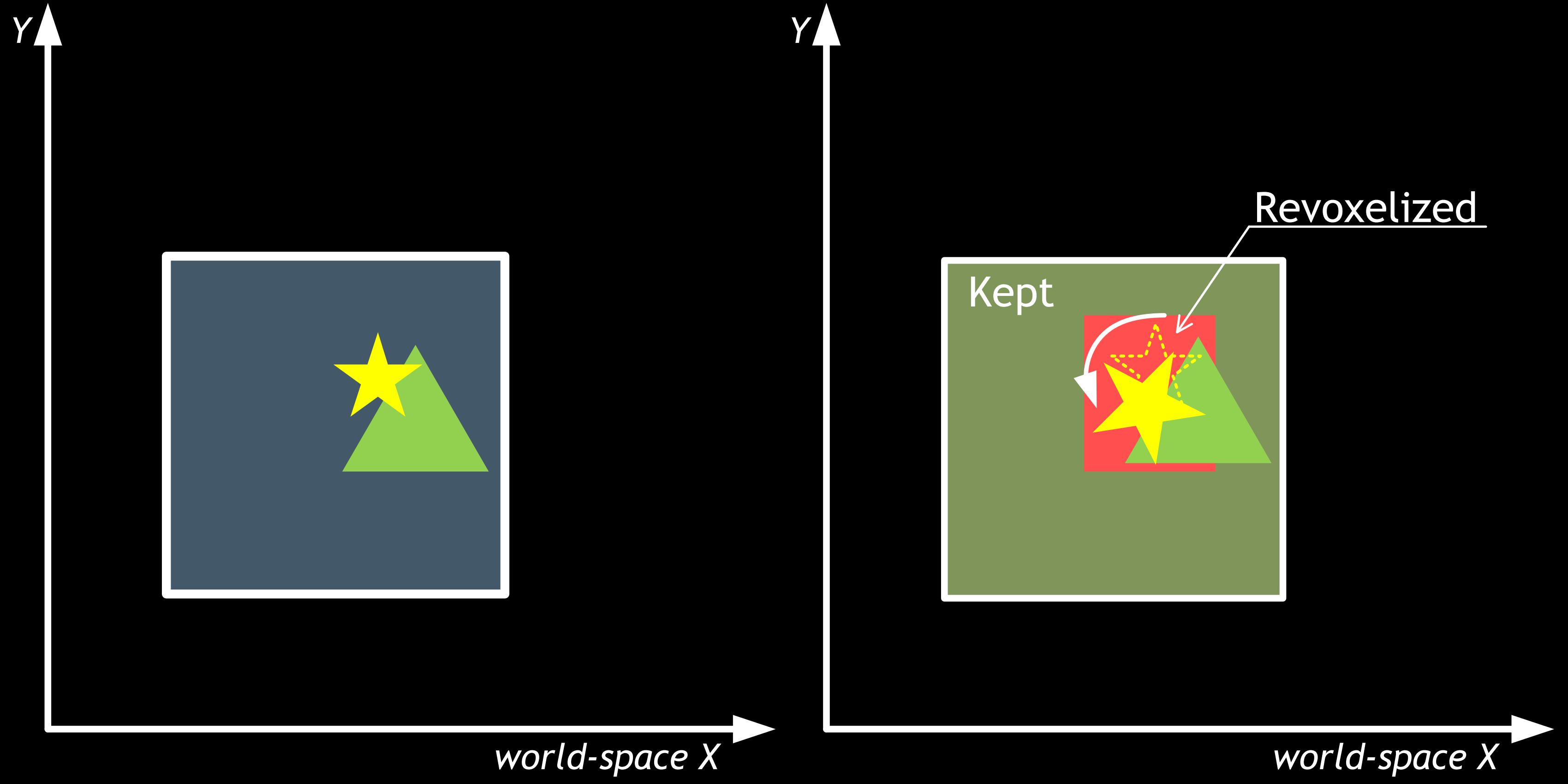
When the camera moves, most of the clipmap data remains valid.





INCREMENTAL UPDATE: OBJECTS MOVE

If some objects change, only the corresponding regions need to be revoxelized.



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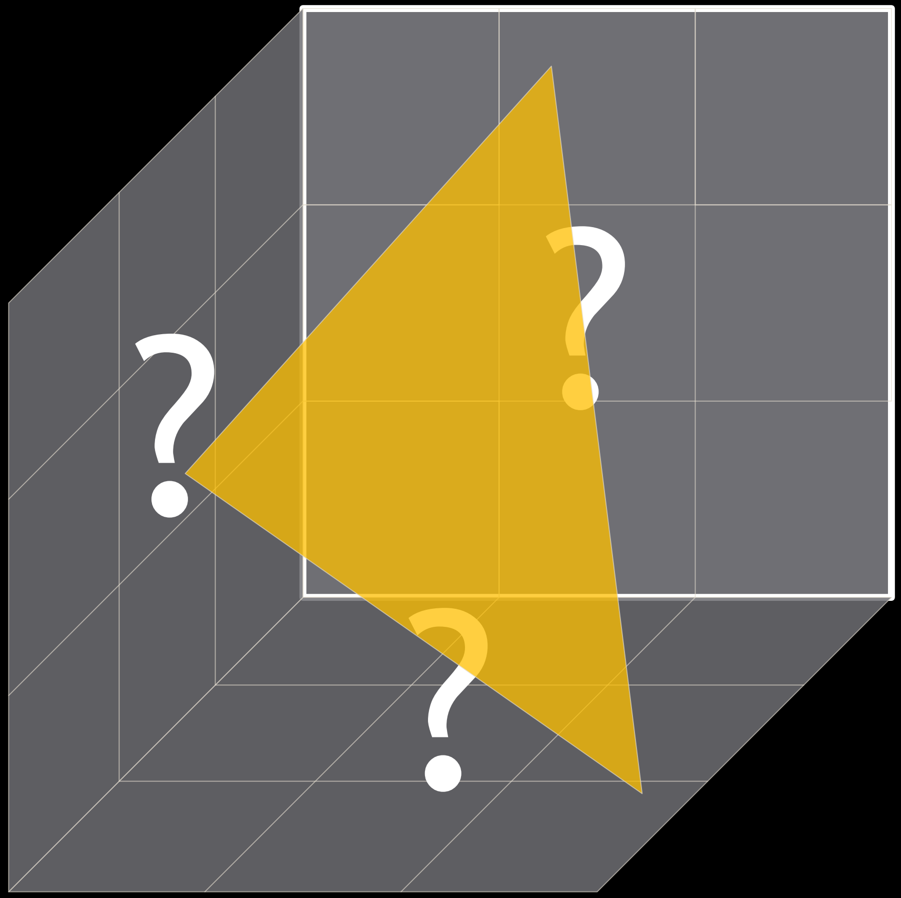
VOXEL TEXTURE CONTENTS

- Opacity textures
  - 3 or 6 opacity directions for each voxel
  - "How opaque is the voxel when viewed from a certain direction"
  - 3 for HQ tracing, 6 for LQ tracing: less self-shadowing
  - Stored as 1 or 2 RGB10A2 textures

- Emittance textures
  - 3 or 6 emittance directions for each voxel
  - "How much light does the voxel emit to a certain direction"
  - 6 for HQ and second-bounce tracing, 3 for LQ tracing
  - Stored as 3 or 6 RGB10A2 sRGB textures (non atomically updatable)

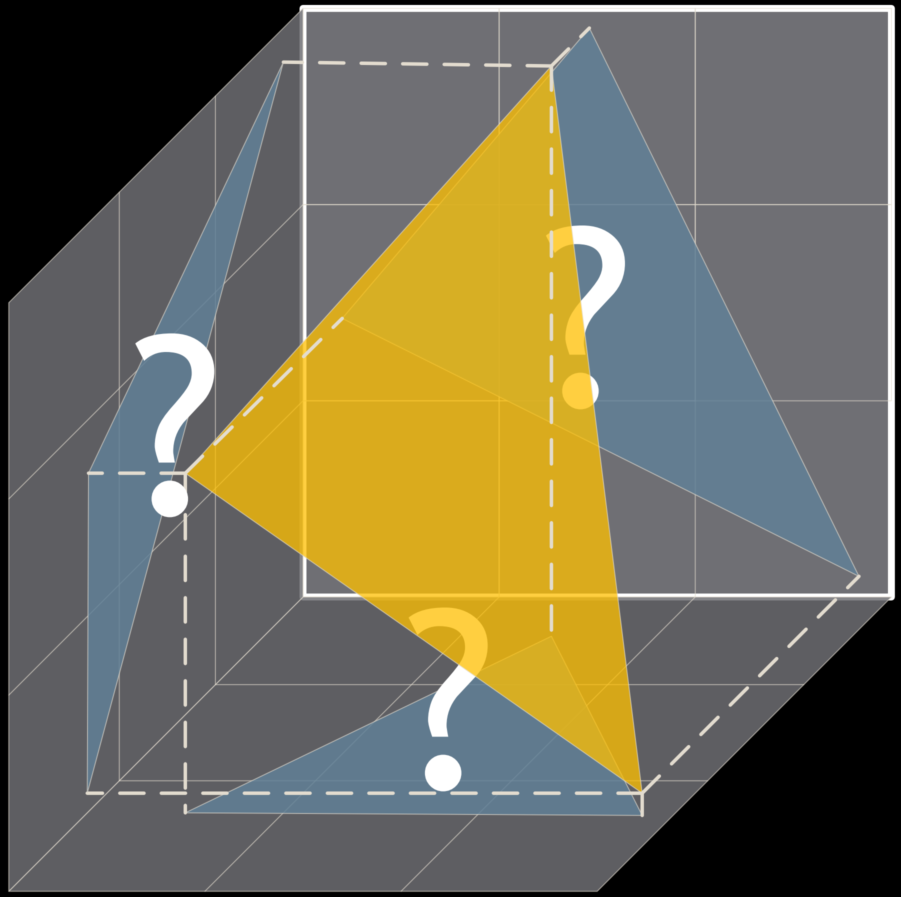
VOXELIZATION FOR OPACITY



This is one voxel.

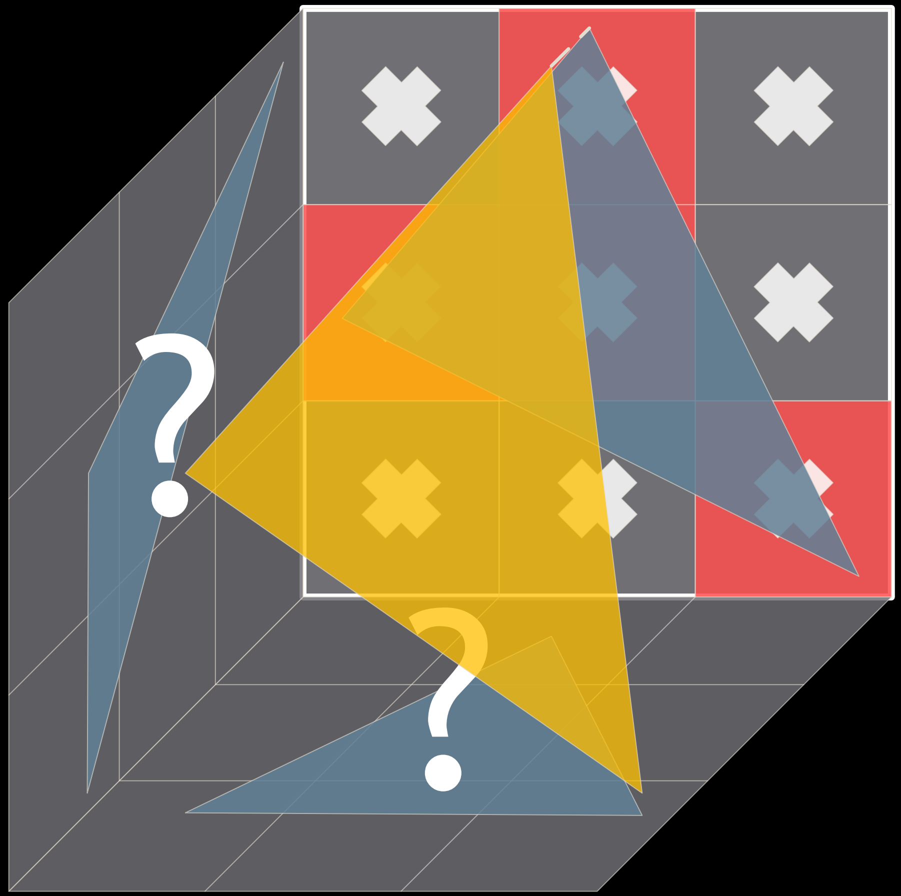
1. We have a triangle and a voxel.

VOXELIZATION FOR OPACITY



2. Select the projection plane that yields the biggest projection area (the back face in this case).

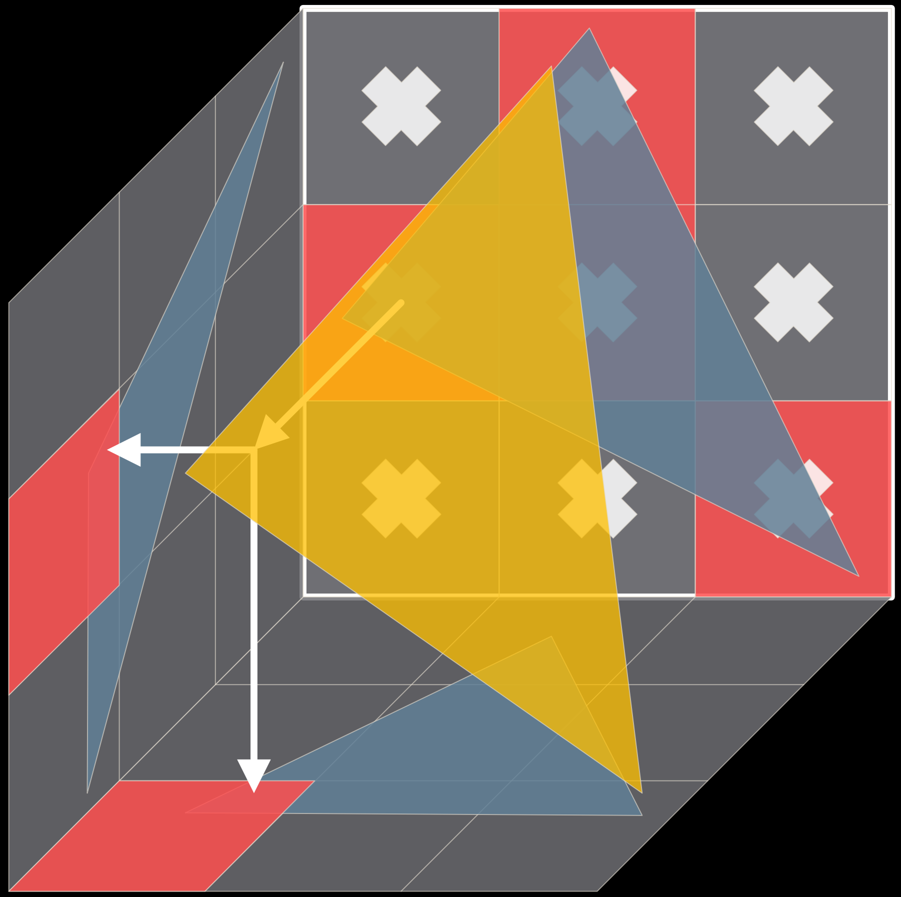
VOXELIZATION FOR OPACITY



3. Rasterize the triangle using MSAA to compute one coverage mask per pixel.

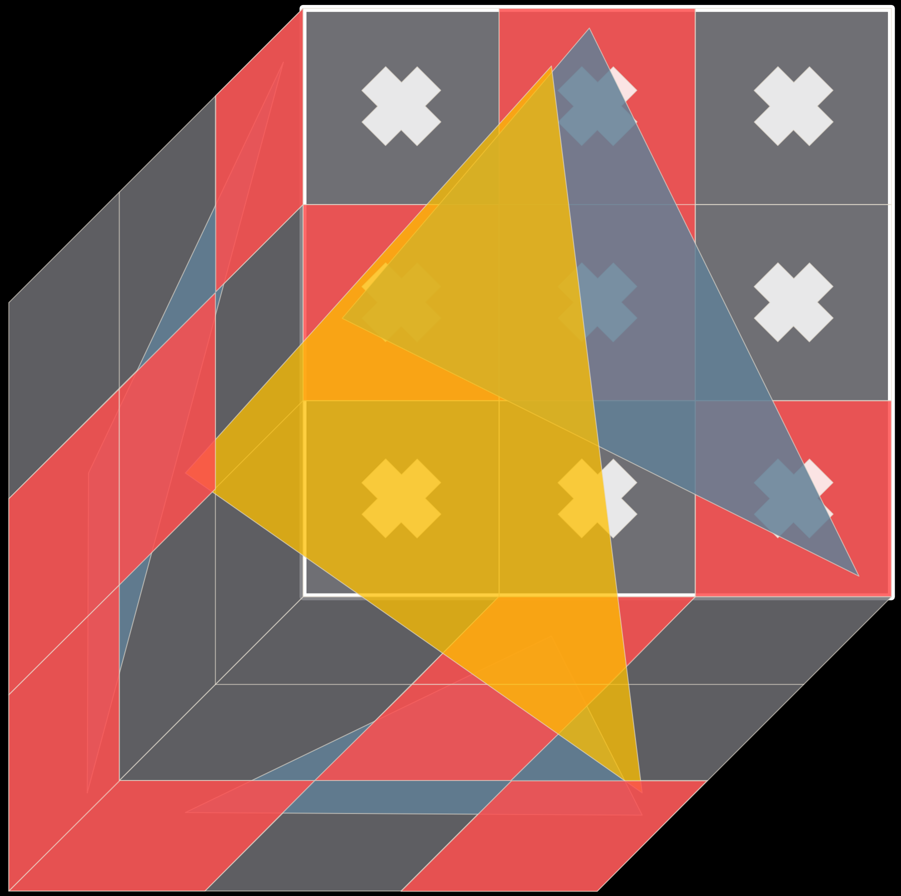
Actual MSAA pattern is different, but we translate those samples onto a regular grid.

VOXELIZATION FOR OPACITY



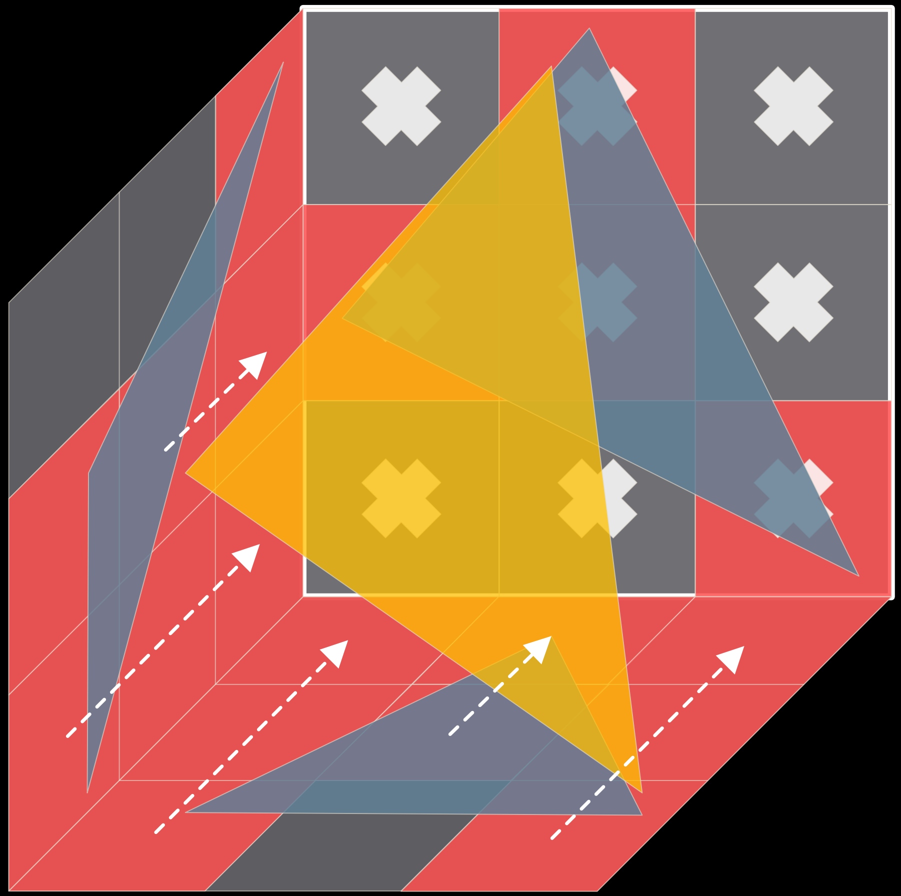
4. Now take the MSAA samples and reproject them onto other planes using the triangle plane equation.

VOXELIZATION FOR OPACITY



5. Repeat that process for all covered samples.

VOXELIZATION FOR OPACITY

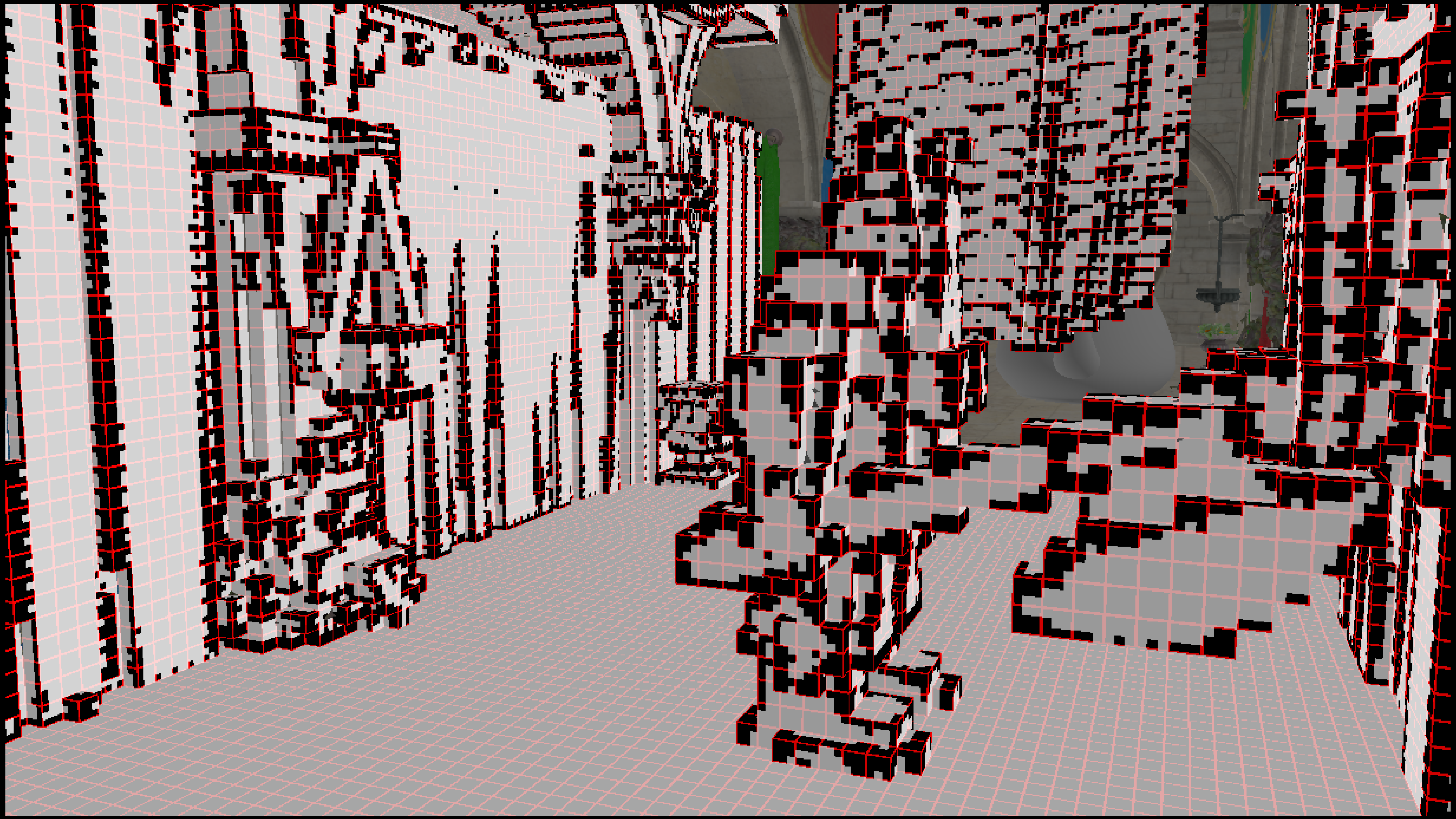


6. Thicken the result by blurring all the reprojected samples.

Some samples may go into the closer or further voxels depending on the Z-slope of the triangle.

VOXELIZATION: SCENE GEOMETRY

VOXELIZATION: DIRECTIONAL COVERAGE



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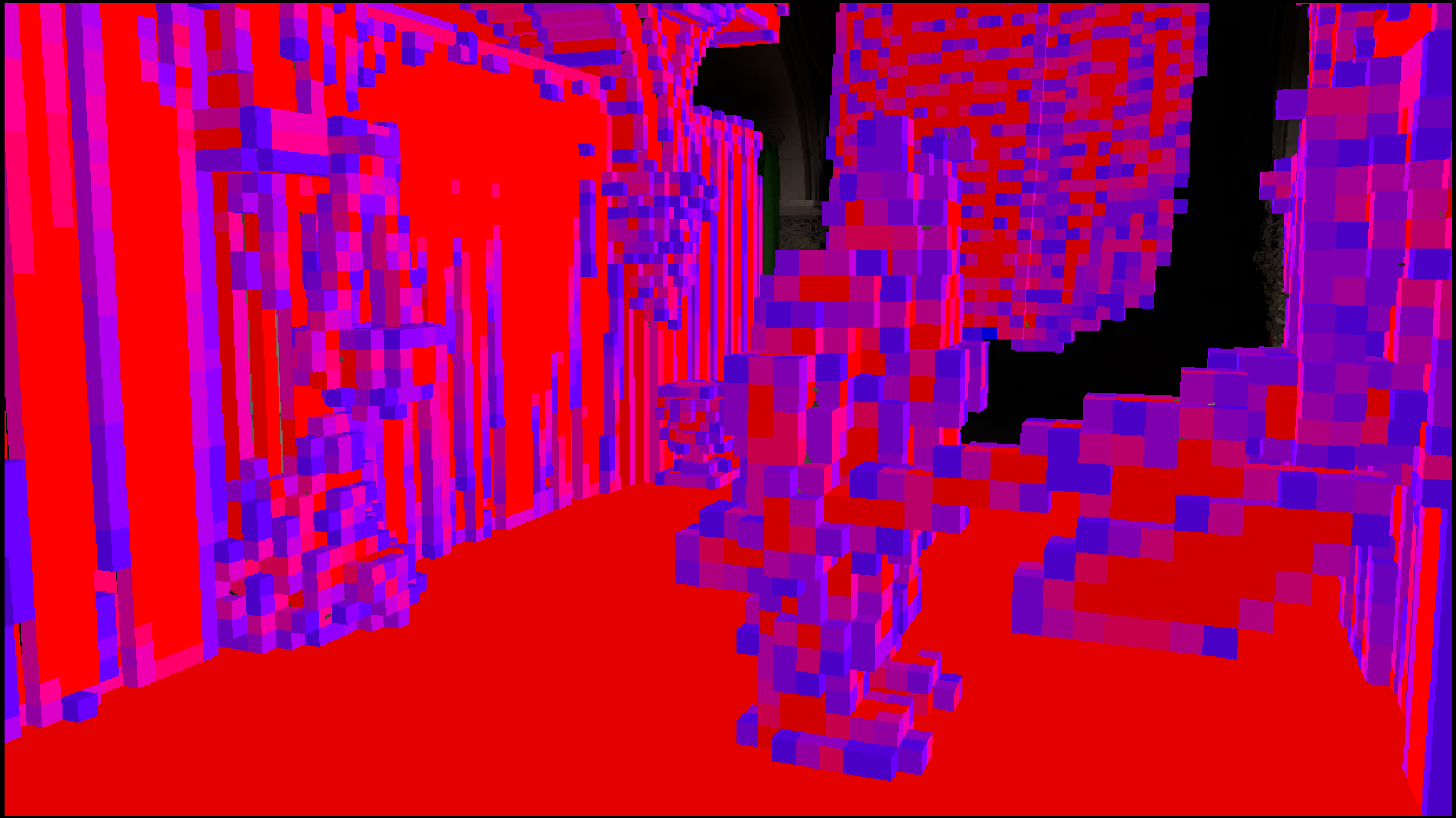
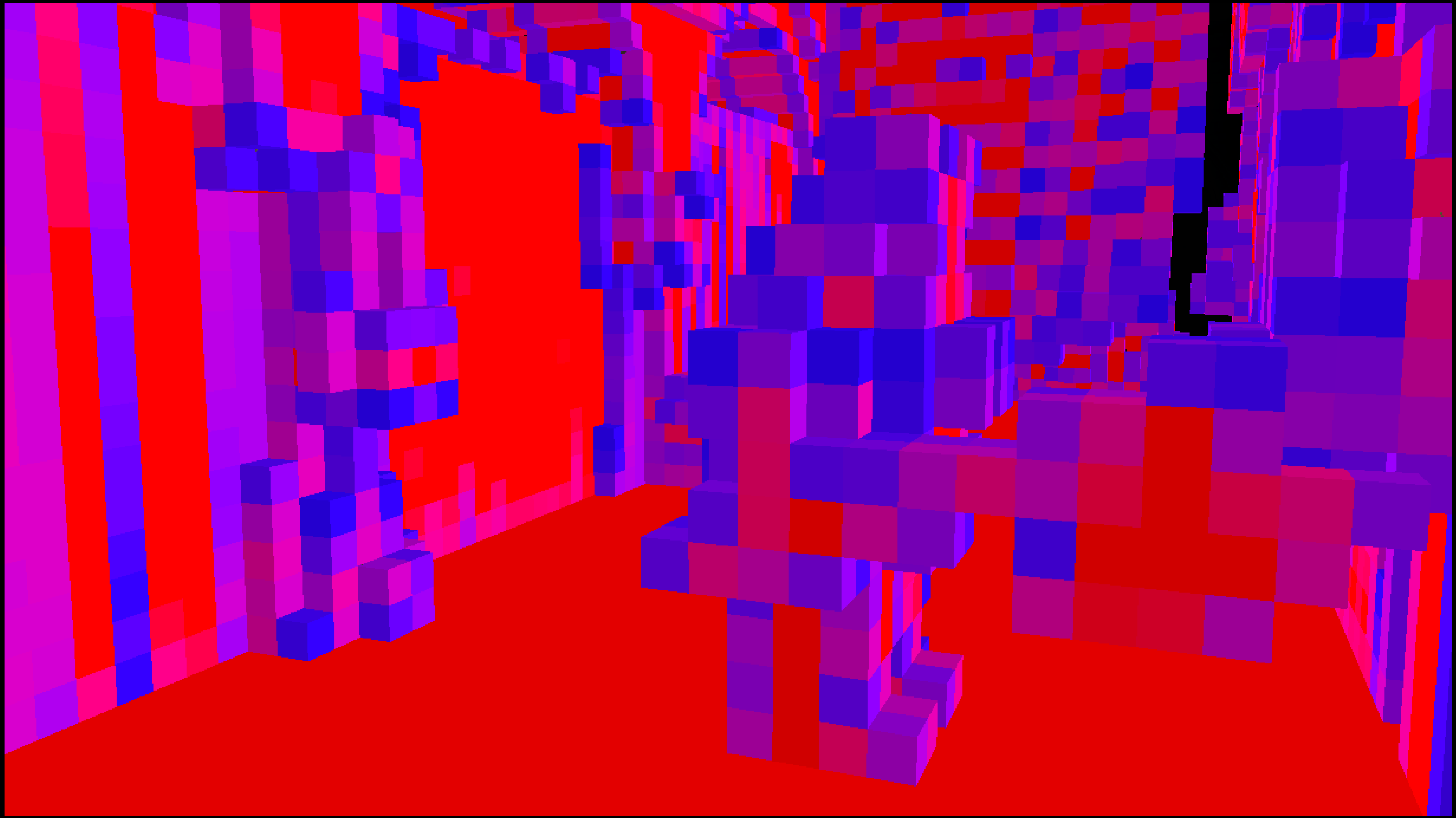
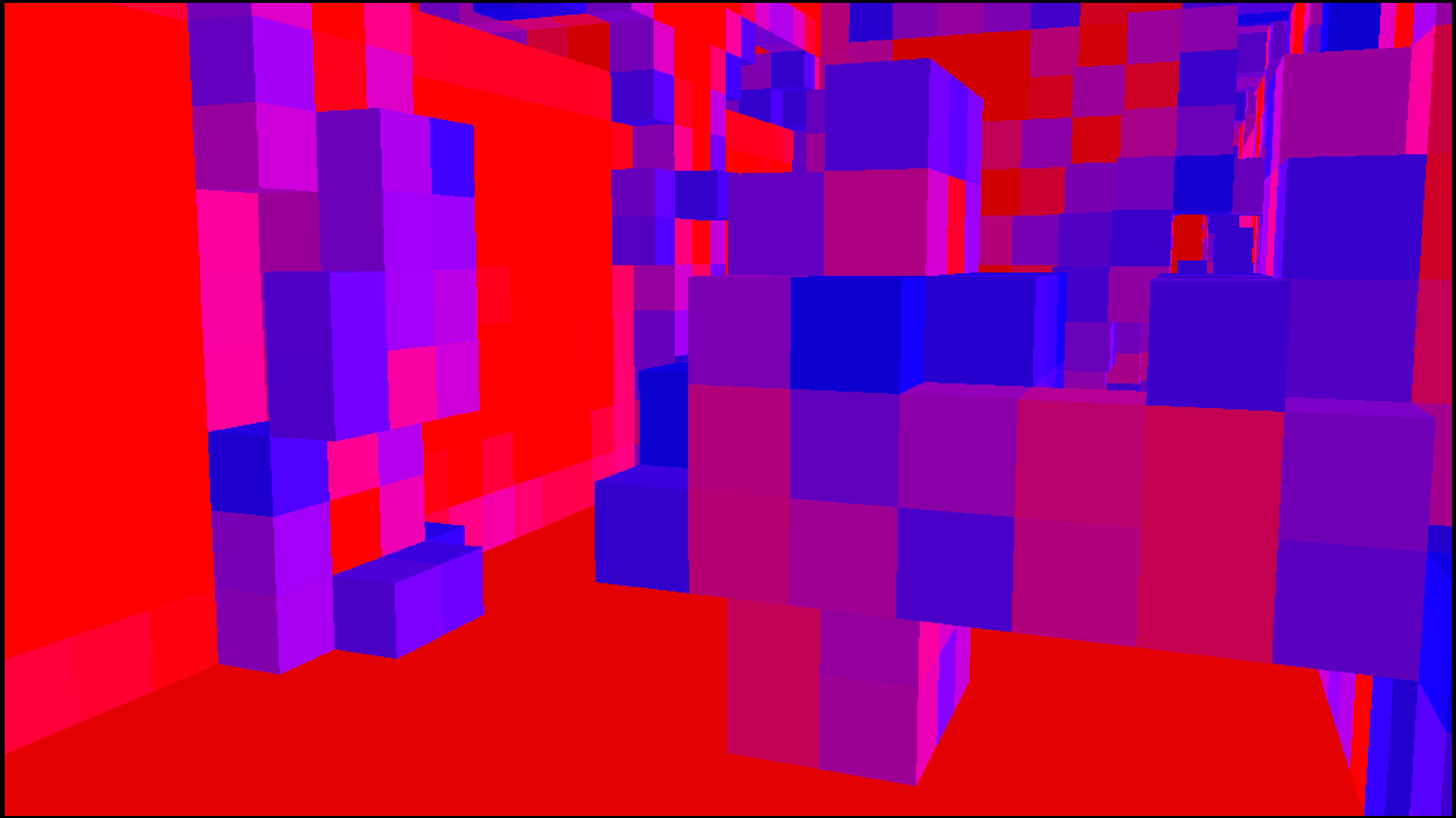
VOXELIZATION: OPACITY



VOXELIZATION: DOWNSAMPLING 1



VOXELIZATION: DOWNSAMPLING 2



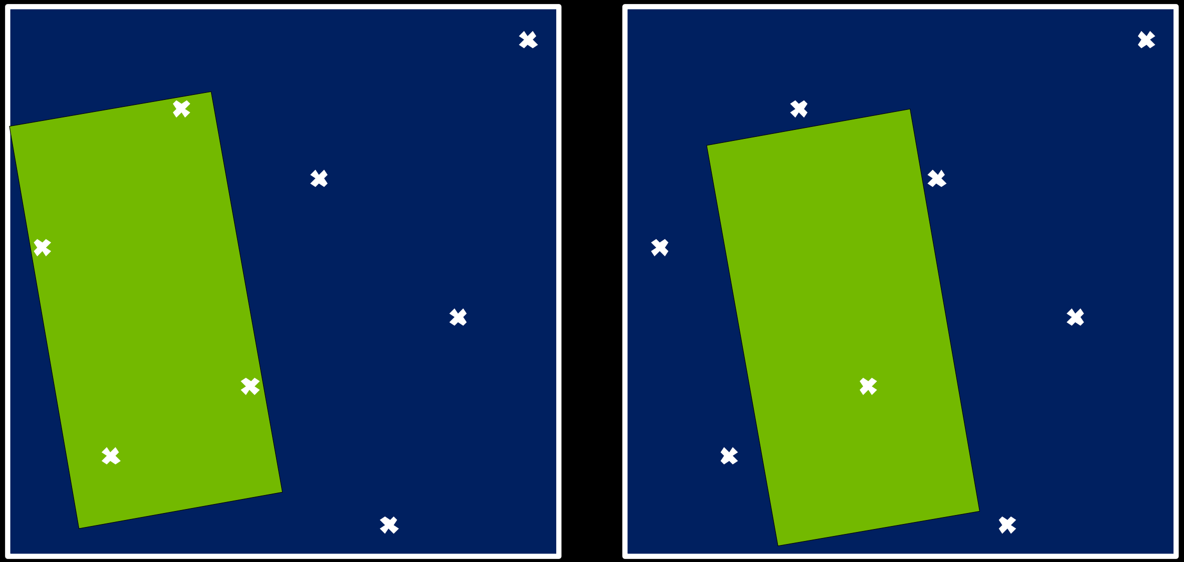
VOXELIZATION FOR EMITTANCE

- Step 1: compute approximate brightness for each voxel
  - Use the coverage mask to weigh the emittance texture/color
- Step 2: accumulate the brightness and normal in emittance textures
  - There are 6 textures, one per direction, storing RGB10 sRGB data
  - Need R32U to perform atomics => 3 textures for emittance, 3 for normal
- Step 3: Convert the brightness data to directional emittance

VOXELIZATION FOR EMITTANCE

- Aliasing: small objects change apparent brightness abruptly
- Appears on remote regions of the clipmap
- Possible solutions are extreme (adaptive) supersampling and analytical coverage computation

- 8x MSAA pattern
- Object covers:
  - Left: 4 samples
  - Right: 1 sample

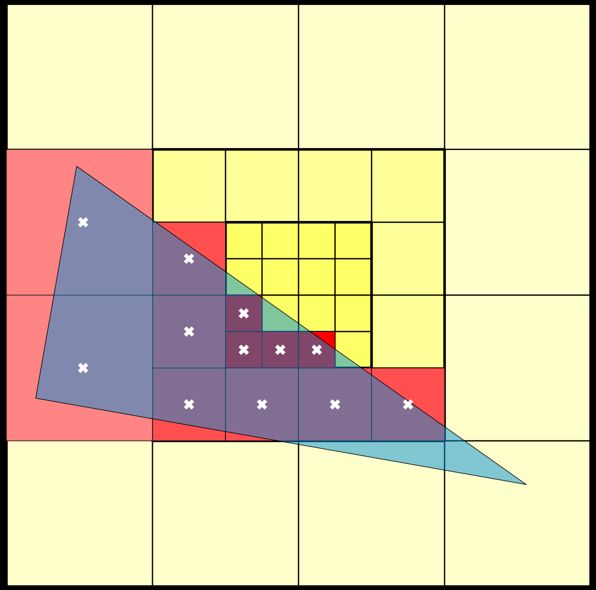


MULTI-RESOLUTION VOXELIZATION

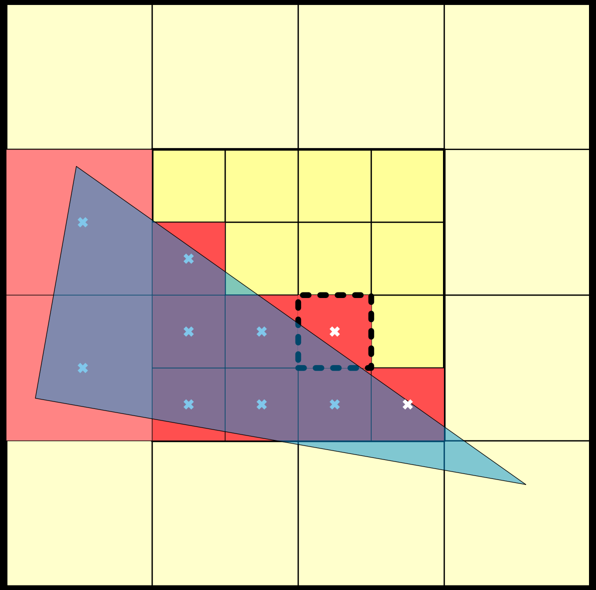
- MIP-map: downsample finer levels to get coarser levels
- Clipmap: there are no finer levels for most of coarser levels
- Rasterize every triangle at several resolutions
  - Obtain center regions of coarser levels by downsampling finer levels
  - Use GS instancing to rasterize one triangle several times

MULTI-RESOLUTION VOXELIZATION

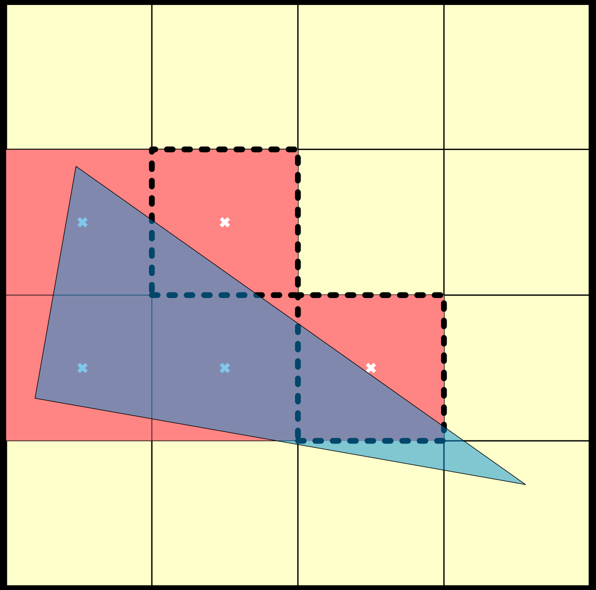
Voxelization with downsampling yields higher quality results than multi-res voxelization.



Rasterize…



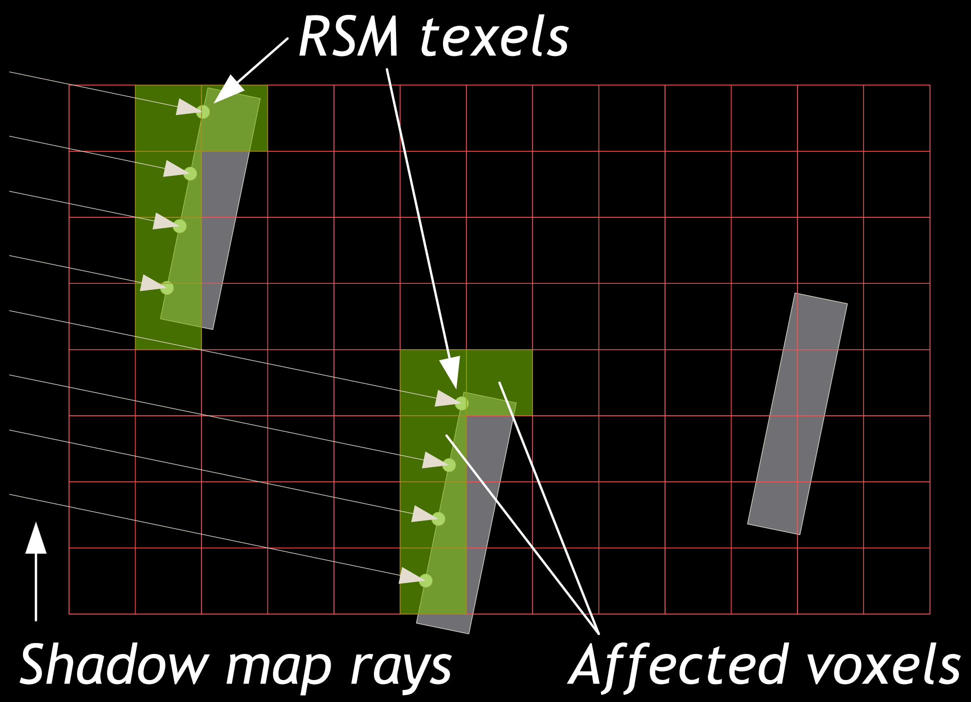
Downsample once



Downsample twice

LIGHT INJECTION

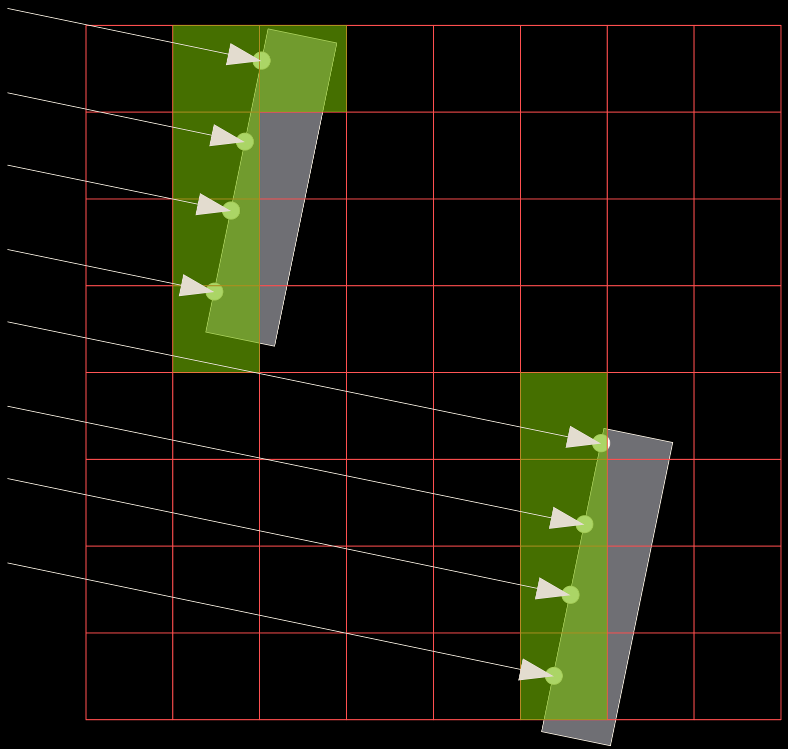
- A process of calculating emittance of voxels that contain surfaces lit by direct lights
- We take information from reflective shadow maps (RSMs)

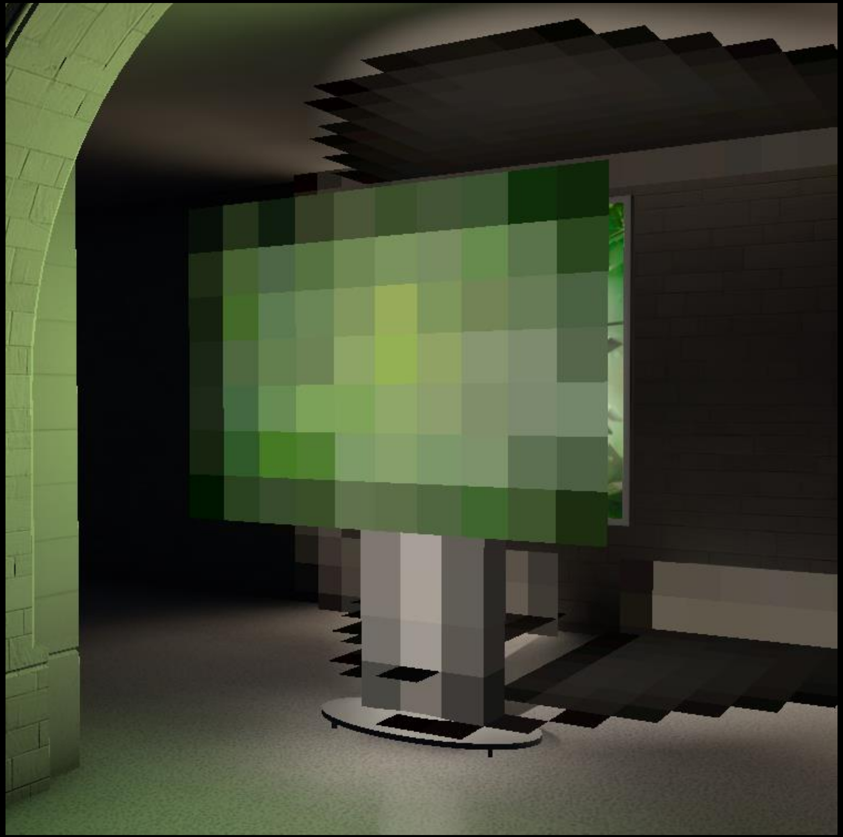


LIGHT INJECTION ALGORITHMS

- Simplest option: test every voxel center against the RSM
  - Consider only voxels with nonzero opacity
  - If a voxel is lit, take the color and normal from the RSM
  - Problems: aliasing, false lighting on object boundaries
- Better option: gather all RSM texels that belong to the voxel
  - Many texture fetches per voxel, most of them are useless
- Even better option: scatter RSM texels into voxels using atomic operations
  - Requires more memory, which we allocate sparsely in a separate texture

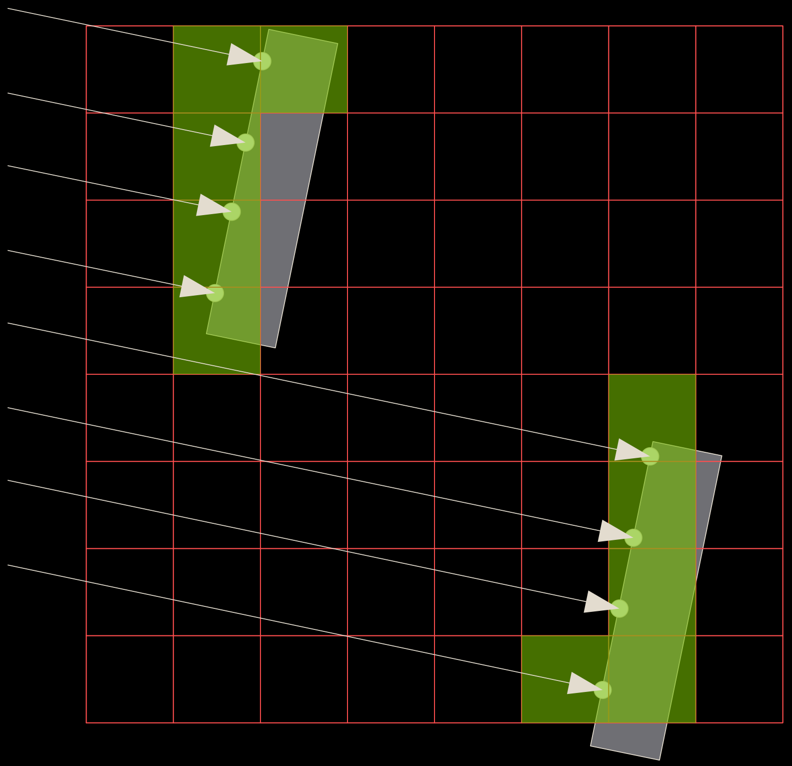
LIGHT INJECTION ALIASING





Slight changes in object or light positions sometimes change the lighting significantly.

LIGHT INJECTION ALIASING



Slight changes in object or light positions sometimes change the lighting significantly.

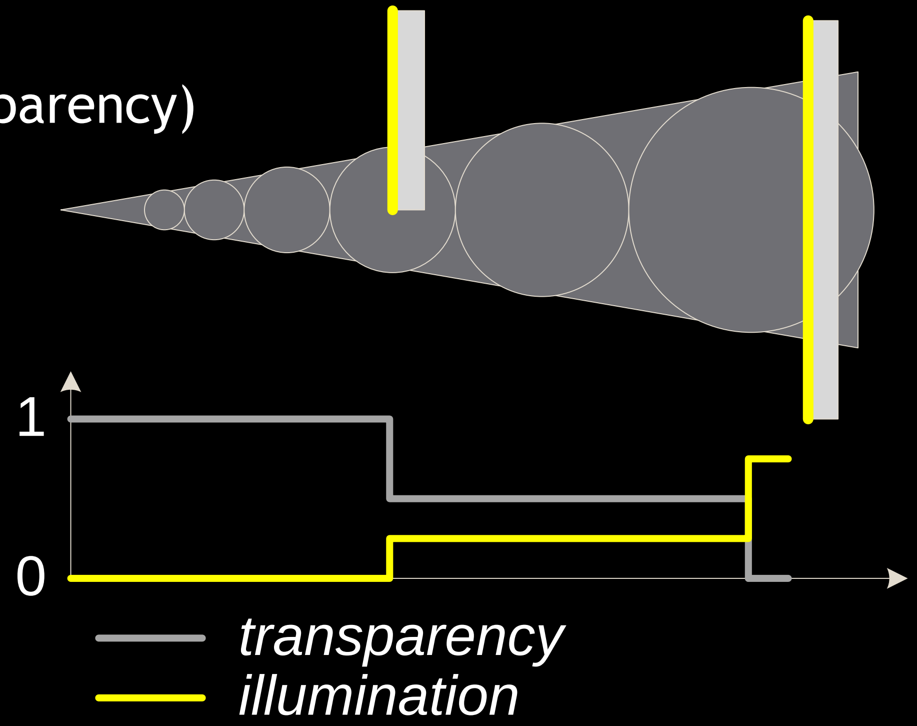
LIGHT INJECTION PRE-FILTERING

- Need to pre-filter the RSM point cloud before injecting
  - Every texel will affect more than 1 voxel (3^3 or even 5^3)
  - Expensive to inject with scattering: atomics will be a bottleneck
- Impractical to use the same filter kernel for all clip levels
  - A kernel that removes aliasing on all levels is very large
- Different filter kernel sizes may result in injected/downsampled mismatch

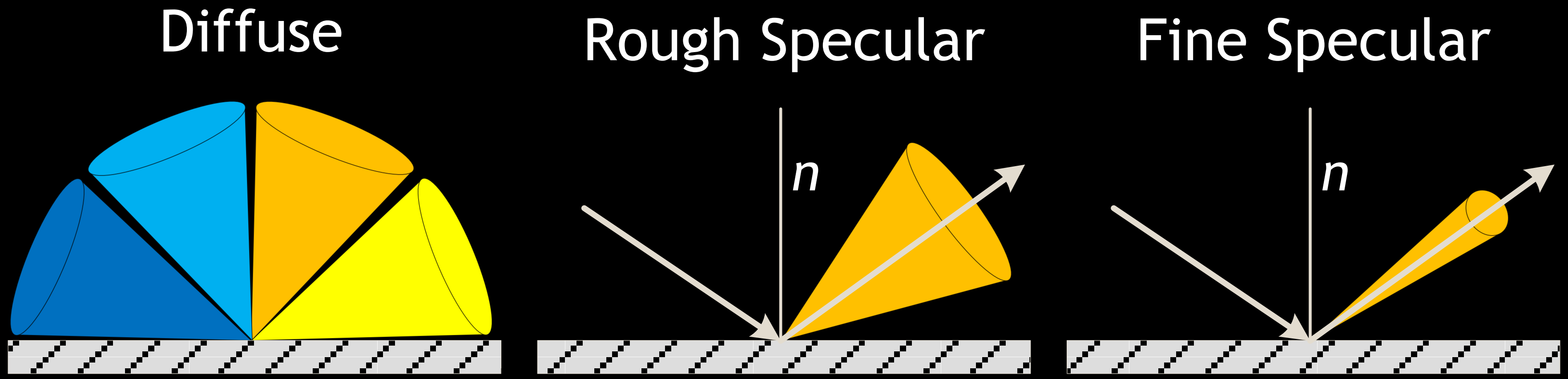
CONE TRACING BASICS

- Several cones are traced from every visible surface
- A cone marches through the clipmap accumulating:
  - transparency (1-opacity)
  - illumination (emittance * transparency)

Each sample is taken
from a coarser LOD
than the previous one.



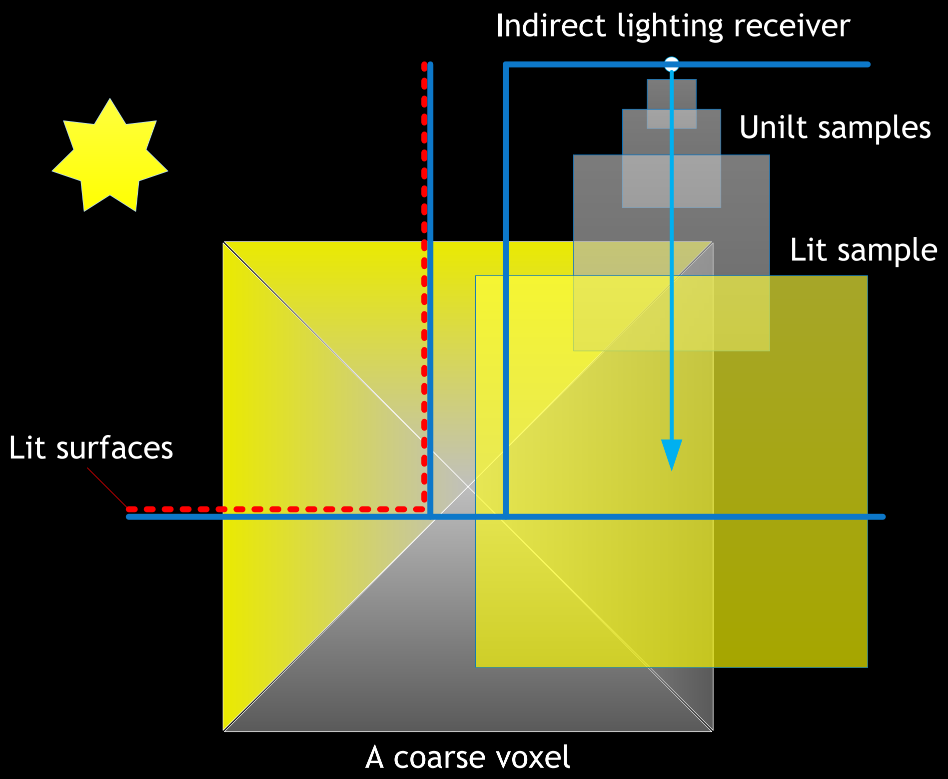
DIFFUSE AND SPECULAR CONE TRACING



SPARSE DIFFUSE CONE TRACING

- Diffuse lighting is usually low-frequency
  - HQ cone tracing for every pixel is redundant
- We trace every Nth pixel on the screen
  - N = 4…16
  - Rotated grid pattern to reduce aliasing
- Interpolate using a bilateral filter
  - MSAA resolve fits naturally into the interpolation pass

LIGHT LEAKING



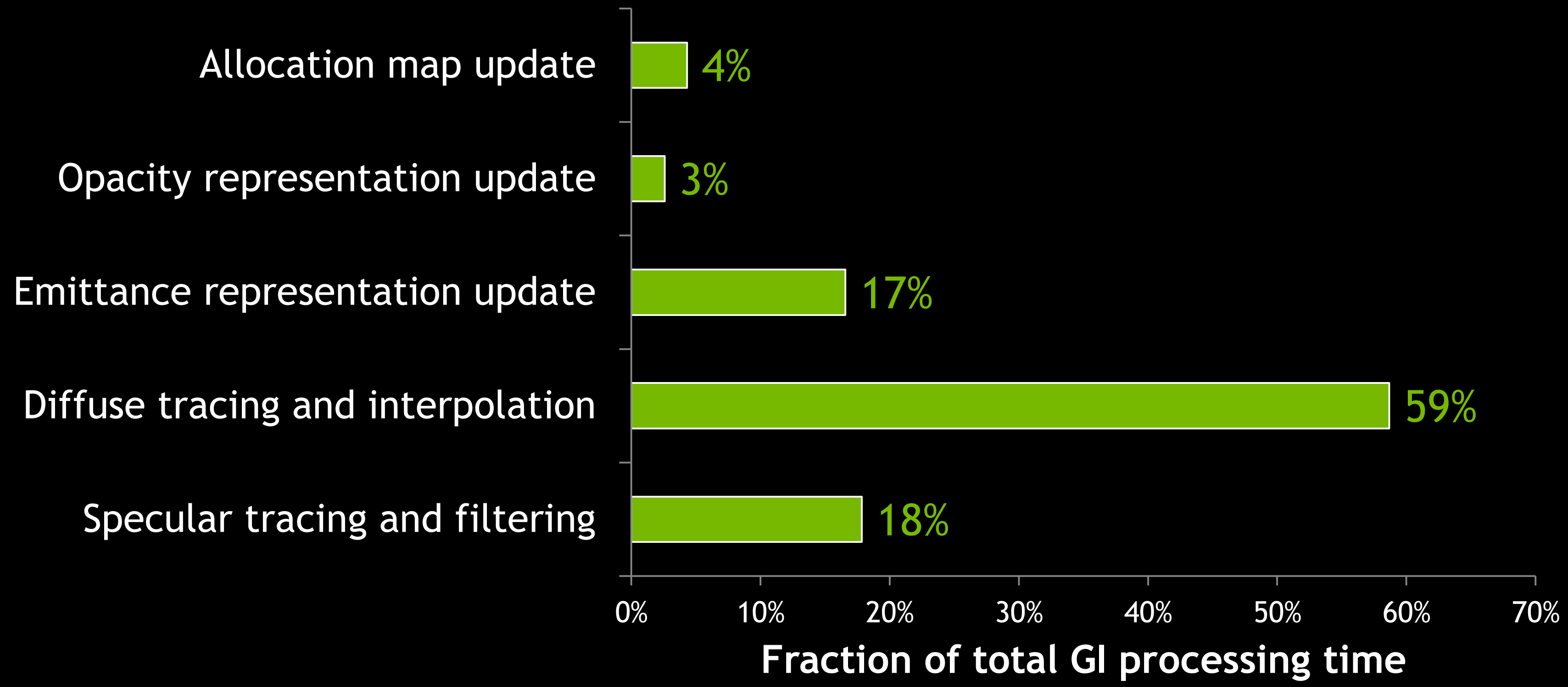
PERFORMANCE

- Full GI is practical on current mainstream GPUs
  - e.g. GeForce GTX 770
- Voxel-based AO works well on low-end GPUs, too
  - Looks much better than SSAO
- GI processing time per frame, in ms:

	AO only	Med	High	Ultra
GTX 650 (GK107)	14.3	28.1		
GTX 770 (GK104)	3.8	7.4	12.9	
GTX TITAN (GK110)	3.1	6.6	9.6	25.4

@ 1920x1080

RENDERING TIME BREAKDOWN



High quality settings: 1920x1080, 17 cones, trace every 9th pixel. GTX TITAN.

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CONCLUSION

- Fully dynamic GI becomes practical on mainstream GPUs
  - Low end GPUs can benefit from much higher-quality AO
- Future work
  - Further reduction of aliasing issues
  - Reduce the amount of content changes necessary
- Planned to be released as NVIDIA GI Works library

QUESTIONS?

- mailto: alpanteleev@nvidia.com

- Thanks:
  - Cyril Crassin
  - Evgeny Makarov
  - Khariton Kantiev
  - Monier Maher
  - Holger Gruen
  - Yury Uralsky
  - Sergey Bolotov
  - Alexey Barkovoy
  - Miguel Sainz

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BACKUP

SPARSE DIFFUSE CONE TRACING

Every 4th pixel

8.0 ms tracing
0.7 ms interpolation

Every 9th pixel

4.0 ms tracing
0.75 ms interpolation

Every 16th pixel

3.0 ms tracing
0.8 ms interpolation

Measured on a GTX 680 at 1280x800, no AA, 17 diffuse cones.

SPARSE DIFFUSE CONE TRACING

Every 4th pixel

Every 9th pixel

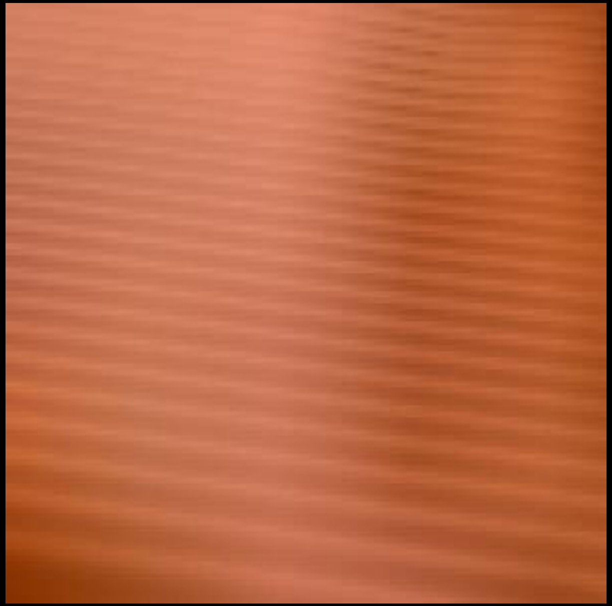
Every 16th pixel

And now we slightly move the camera… See the difference.
The left image is relatively stable, and the right image is more noisy.

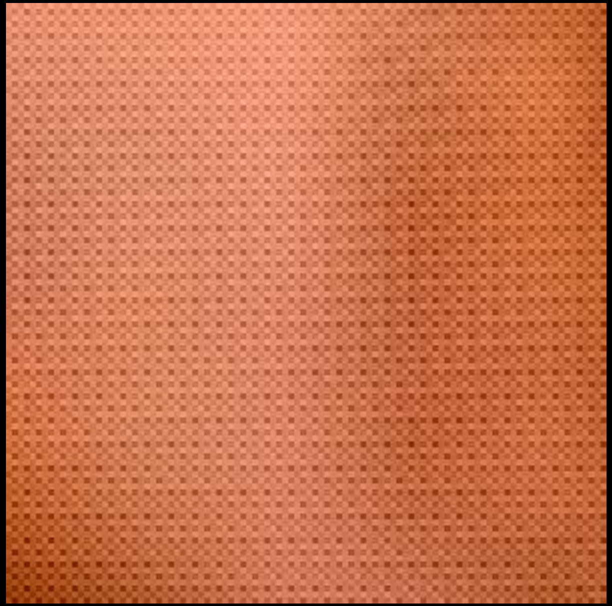
NOISY SPECULAR CONE TRACING

- Tracing specular cones sparsely only works for flats
  - And a low tracing step is needed to avoid banding
- Dense tracing is expensive due to small tracing step
  - Large step results in banding
- We use noisy dense tracing:
  - Add a pseudo-random offset to every specular cone
  - Use a 4x4 blue noise matrix bound to screen pixels
  - Trace with step = 1.0 voxels
  - Filter the results with a 4x4 kernel + bilateral

SPECULAR BANDING REMOVAL



Banding in dense tracing



Adding noise…

And filtering that noise.

The images are displayed with enhanced contrast.