CG Final Project Report

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We do not use the prebuilt intersection library

Work Distribution

Reflected in "final-project-workload-final.xlsx"

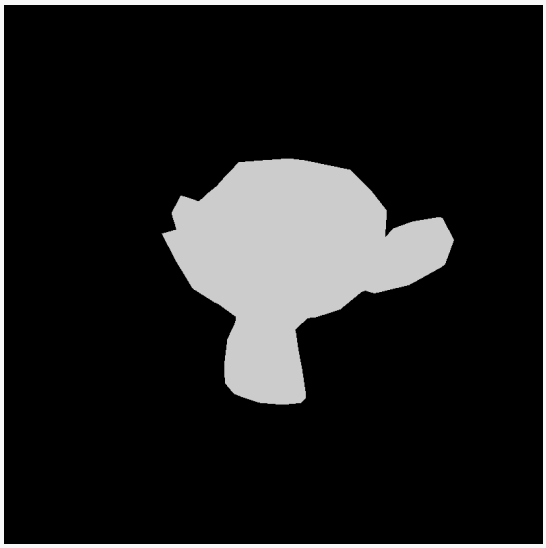
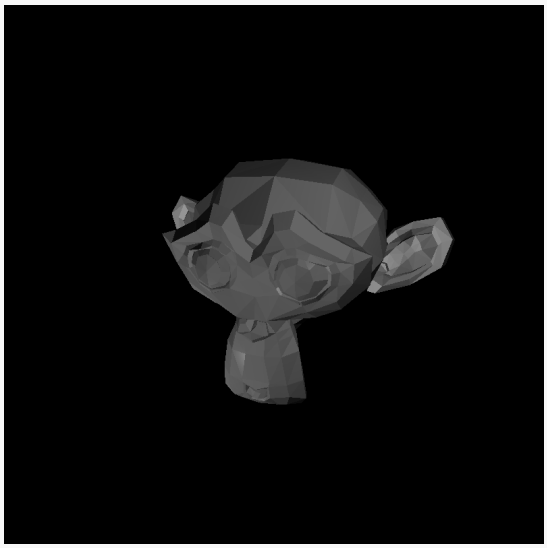
Basic Features

Shading

Implementation

Following the Phong Model, shading is calculated using the diffuse and specular terms. If shading is disabled, then the
diffuse color (kd) is returned. The light contribution in the scene is calculated over all light sources and depends on
the type of light (point/segment/parallelogram). The resulting color is the average over all light sources.

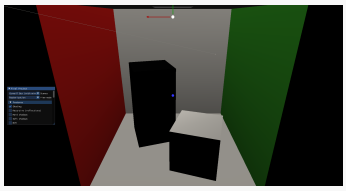
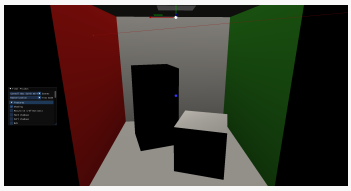
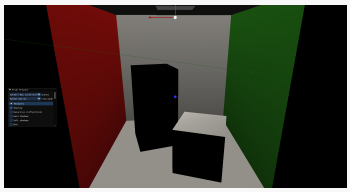
Examples

	
Monkey without shading	*Monkey with shading*

	
Teapot without shading	*Teapot with shading*

Visual Debug

The ray takes the calculated shading color of the object that it hits.

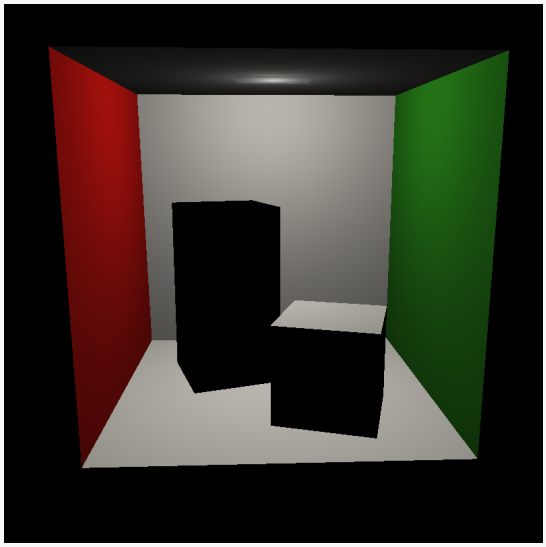
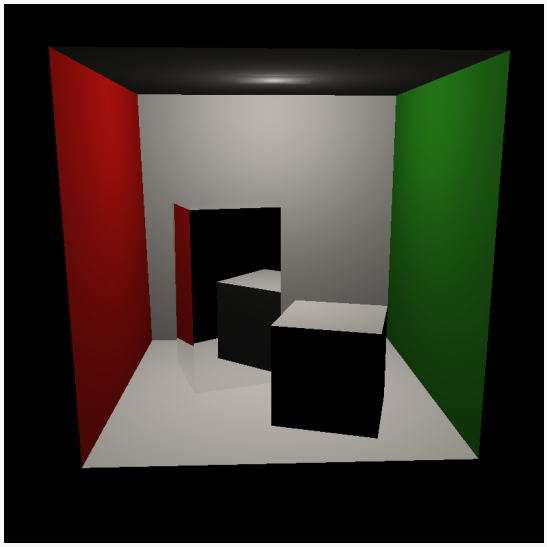
		
Gray ray in Cornell box	*Red ray in Cornell box*	*Green ray in Cornell box*

Recursive ray-tracer

Implementation

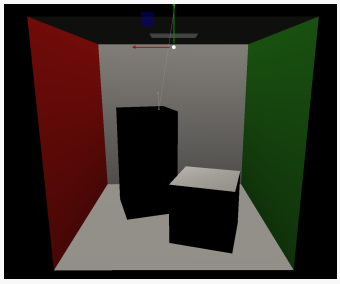
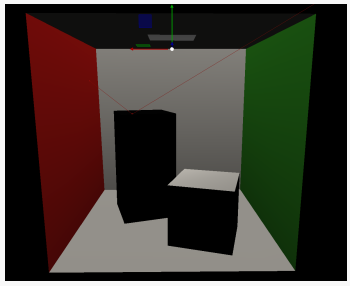
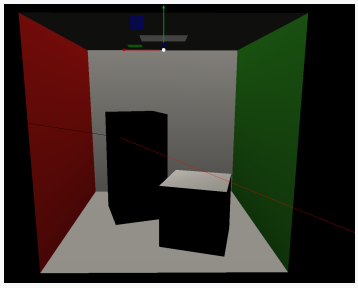
In the getFinalColor() method, if recursion is enabled, we can obtain mirror-like surfaces, as long as the materials hit
have non-zero specular terms. If this is the case, we recursively call the method to obtain the color that is reflected
off the surface of the mirror-like object. Using the formula from the lectures `Lo += hitInfo.material.ks * reflectedColor`,
where `Lo` is the final color, we can see the reflections from the mirror object!

Examples

	
Cornell box with shading and no *recursion*	*Cornell box with shading* and *recursion*

Visual Debug

Similar to shading's visual debug, the ray takes the final colour of the object that it hits, this time including any
potential reflections off surfaces.

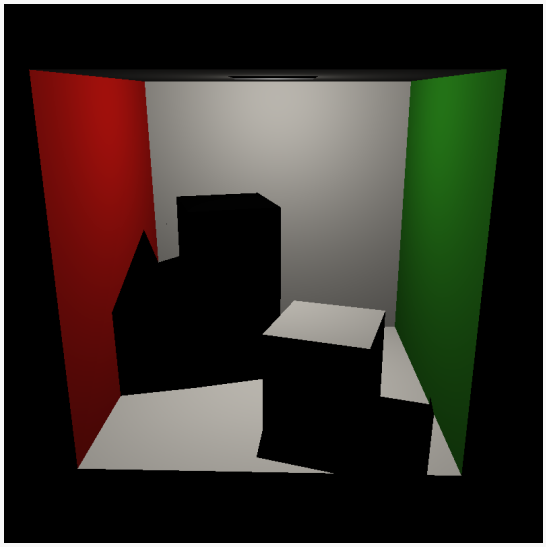
		
Gray reflection off wall	*Red reflection off wall*	*No hit, black reflection*

Hard shadows

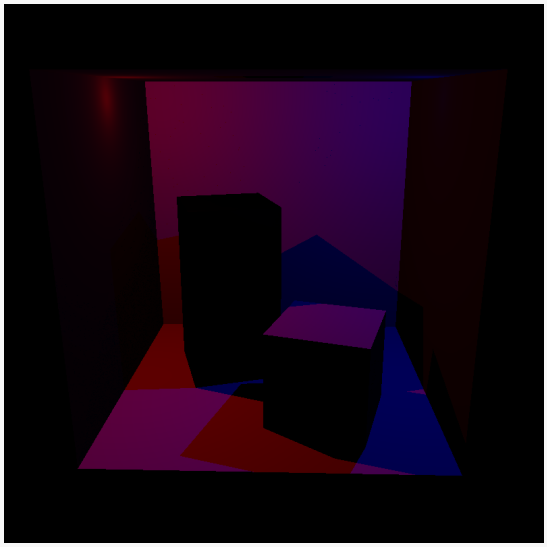
Implementation

A ray is shot from all intersection points to each point light; if it intersects geometry before the light the point
is marked as in shadow. Then the color determined by the shading function is multiplied by the average color
of all lights that reach the sampled point.

Examples

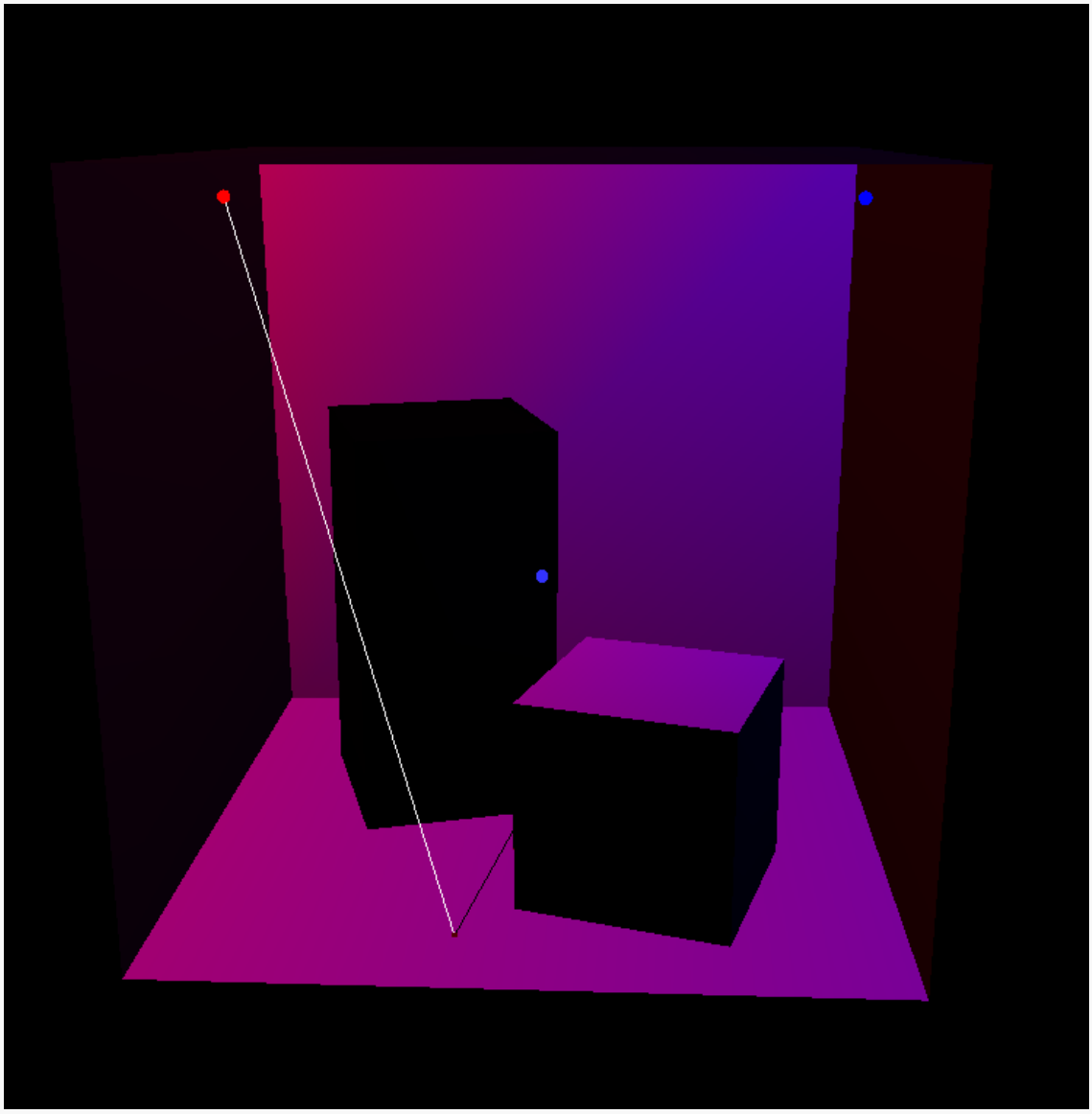


Single white light



Two colored lights

Visual Debug



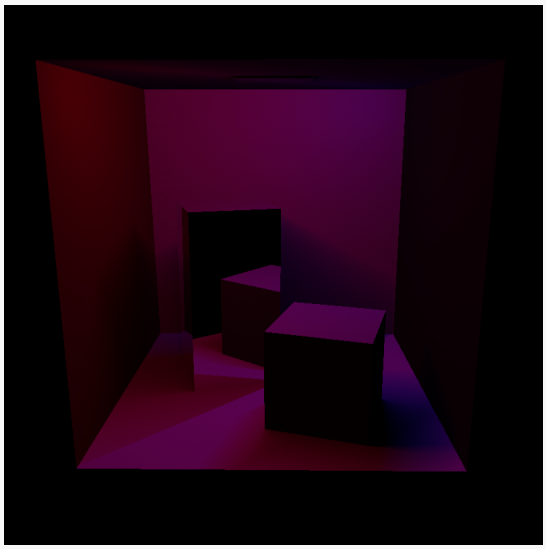
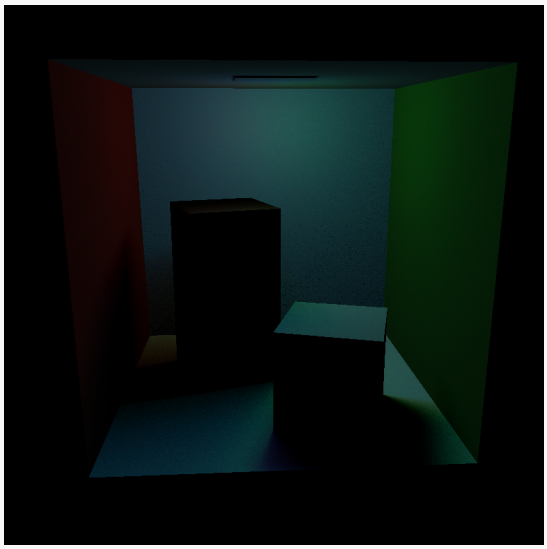
The color of the ray indicates transparency of the intersected meshes

Area lights

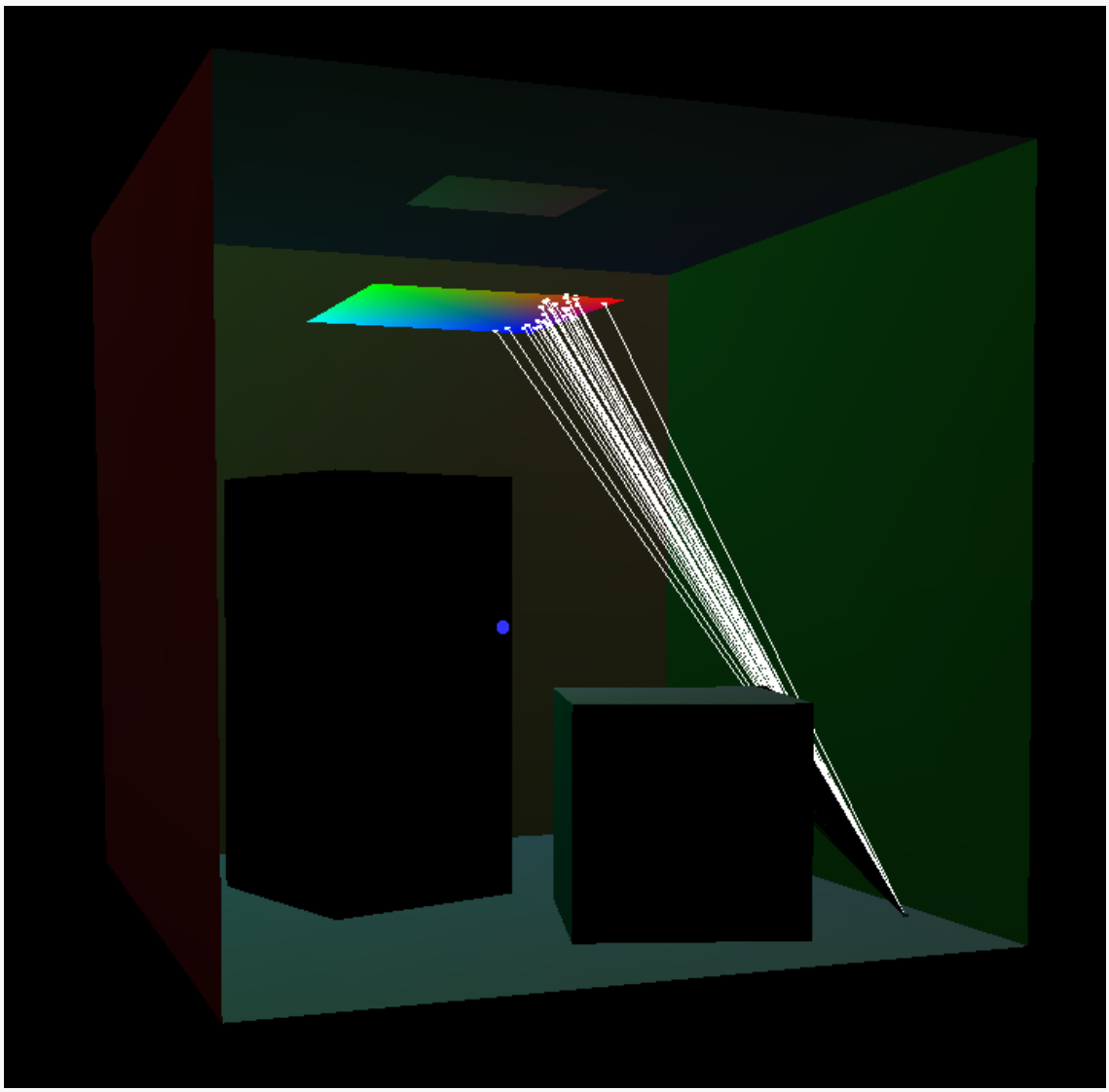
Implementation

A number of samples are taken randomly from the light, using linear (for segment lights) or bilinear (for area lights)
interpolation to determine the color. Then the samples are checked for visibility (see Hard Shadows)
and averaged together.

Examples

	
Segment light	*Area light*

Visual Debug



All samples are visualised; the color of the ray again indicates transparency

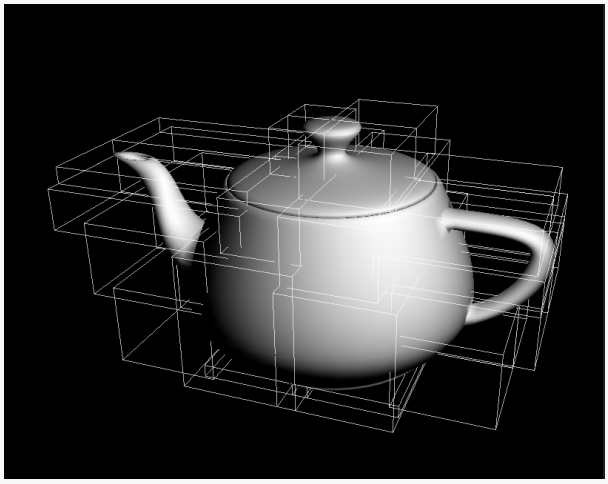
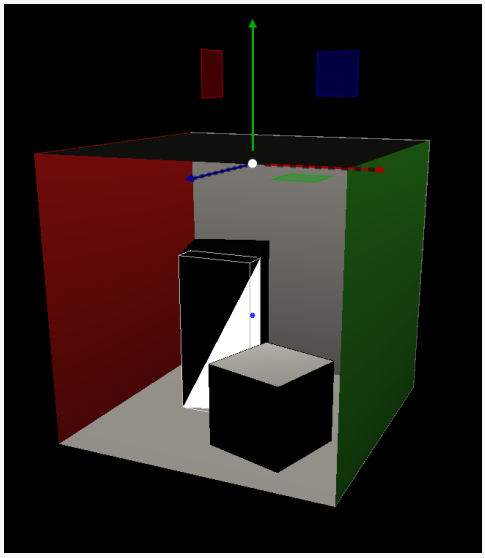
BVH generation

The `Node` structure is designed according to the assignment requirement, I use 4 indexes to locate a triangle, `TriangleCoordinate = (meshIndex, vertexIndex1,vertexIndex2,vertexIndex3)` .when a bvh tree is created, it goes through all the triangles and store the triangle coordinates in a vector, then it will be used in method `treeConstruction` which means to fill the global variable `tree`.

`treeConstruction` is a recursive function, at each layer the current node is generated according to the triangles it contains, then spilt the triangles in the middle and has the recursive calls for the next layer(if needed).

parameter `maxdepth` can be adjusted to control for the final shape of the `tree`, for default it's set to 10.

The effect of the BVH cannot be shown in the rendered image because it doesn't influence the appearance of the scene, but the improvement of the render speed is present in the "performance test" block.

	
AABBs for BVH nodes with level = 5	*4th leaf of the cornell box*

BVH traversal

Implementation

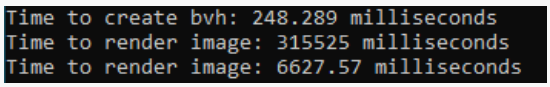
Using an iterative BFS algorithm implemented using a priority queue (instead of a normal queue) which holds indexes in
the data structure, the BVH traversal goes through each level of the acceleration data structure checking for
intersections with AABBs (if internal node) or primitives (if leaf node). It keeps (and continuously updates) a minimum
value for `ray.t`. This way it knows whether to visit the nodes that it intersects (if `ray.t < minRayT` then the
node is worth checking, otherwise the node is further away from the nearest primitive intersection).

To motivate the use of the priority queue, it seems that using a normal queue rarely, if at all (think 1:100), find
intersected nodes that will not be visited (this means that using a queue mostly evaluated nodes starting from the
farthest to the closest; this is bad because it means it checks all the nodes instead of discarding some of them).
The priority queue performs better in this manner and actually finds and "discards" intersected but not visited nodes
(see visual debug).

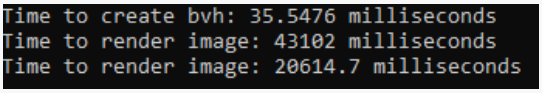
Examples

For clarity: The first render time is *without* BVH enabled, the second render time is *with* BVH enabled.
The render times decrease proportionally to the number of triangles/primitives. The more complex the object/image, the
better BVH performance!

`Time to create bvh: 248.289 milliseconds`
`Time to render image: 315525 milliseconds`
`Time to render image: 6627.57 milliseconds`
	`Time to create bvh: 35.5476 milliseconds`
	`Time to render image: 43102 milliseconds`
	`Time to render image: 20614.7 milliseconds`



Dragon render times - from 5 minutes to 7 seconds!

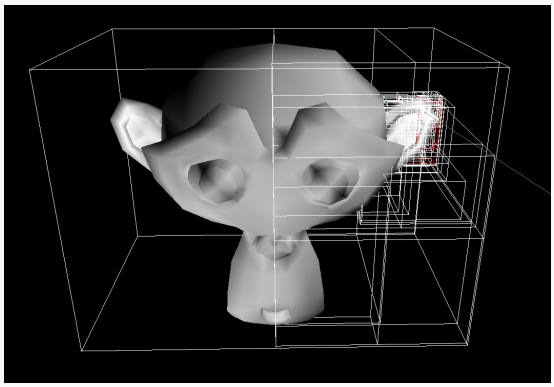


Teapot render times

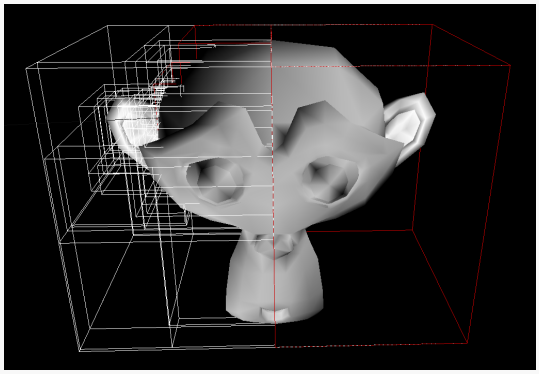
Visual Debug

When shooting a ray, (*only*) intersected nodes are visualized with the color white. The final primitive hit is also drawn in
white. This is visible in the 4th example.

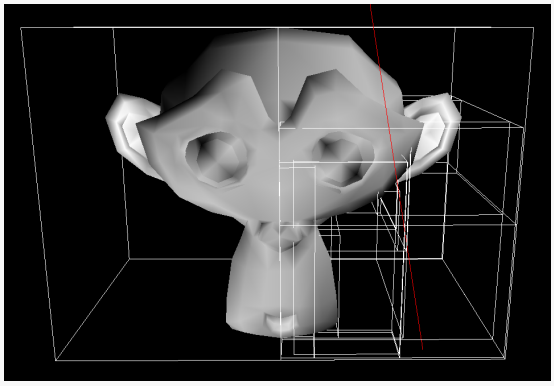
Nodes that are intersected but not visited are visualized with the color red. This option can be turned on/off by
checking a box (the "Draw intersected but not visited nodes with a different colour" flag) in the Debugging section of
the menu in OpenGL. This feature is best seen in examples 2 and 4.



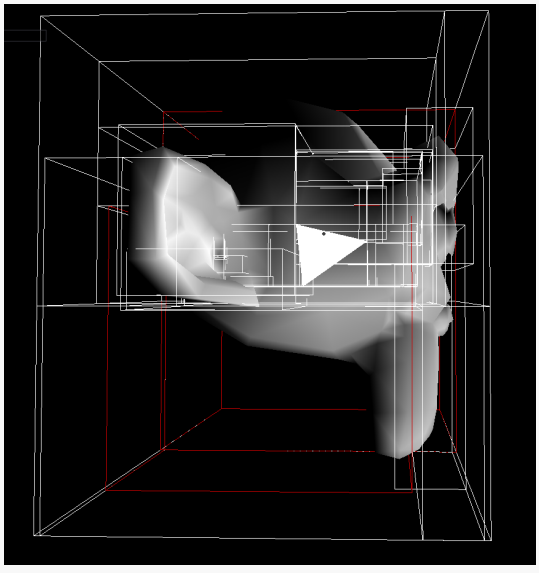
Example 1 - left ear hit



Example 2 - right side of head hit



Example 3 - no primitive hit



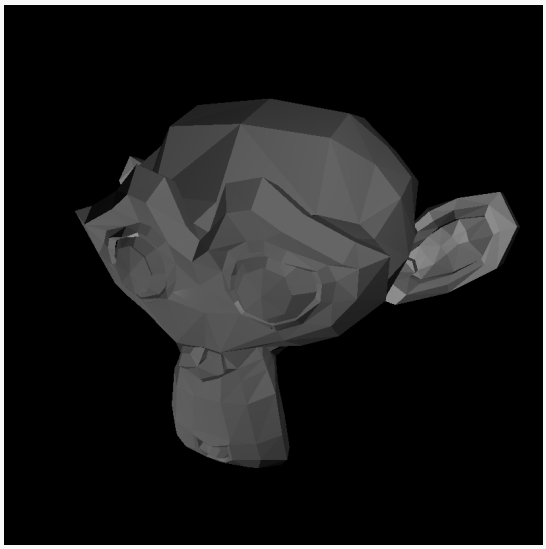
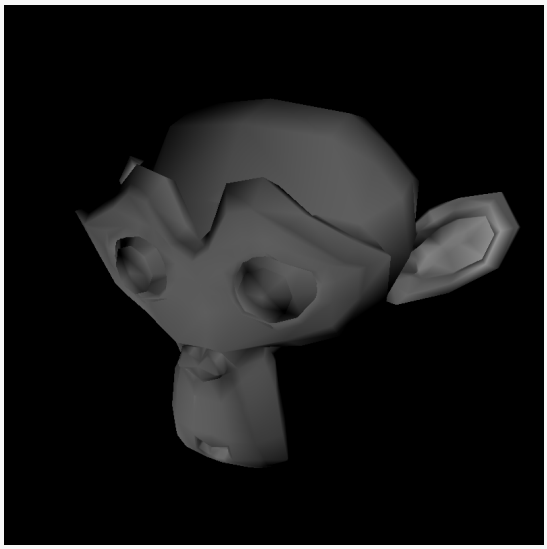
Example 4 - drawn primitive

Normal interpolation

Implementation

Normal is calculated using barycentric coordinates obtained in intersection and later used in shading and reflections.

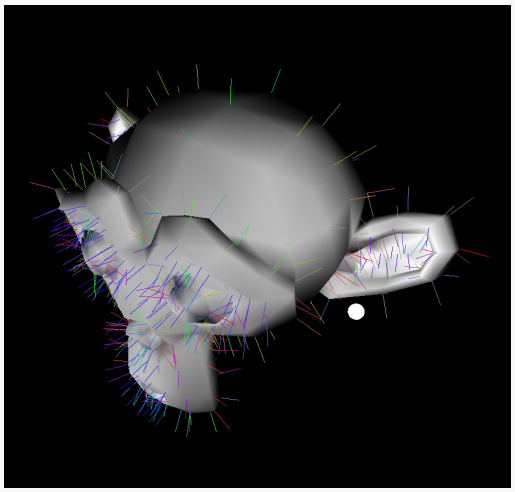
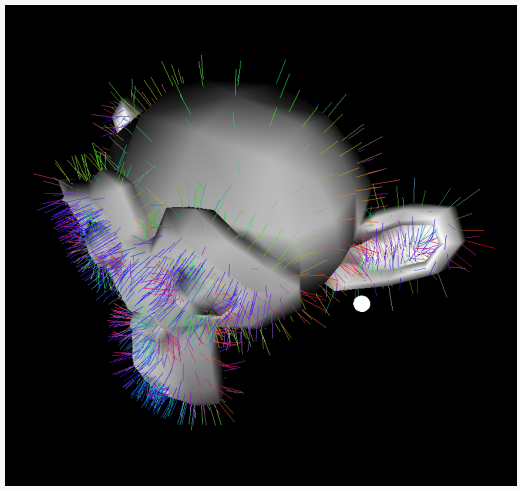
Examples

	
Without interpolation	*With interpolation*

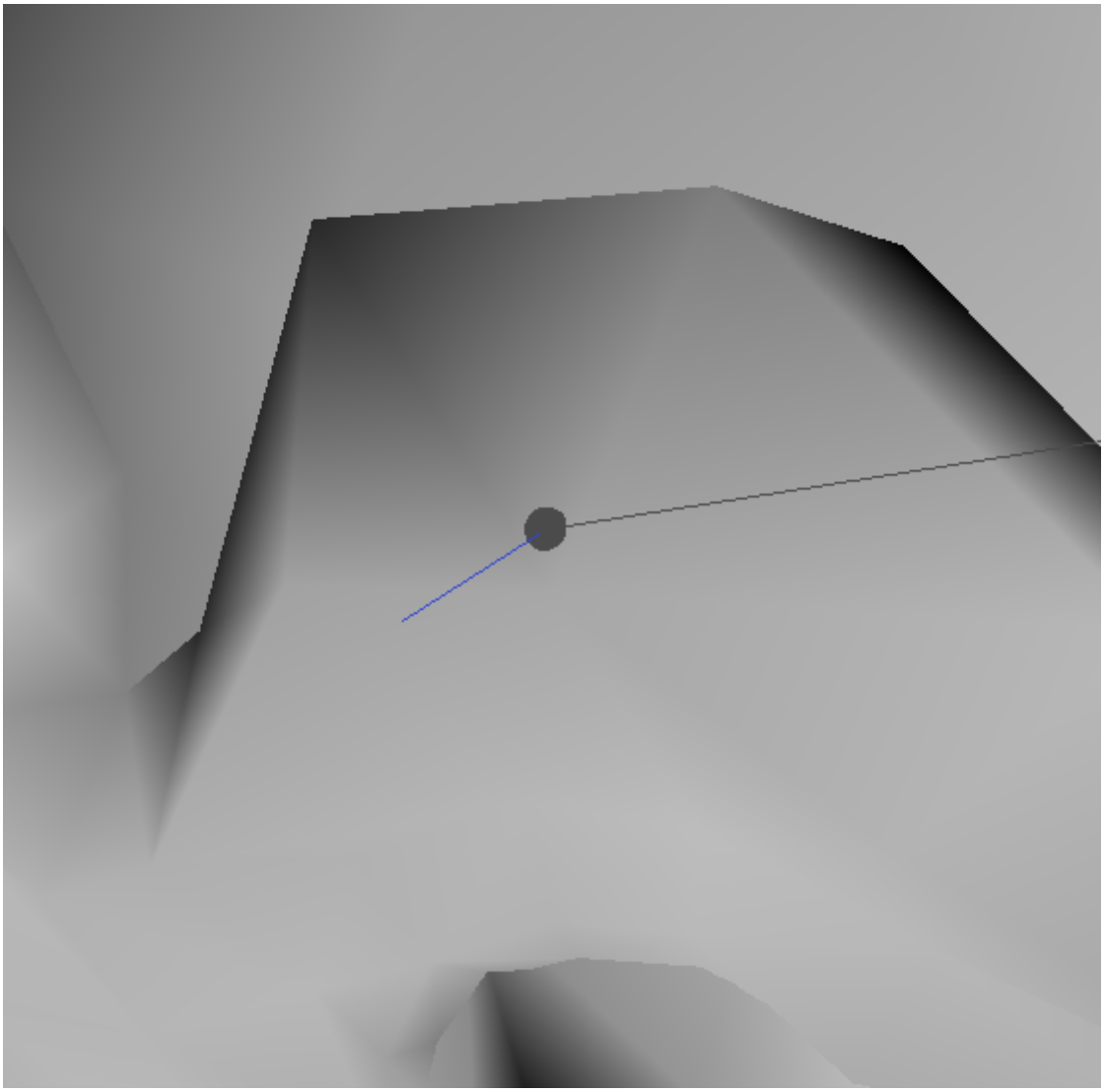
Visual Debug

There are two (not mutually exclusive options):

1. Draw normals at vertices and intermediate points:

	
Only vertices	*Vertices and points in between*

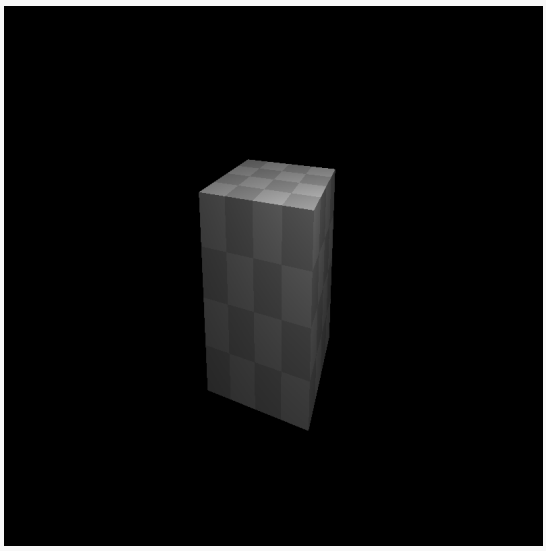
2. Draw normals at intersection points with debug rays

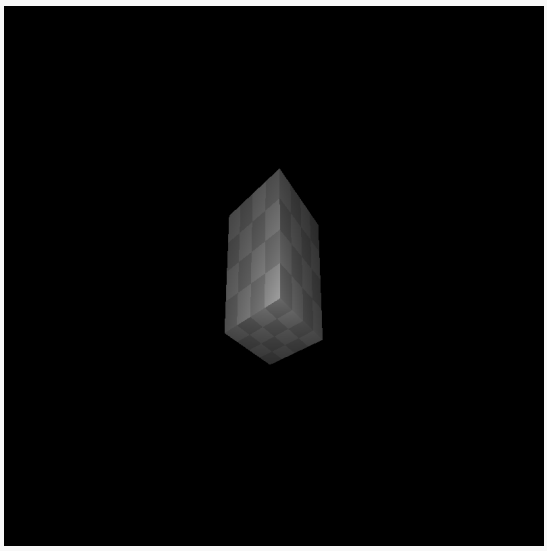


Texture

After the intersection point is generated, it's texture coordinates is calculated by interpolation, then the corresponding pixel is retrieved as a substitution for `hitInfo.material.kd`.

the debug ray will get color of the texture if texture mapping is enabled, we can also debug by checking the textured cube in ray-traced mode.





front 3 sufaces	*back 3 surface*

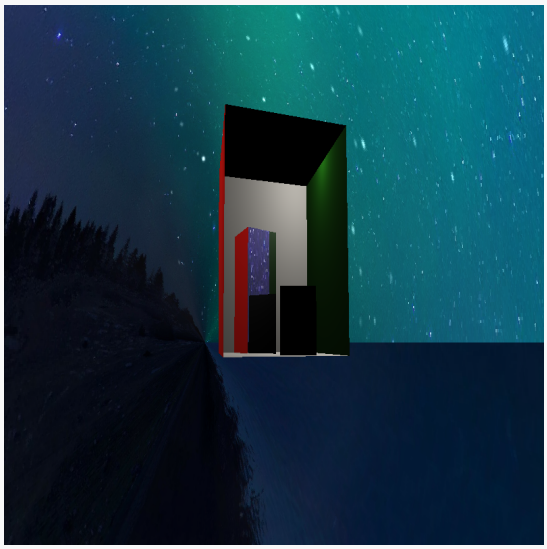
Extra Features

Environment maps

Method `glm::vec3 acquireTexelEnvironment(const Image& image, const glm::vec3& direction, const Features& features)` is made to retrieve the corresponding pixel of the environmental texture given the direction of the camera. A vector function is created to mapping normalized 3d vectors to a 2d vector (u,v) while u,v are values between 0 and 1. Then the uv coordinate is scaled according to the size of the texture and it's converted to the pixel index.

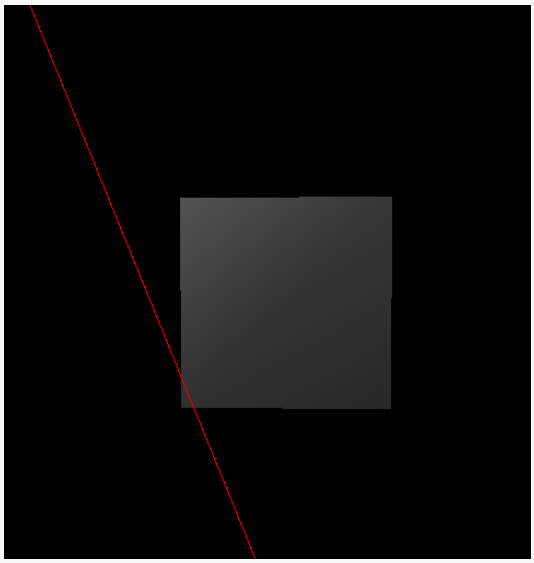
This method is called when the ray has no hit so it can create a background looking.

Without reflection

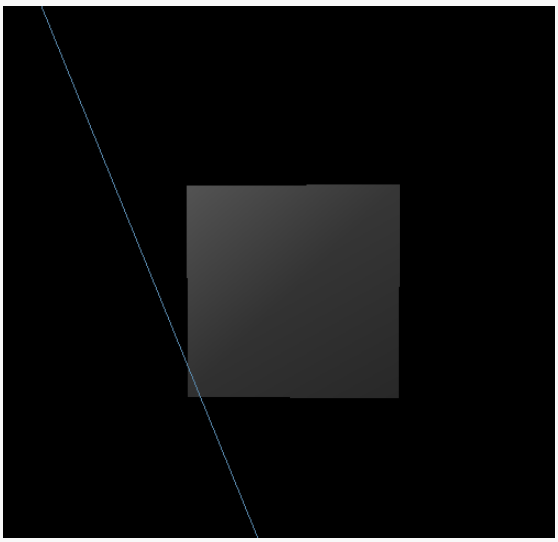


With reflection

The debug ray is used for the visual debug, if it has no hit with the environmental mapping open, the ray supposed to have the color of the environmental texture. or it's red as default.



Without environmental mapping



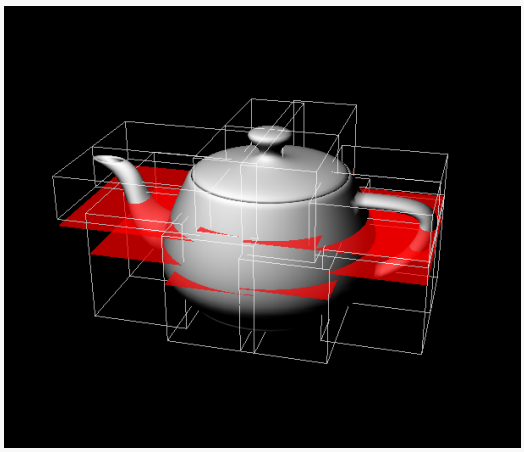
With environmental mapping

SAH+binning

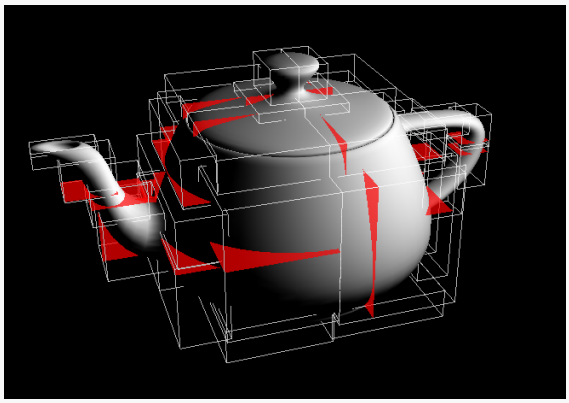
Now the splitting axis and boundary triangle are chosen base on the surface area heuristic. For each splitting the method `std::tuple<int, int> SurfaceAreaHeuristics(Scene* pScene,std::vector<glm::vec4>& traingleIndex)` is called, which will go through all the possible axis and bins, for each split choice, its score is calculated by $SurfaceAreaA * NumberofTrianglesA + SurfaceAreaB * NumberofTrianglesB$ (A and B are AABBs of the splited node). And the final criteria is determined by the one that has the smallest score. All the rest part is identical to BVH.

`float getSurface(const AxisAlignedBox& boundary)` is made auxiliary for the score calculation.

The splitting plane can be drawn with AABBs, indicating where the node gets splited, for BVH all the planes towards the same direction and always near the middle of the AABB, but for SAH splitting planes vary a lot.



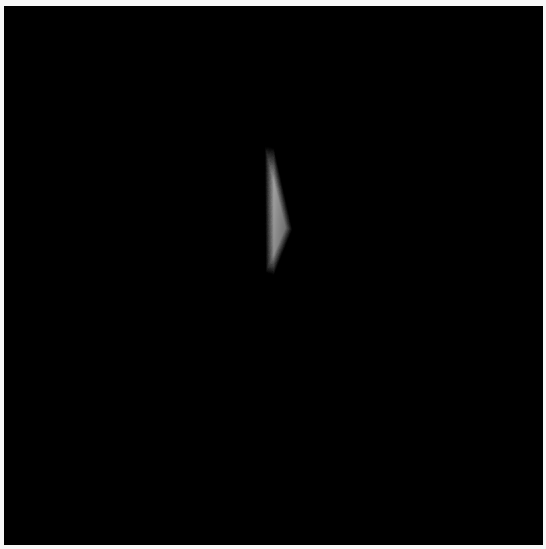
BVH splitting criteria



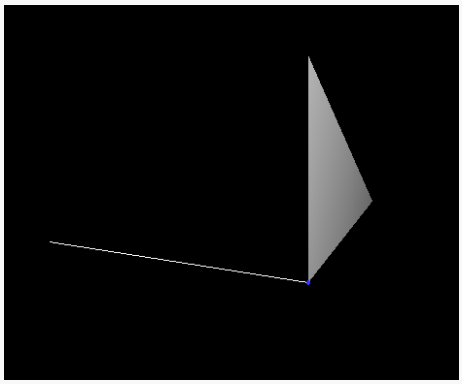
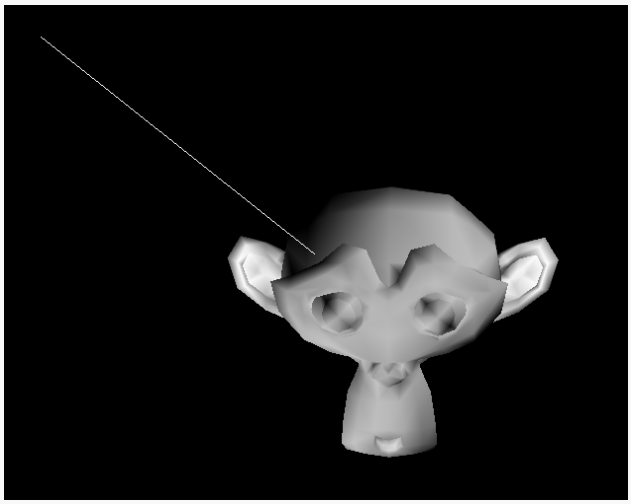
SAH splitting criteria

Motion blur

The motion direction and motion speed can be configured via the GUI, the motion direction is considered as the same with its normalized value, and the motion speed is a relative value without physical meaning. During rendering, `glm::vec3 motionBlur(const Scene& scene, const BvhInterface& bvh, const Ray& cameraRay, const Features& features)` is called, in which every ray's origin will have a offset within `(0, motionspeed•motion direction)`. for each ray, we sample the offsets in the range mentioned above, and the number of samples can be configured by GUI. The mean of the color those ray hits donates the final color of the pixel.

	
blured triangle(speed = 0.13)	*blured monkey(speed = 0.2)*

For visual debug a line segment can be drawn whose direction represents the motion direction and the motion speed is reflected in the length of the segment(relative value).

	
triangle motion	*monkey motion*

Bloom filter

Implementation

Bloom filtering is done on the final rendered image in the `renderRayTracing` method in the `render.cpp` file.
Following the model from the lecture, only pixels with color above a certain threshold are taken for filtering
(take a grayscale value which is represented by the highest term in RGB form: `max(red, green, blue)`). Then, a filter
is applied over these pixels. Instead of box filter (average of 9 pixels), as in the lecture, 2-pass gaussian filter is
used. This method provides a better blur because of usage of weights following a gaussian distribution, as opposed to
all pixels having the same weight (1/9) as in the box filter. 2-pass gaussian blur is better than normal gaussian blur

in terms of performance. In the end, the original image pixel is added to the filtered pixel to obtain the bloom effect.

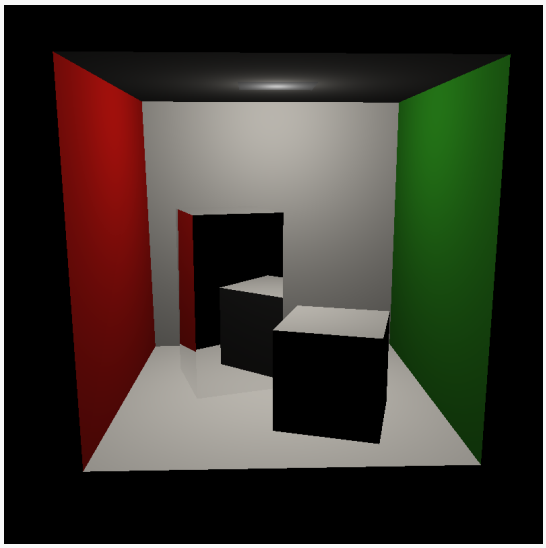
When enabling bloom filter in the OpenGL menu, there are 2 extra parameters which can be specified: `threshold` and
`intensity`. Both have Slider GUIs ranging from 0 to 1. `Threshold` controls how bright pixels should be in order to be
taken into account by the filter: high threshold means less pixels taken into account, lower threshold means more pixels.
`Intensity` controls how strong the light emission is on the filter: high intensity, stronger light emission.

Here are the sources which helped in implementing this feature:

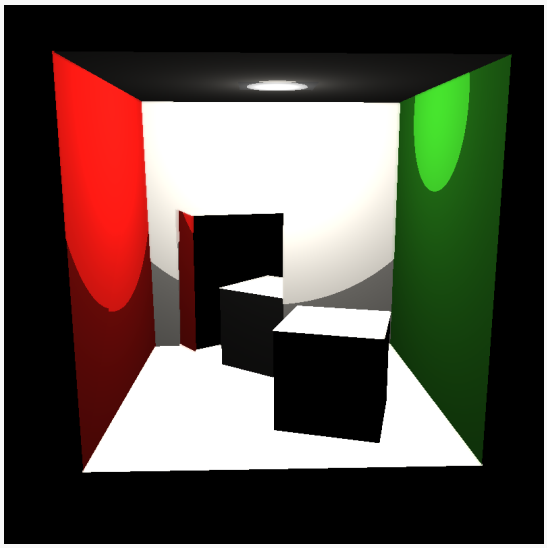
- Learn OpenGL Bloom
- Catlike coding - unity - bloom
- 3D Game Shaders For Beginners
- Shadertoy
- Wikipedia Box blur, while gaussian blur was used instead of box blur, this source helped in the implementation.

Examples

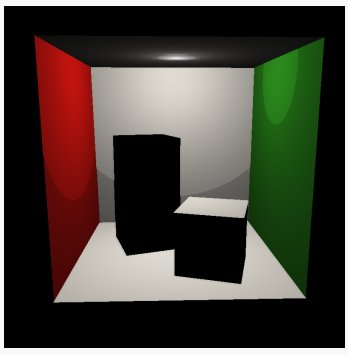
Cornell Box examples



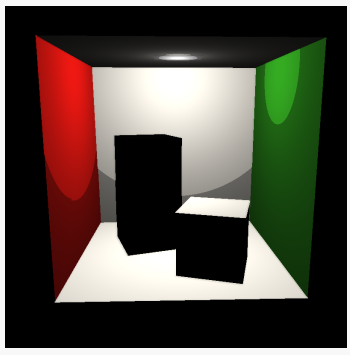
Bloom with 0 intensity



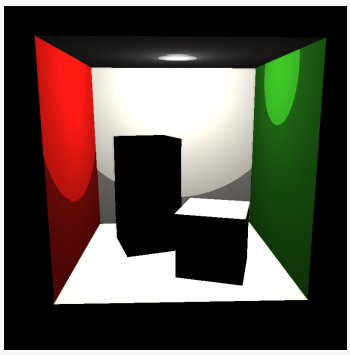
Bloom with 1 intensity



Low intensity

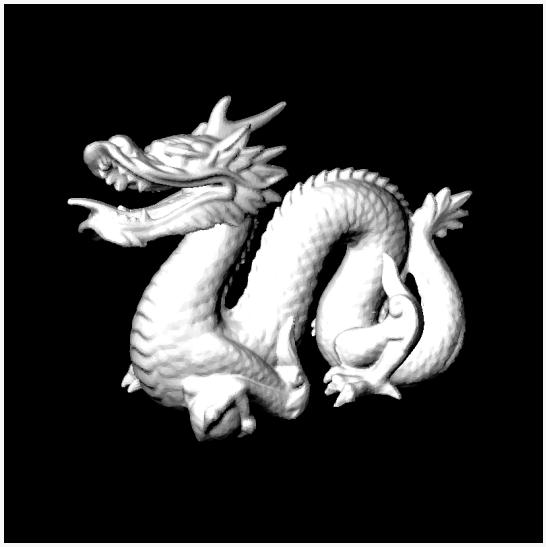
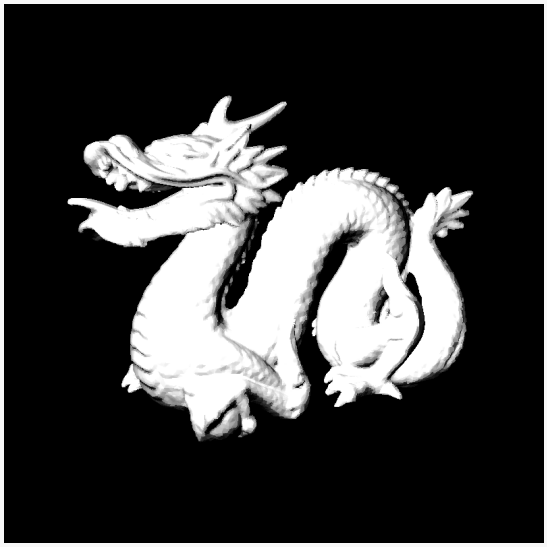


Medium intensity



High intensity

Dragon examples

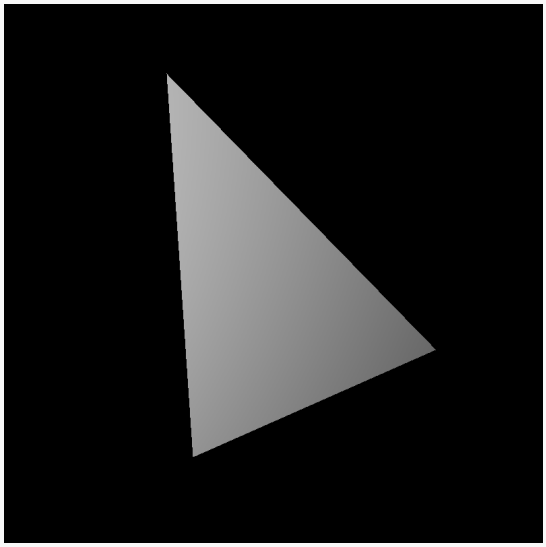
	
Low threshold, low intensity	*Low threshold, high intensity*
	
High threshold, low intensity	*High threshold, high intensity*

Irregular sampling

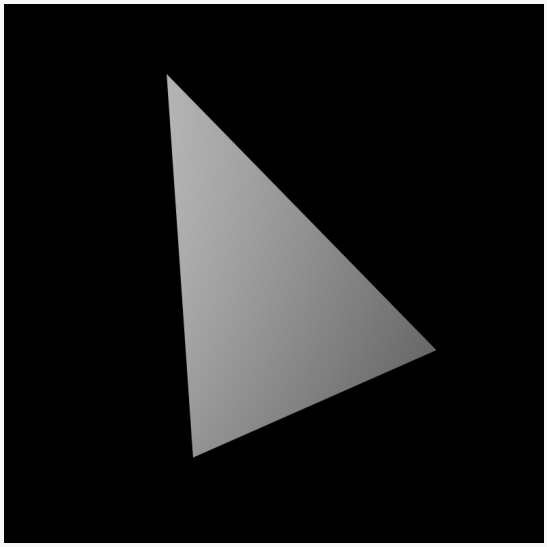
Implementation

Instead of taking one sample per pixel, a jittered grid of samples is taken, which eliminates jagged edges.

Example

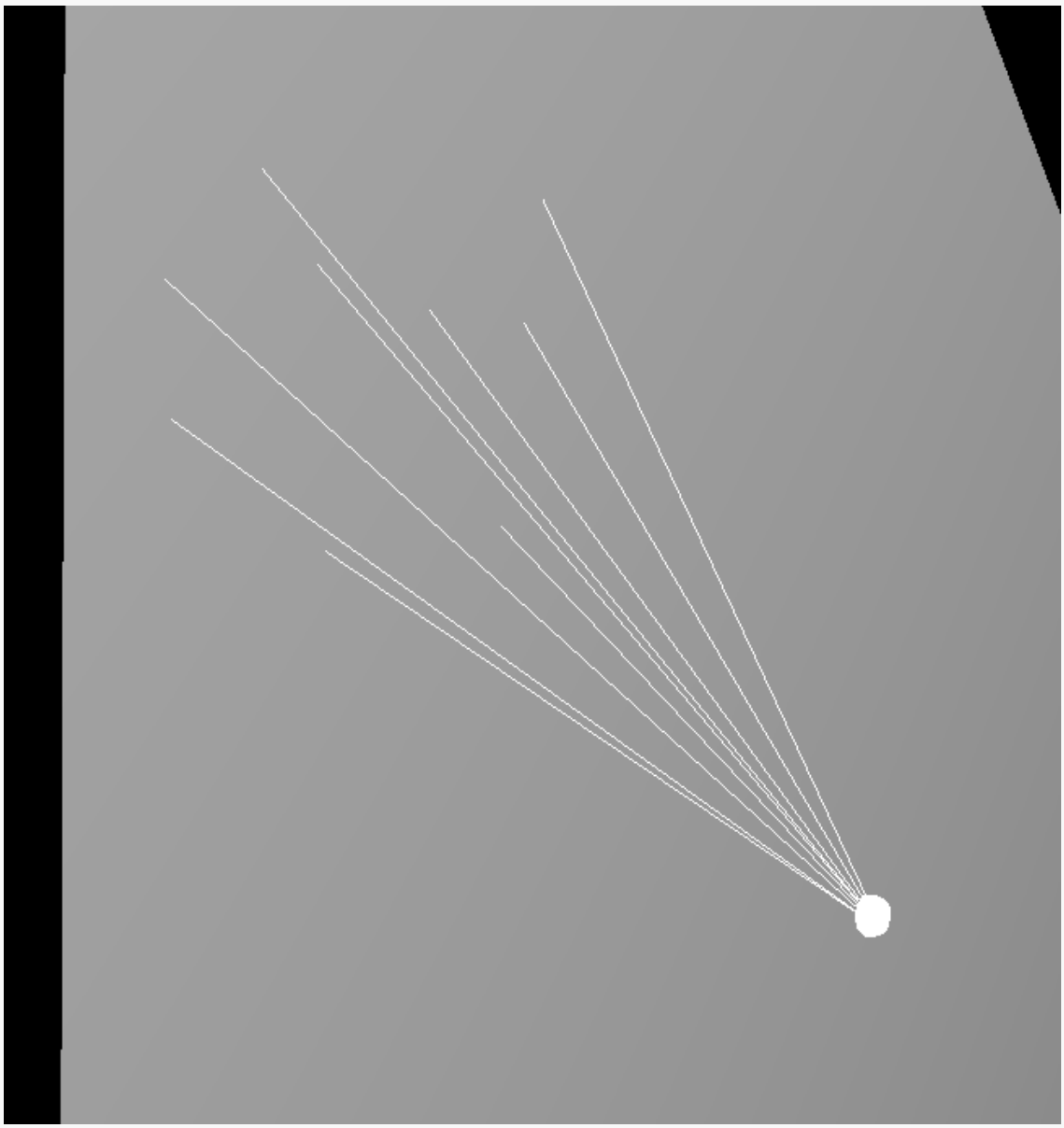


Notice the jagged edges without irreguar samping



With irreguar sampling, the edges are smooth

Visual Debug



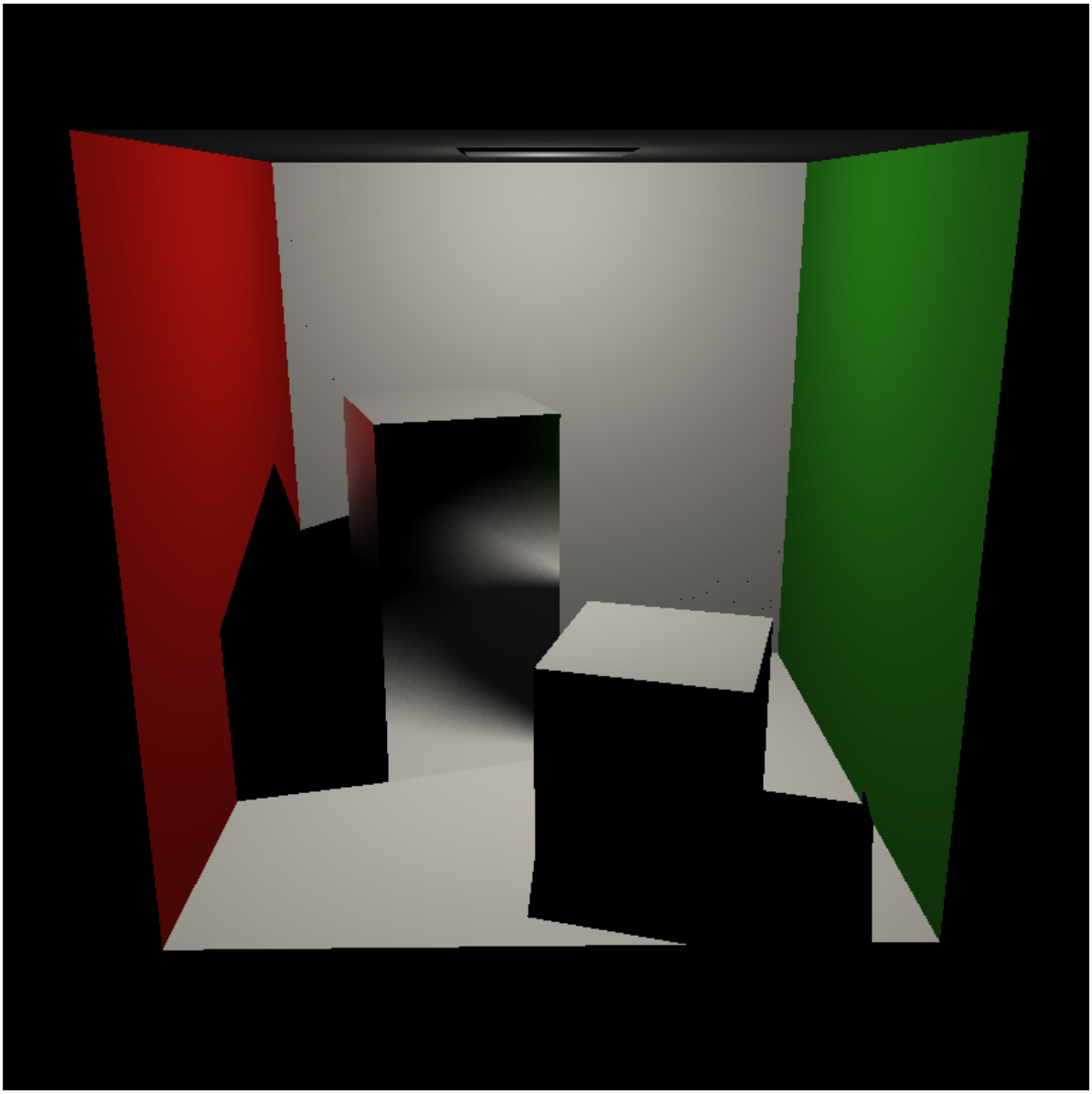
All samples are visualised

Glossy reflections

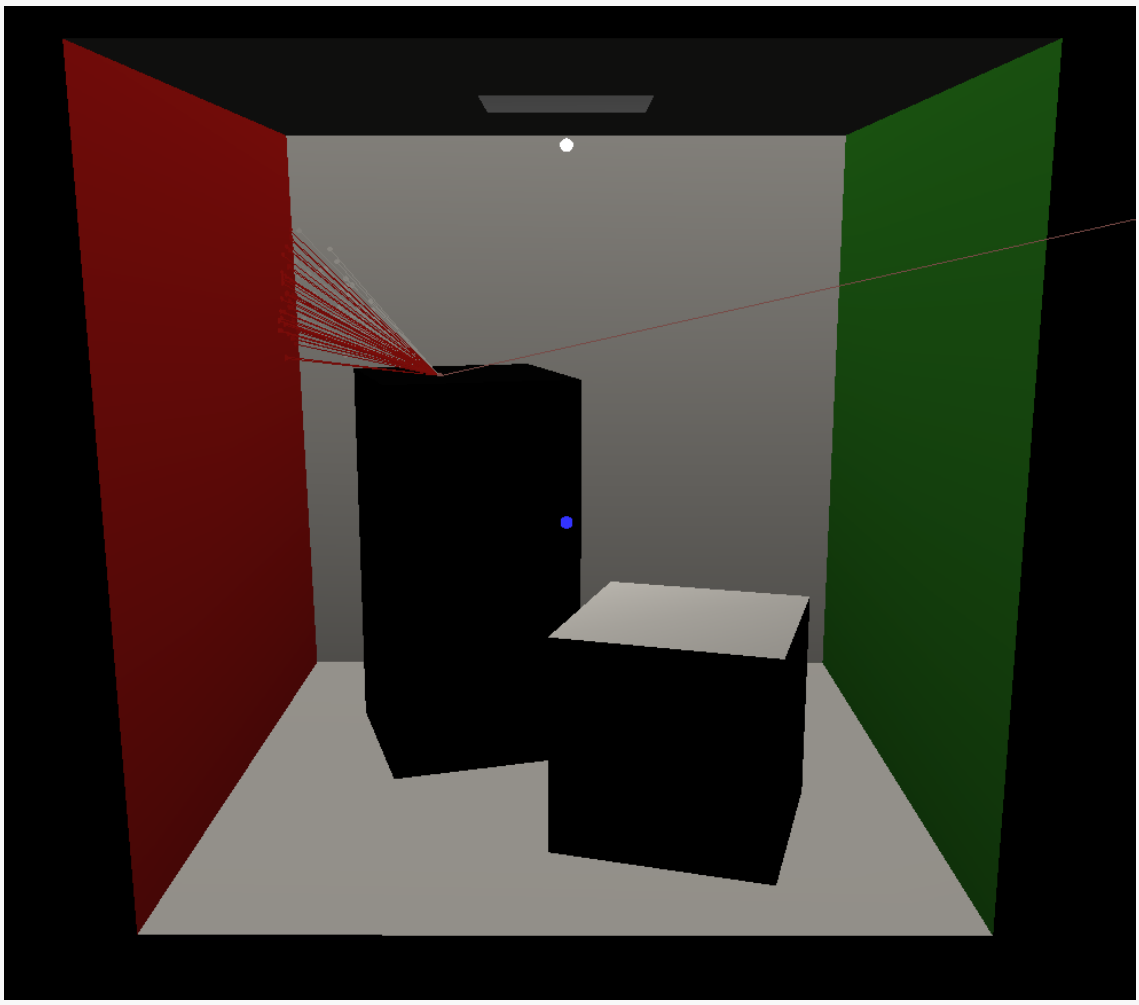
Implementation

When taking reflection samples, instead of taking just one, a number (controlled by the user) of samples is taken,
and each sample's direction is offset by a uniformly distributed point on a circle perpendicular to the direction
with radius `1/shininess`. All samples with direction away from the mesh (`direction · normal > 0`) are then averaged
to determine the final result.

Example



Visual Debug



All samples are visualised

Transparency

Implementation

When a sample ray hits a transparent surface, shading is calculated for the intersection point, a new sample is taken
in the same direction from the intersection and both results are combined using alpha blending.

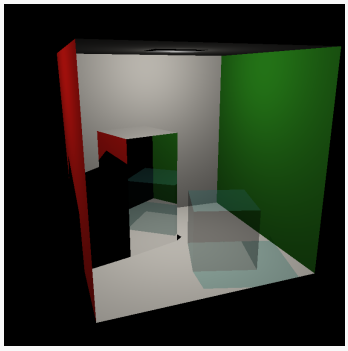
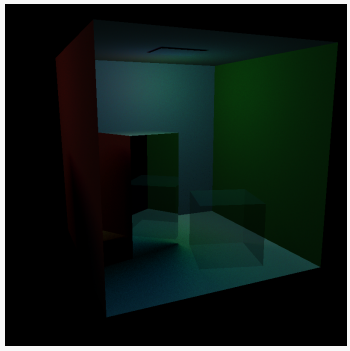
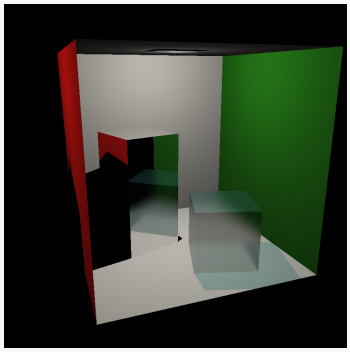
This is done both for direct samples and shadow rays; `testVisibilityLightSample` has been modified to take return
a `glm::vec3` indicating the colour of the shadow (which is later combined with the colour ofthe light).

Additionally, an option for translucency has been added: similar to glossy reflections,
instead of taking one sample when hitting a transparent surface, a number of randomly offset samples is taken.
The number of samples is controllable with a slider in the GUI.

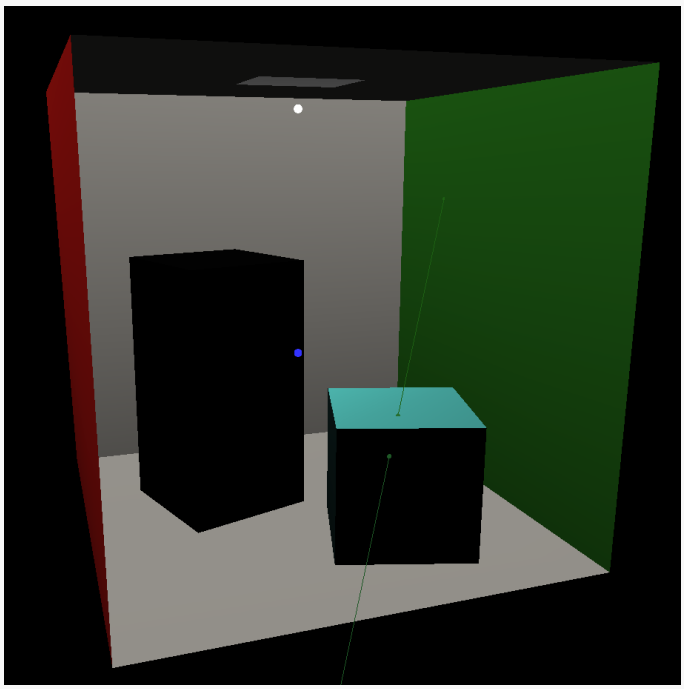
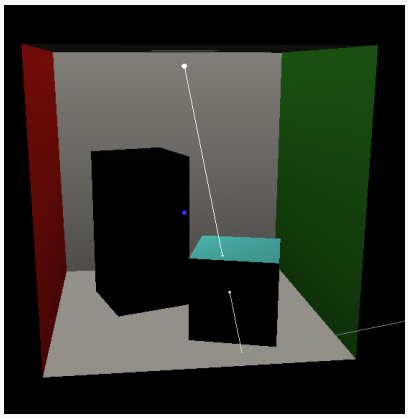
Examples

For the following images the *Cornell Box* scene was modified by replacing the small box's default material with this:

```
newmtl shortBox
Ns 10.000002
Ka 1.000000 1.000000 1.000000
Kd 0.3000 0.710000 0.680000
Ks 0.000000 0.000000 0.000000
Ke 0.000000 0.000000 0.000000
Ni 1.000000
d 0.200000
illum 1
```

		
Transparency with point light	*Transparency with area light*	*Translucency*

Visual Debug

	
Debug rays pass through	*Shadow rays also pass thhrough*

Depth of field

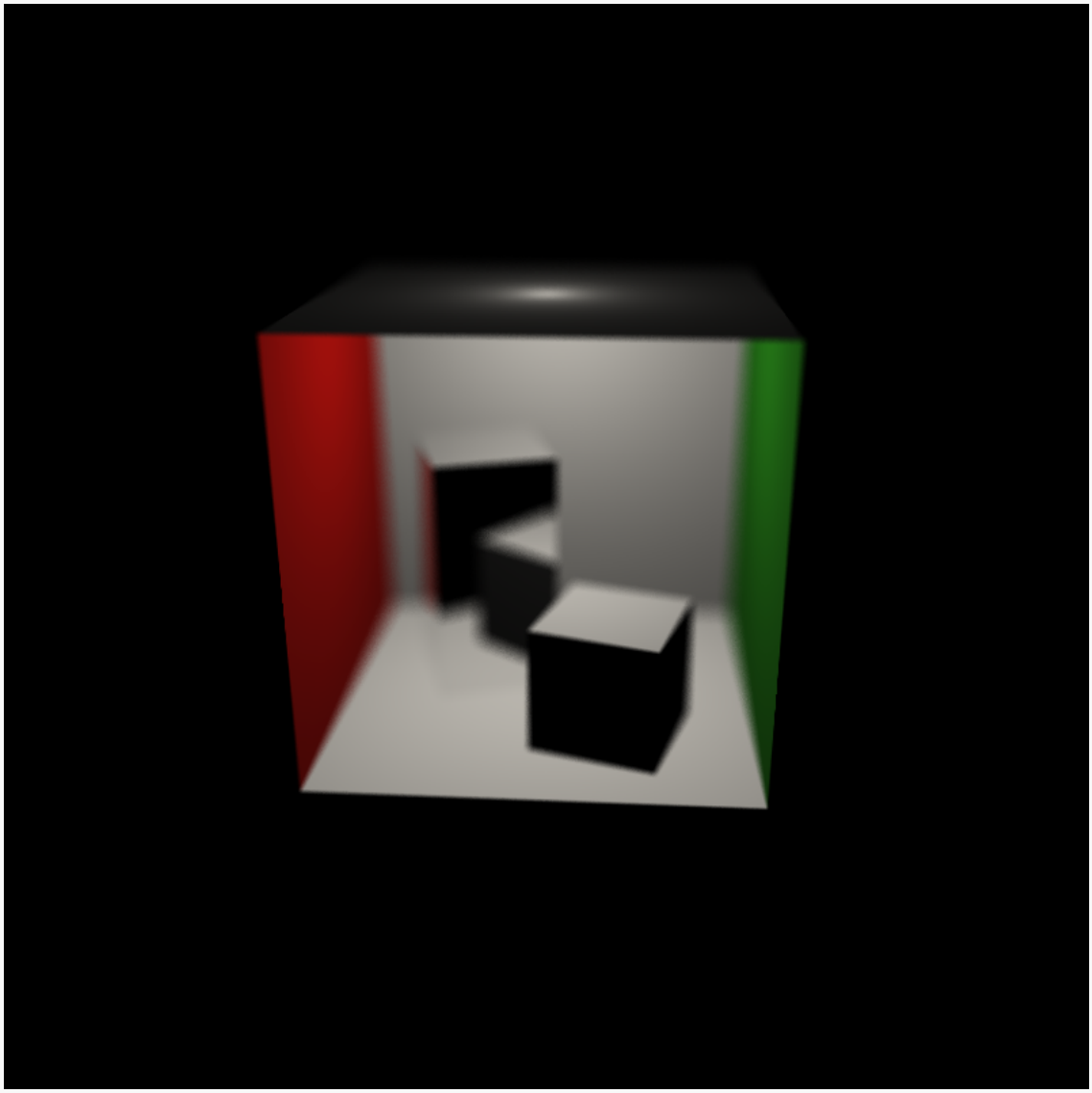
Implementation

Instead of shooting one ray, a number of samples is averaged. Each sample's origin is offset by a uniformly chosen
random point on the aperture, a circle perpendicular to `camera.forward` and centered on the camera's position,

and the sample's direction is found by taking the vector from the original's vector origin to its intersection
with the focal plane and offseting it the same distance as the origin, but in the opposite direction. This causes
all samples to converge on a single point on the focal plane.

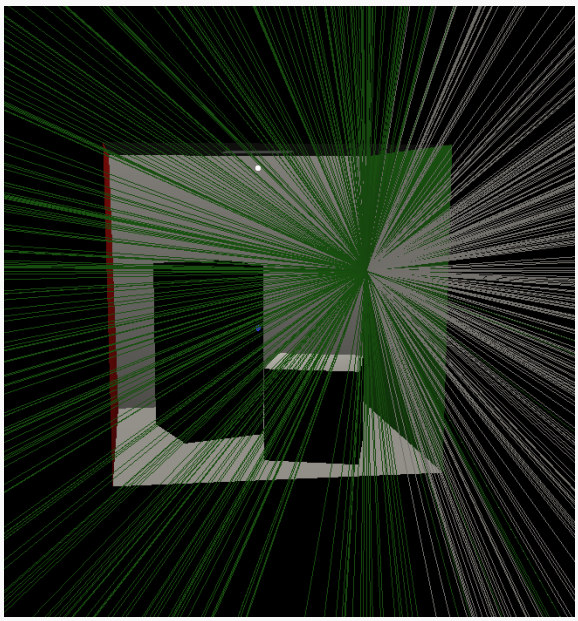
Focal length, aperture size and number of samples are user-controlled with sliders in the GUI.

Example

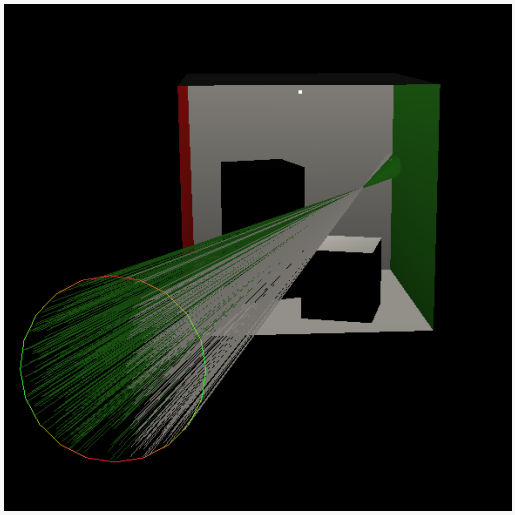


Focal length 2.5, aperture size 0.1

Visual Debug



All samples are visualised



Aperture is also shown

Performance test

	Cornell Box	**Monkey**	**Dragon**
Num triangles	32	967	87130
Time to create (BVH)	0.0571ms	1.8861ms	219.089ms
Time to render (BVH)	0.45324s	5.8615s	14,422s
Time to create (SAH)	0.9478ms	5.7154ms	885.793ms
Time to render (SAH)	0.259522s	3.32616s	10.5918s
BVH levels	4	7	10
Max tris p/ leaf node	8	8	86

**all the tests is measured within one execution, in the release mode, with all inrelavant feactures off.*