Rendering assignment one

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December 19, 2012

Introduction

This is my handin for the first three weeks for the course "Rendering". The last part contains the screenshots required for this handin.

Part 1 - the image loop

The task was to implement the loop over all pixels. This was simply done as a double for loop:

```
1  void RenderEngine::render()
2  {
3    cout << "Raytracing";
4    Timer timer;
5    timer.start();
6
7    #pragma omp parallel for private(randomizer)
8
9    for(int j = 0; j < static_cast<int>(res.y); ++j)
10   {
11     for(int k = 0 ; k <static_cast<int>(res.x) ; k++)
12     {
13       image[j*res.x + k] = tracer.compute_pixel(k,j);
14     }
15     if(((j + 1) % 50) == 0)
16       cerr << ".";
17   }
18   timer.stop();
19   cout << "\n\n" << timer.get_time() << " secs \n" << endl;
20
21   init_texture();
22   done = true;
23 }
```

We start by writing to the console and initialising a timer which tells how long it took to render the frame. Line 7 instructs the compiller to distribute the loop iterations encountered in the next for loop. I think this is done to allow multicore support. The loop itself is just a simple double for loop that loops over all the pixels in the image where

the limits for the loop is the width and height of the image. for each pixel is the compute pixel function called with the coordinates of the current pixel. For each 50th horizontal line that has been rendered a dot is sent to the console. At last the timer is stopped and the time is shown. The texture is then shown and the done flag set to true.

Part 2 - generating camera rays

The goal of this part was to set up the cameras and generate rays from it. First we needed to set up the `set` function of the camera. This was implemented in the following way:

```
1  void set(const optix::float3& eye_point,
2           const optix::float3& view_point,
3           const optix::float3& up_vector,
4           float focal_distance)
5  {
6    eye = eye_point;
7    lookat = view_point;
8    up = up_vector;
9    focal_dist = focal_distance;
10
11 ip_normal = optix::normalize(lookat - eye);
12 ip_xaxis = optix::normalize(optix::cross(ip_normal, up));
13 ip_yaxis = optix::cross(ip_xaxis, ip_normal);
14
15 float fovInRadians = 2*atan(1.0f/2.0f*focal_dist);
16
17   fov = fovInRadians * 180 * M_1_PIf;
18
19 }
```

First we set up the camera basis. This is first done by creating the normal vector to the image plane by substracting the lookat point's coordinates from the eye point's coordinates Next the x-axis of the camera basis is created by taking the cross product between the normal vector and the up vector. The y-axis is then created by crossing the x-axis and the normal vector(z-axis). All of the resulting vectors are also normalized so they form a set of proper orthonormal basis vectors. The field of view is implemented by rearranging the equation:

$$h = 2d\tan(\frac{fov}{2})$$

to:

$$fov = 2\arctan(\frac{1}{2}d) * blah$$

Since this is in radians we need to convert it to degrees so the final equation becomes:

$$fov = 2\arctan(\frac{1}{2}d) * 180 * frac1\pi$$

The function `get_ray_dir` is implemented next:

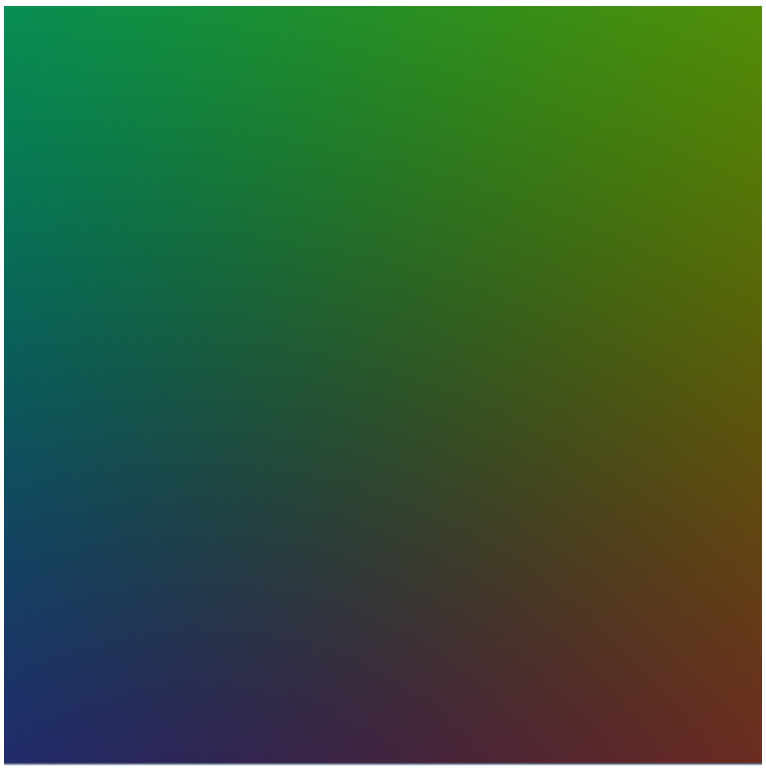
```
1  optix::float3 get_ray_dir(const optix::float2& coords) const
2  {
```

```
3       optix::float3 dir = ip_xaxis*coords.x + ip_yaxis*coords.y + ip_normal*
            focal_dist;
4
5       dir = optix::normalize(dir);
6
7       return dir;
8     }
```

This is simply a mater of transforming the normalized device coordinates into the corresponding point in the image plane world units. This is done by a change of basis. The `get_ray` is the last function in the camera to implement:

```
1   optix::Ray get_ray(const optix::float2& coords) const
2   {
3     return optix::Ray(eye, this->get_ray_dir(coords), 0, 0.1f);
4   }
```

The origin is simply the eye position, while the direction is determined by the normalized device coordinates that is given as input to the function. We then use the `compute_pixel` to get the result:



Which is what we expected.

Part 4 and 5 - Conditional Acceptance of Collision, Shading, and Hard Shadows

The task was here to implement ray-plane-, ray-triangle- as well as ray-sphere intersection and afterwards implement the surfaces as lambertian reflectors. This is done by implementing the `intersect` function in each of the three primitives. For a ray:

$$r(t) = \mathbf{o} + t\mathbf{w}$$

and plane:

$$ax + by + cz + d = 0 \Leftrightarrow \mathbf{p} * \mathbf{n} + d = 0$$

By putting the ray definition into the equation for the plane and solving for t we find at what distance along the ray we intersect the plane.

$$(\mathbf{o} + t\mathbf{w}) * \mathbf{n} + d = 0 \Leftrightarrow t = \frac{\mathbf{o} * \mathbf{n} + d}{\mathbf{w} * \mathbf{n}}$$

We then check if the found distance is between the minimum and maximum values we have now. If it is we record the hit. In the code this is done like this:

```
1  bool Plane::intersect(const Ray& r, HitInfo& hit, unsigned int prim_idx)
       const
2  {
3    float t = -( optix::dot(r.origin, get_normal()) + d ) / ( optix::dot(r.
       direction, get_normal()) );
4
5    if(t >= r.tmin && t <= r.tmax)
6    {
7      hit.has_hit = true;
8      hit.position = r.origin + r.direction*t;
9      hit.dist = t;
10         hit.geometric_normal = get_normal(); // (the normalized normal of
               the plane)
11         hit.shading_normal = get_normal();   //   (the normalized normal of
                the plane)
12         hit.material = &material;             //      (pointer to the
               material of the plane)
13
14     return true;
15   }
16   else
17   {
18      return false;
19   }
20 }
```

The sphere is implemented in a similar way:

```
1  bool Sphere::intersect(const Ray& r, HitInfo& hit, unsigned int prim_idx)
       const
2  {
3    float bDiv2 = optix::dot( (r.origin - center) , r.direction );
4    float c = optix::dot( (r.origin - center), (r.origin - center));
5    c += - radius*radius;
6
7    if(bDiv2*bDiv2 - c >= 0)
8    {
9      //std::cout << "in plane " << hit.has_hit << "\n";
10     float t = - bDiv2 - sqrt(bDiv2*bDiv2 - c);
11
12     if(t > r.tmin && t < r.tmax)
```

```
13      {
14        hit.has_hit = true;
15        hit.position = r.origin + r.direction*t;
16        hit.geometric_normal = optix::normalize(hit.position - center); // (
              the normalized normal of the plane)
17        hit.shading_normal = hit.geometric_normal;    //    (the normalized
              normal of the plane)
18        hit.material = &material;                //       (pointer to the
              material of the plane)
19
20        return true;
21      }
22    }
23    return false;
24  }
```

Here we insert the ray equation into the equation for the sphere:

$$(p-c)*(p-c) = r^2 \Leftrightarrow t = (\mathbf{o}-\mathbf{c}+t\mathbf{w})*(\mathbf{o}-\mathbf{c}+t\mathbf{w}) = r^2$$

This yields a second degree polynomial with the a,b and c coeficients equal to:

$$a = \mathbf{w}*\mathbf{w} = 1b/2 = (\mathbf{o}-\mathbf{c}*\mathbf{w}c = (\mathbf{o}-\mathbf{c})*(\mathbf{o}-\mathbf{c}) - r^2$$

This is solved by finding the first root:

$$t_1 = -b/2 - \sqrt[2]{(b/2)^2 - c}$$

Of course if the determinant $(b/2)^2$ is less than zero then there is no intersection. Due to time constraints I have not implemented the ray-triangle intersection myself but have used the one in the optix library.

Triangle intersection is based on finding the baryocentric coordinates of the hit between the triangle and the ray. If we dfine the triangle to have the sides:

$$e_1 = V_1 - V_0$$

$$e_2 = V_2 - V_0$$

We can use it together with point V0 to create an affine combination that spans the plane of the triangle with the baryocentric coordinates (u,v). A formula for a point on the plane of the triangle is therefore:

$$T(u,v) = V_0 + ue_1 + ve_2$$
$$T(u,v) = V_0 + u(V_1 - V_0) + v(V_2 - V_0)$$

This can be rearanged to:

$$T(u,v) = (1-u-v)V_0 + uV_1 + vV_2$$

Since we are only interested in points inside the triangle we have that:

$$u \geq 0$$

$$v \geq 0$$

$$u + v \leq 1$$

To compute the uv coordiantes we set the line equation of the ray equal to the equation of the plane in baryocentric coordinates:

$$P = td = (1 - u - v)V_0 + uV_1 + vV_2$$

by rearanging the equation we can express it as a matrix product:

$$\begin{bmatrix} -d & V_2 - V_0 & V_1 - V_0 \end{bmatrix} \begin{bmatrix} t \\ u \\ v \end{bmatrix} = P - V_0$$

By using either Cramer's rule or row reduction we can find that:

$$t = \frac{q * e_2}{p * e1}$$

$$u = \frac{p * s}{p * e_1}$$

$$v = \frac{q * d}{p * e_1}$$

Where:

$$s = P - V_0 \quad p = d \times e_2 \quad q = s \times e_1$$

Below is my implementation of this approach which also checks if the ray and triangle are parallel before it proceeds to calculate the intersection.

```
1  bool intersect_triangle(const Ray& ray,
2                          const float3& v0,
3                          const float3& v1,
4                          const float3& v2,
5                          float3& n,
6                          float& t,
7                          float& v,
8                          float& w)
9  {
10   //find sides of triangle
11   float3 e1 = v1 - v0;
12   float3 e2 = v2 - v0;
13
14   //find perpendicular vector between ray direction and one of the sides
15   float3 p = optix::cross(ray.direction, e2);
16
17   //take the dot product between this vector and the other side of the
         triangle
18   float a = dot(e1, p);
19
20   //if a is equal to zero then the ray is parallel with the triangle and no
         intersection ocurs
21   if(a == 0 || (a < 0.001f && a > -0.001f))
22   {
```

```
23      return false;
24    }
25    //compute denominator
26    float f = 1.0f/a;
27
28    //compute barycentric coordinates and check if they are within the
          accepted boundaries
29    float3 s = ray.origin - v0;
30    v = f * dot(s,p);
31    if(v < 0.0f || v > 1.0f)
32      return false;
33
34    float3 q = cross(s, e1);
35    w = f * dot(ray.direction, q);
36    if(w < 0.0f || w + v > 1.0f)
37      return false;
38
39    t = f * dot(e2,q);
40
41    //calculate normal
42    n = cross(e1, e2);
43
44    return true;
45  }
```

A last note, in the Accelerator's render function the max distance of the ray is set to the t value returned from a successful hit. That way we make sure that closer hits overrides hits farther away. This means we in the end shades the pixel according to the closest hit.

Point light implementation & Lambertian shading

The next part is to implement Kepler's inverse square law of radiation that governs how light from a point light spreads. Since I have also implemented a simple version of shadow rays the function look like this:

```
1   bool PointLight::sample(const float3& pos, float3& dir, float3& L) const
2   {
3     if(!shadows)
4     {
5       dir = optix::normalize(light_pos - pos);
6
7       L = intensity / ( optix::length(light_pos - pos) * optix::length(
            light_pos - pos) ) ;
8
9       return true;
10    }
11    else
12    {
13      optix::float3 shadowDir = optix::normalize( light_pos - pos );
14      HitInfo hit;
15
16      optix::Ray shadowRay = Ray(pos, shadowDir, 0, 0.0001f);
17
18      if(!tracer->trace_to_any(shadowRay, hit))
```

```
19      {
20
21        dir = optix::normalize(light_pos - pos);
22
23        L = intensity / ( optix::length(light_pos - pos) * optix::length(
              light_pos - pos) ) ;
24
25        return true;
26      }
27      else
28      {
29        L = make_float3(0,0,0);
30
31        return false;
32      }
33    }
34  }
```

First we check if we should use shadows. If no then we just compute the radiance and return true. If we should use shadows we create a shadow ray and see if it intersects any objects on its way from the surface to the light source. The first part of this is simply to declare variables used to check for shadows. First we find the direction of the shadow ray by finding the vector from the location on the surface to the light source and normalizing it. A HitInfo variable is then declared so we can call the `tracer`'s `trace_to_any` function. This function is used since we only wants to know if the ray hits something. This ray is declared with the direction we made earlier and the position equal to the location on the surface. If the function return false then the light ray hits the surface and we compute the radiance based on the inverse square law and return true. If not then then we set the returned radiance to 0 and return false. When the radiance is calculated we also return the direction of the light ray which we need in order to evaluate Lambert's cosine law.

The last step is to shade the surface according to Lambert's cosine law. This is done in the `Lambertian` shader's `shade` function:

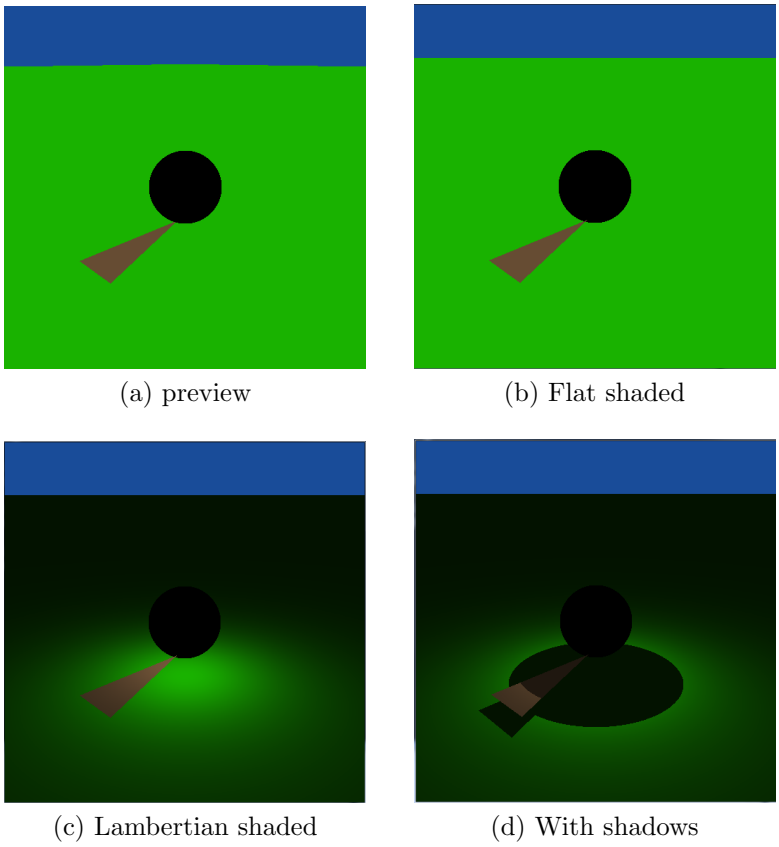
```
1  float3 Lambertian::shade(const Ray& r, HitInfo& hit, bool emit) const
2  {
3    float3 rho_d = get_diffuse(hit);
4    float3 result = make_float3(0);
5
6    // Implement Lambertian reflection here.
7    //
8    // Input:  r          (the ray that hit the material)
9    //         hit        (info about the ray-surface intersection)
10   //         emit       (passed on to Emission::shade)
11   //
12   // Return: radiance reflected to where the ray was coming from
13   //
14   // Relevant data fields that are available (see Lambertian.h, HitInfo.h,
         and above):
15   // lights             (vector of pointers to the lights in the scene)
16   // hit.position       (position where the ray hit the material)
17   // hit.shading_normal (surface normal where the ray hit the material)
18   // rho_d              (difuse reflectance of the material)
```

```
19    //
20    // Hint: Call the sample function associated with each light in the scene
          .
21
22    float3 lambertianBRDF = rho_d * M_1_PIf;
23
24    for(int i = 0 ; i < lights.size() ; i++)
25    {
26      float3 Li;
27      float3 dir;
28
29      if(lights[i]->sample(hit.position, dir, Li))
30      {
31        result += lambertianBRDF * Li * optix::dot(dir, hit.shading_normal);
32      }
33    }
34
35    return result + Emission::shade(r, hit, emit);
36  }
```

We loop over all the lights in the scene and sample each of them. If the point being shaded is hit by the light we add the diffuse reflectance divided by pi, times the radiance returned by the light times the dot product between the direction of the light and the ray.

Part 6 - deliverables

Here is the finished results:

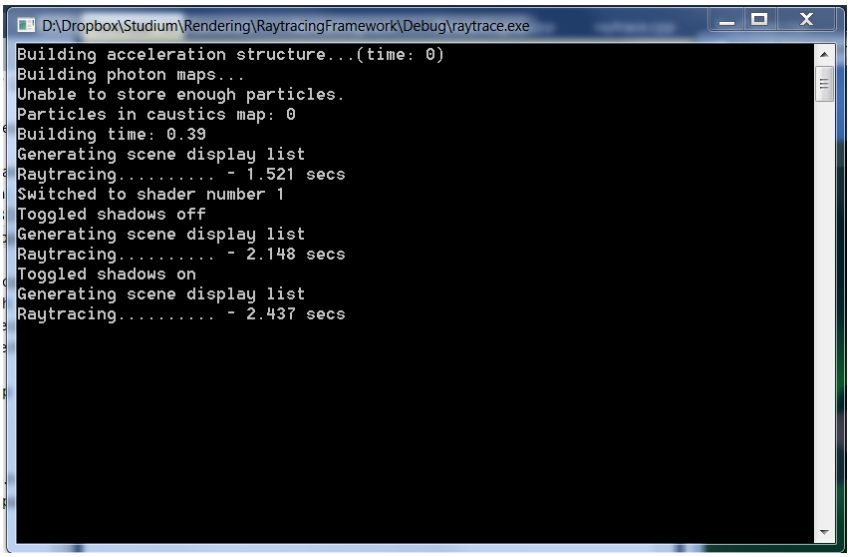


(a) preview (b) Flat shaded

(c) Lambertian shaded (d) With shadows

Figure 1: The different renderings

In the console we can see the rendering time goes up for each extra feature added:



Rendering assignment two

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December 19, 2012

Introduction

This is my handin for the third week for the course "Rendering".

Part 1 - Hard Shadows

I covered this in the last handin so I have chosen not to explain it again.

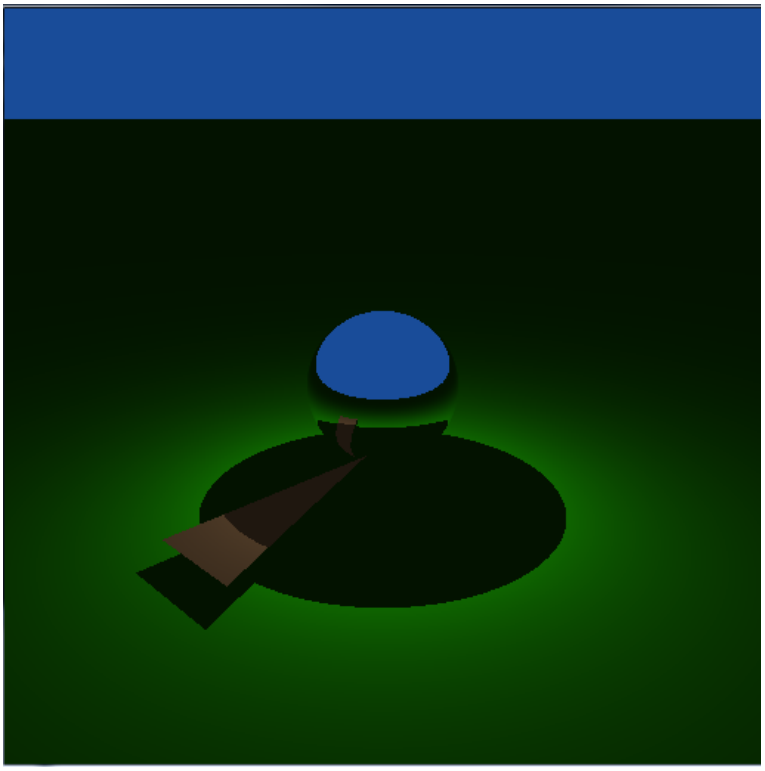
Part 2 - Mirror Reflection

The tracing of reflected rays is implemented in the following way:

```
1  bool RayTracer::trace_reflected(const Ray& in, const HitInfo& in_hit, Ray&
       out, HitInfo& out_hit) const
2  {
3    float3 reflectedDir = optix::reflect(in.direction, in_hit.
       geometric_normal);
4
5    out = Ray(in_hit.position, reflectedDir, 0, 0.01f);
6
7    if(this->trace_to_closest(out, out_hit))
8    {
9      out_hit.trace_depth = in_hit.trace_depth + 1;
10
11     out_hit.ray_ior = in_hit.ray_ior;
12
13     return true;
14   }
15   return false;
```

First the reflected vector is calculated with the use of the reflect function in the optix library. A new ray is then created with start point where the last ray hit and in the direction of the reflection. The ray is then traced. If it hits anything, the outgoing ray's trace depth is set to the incoming ray's plus one. This is done to make sure that the tracing will terminate when a certain trace depth has been reached. The outgoing ray's index of refraction is then set and since it is in the same medium as the incoming ray it

is set to have the same index of refraction as the first ray. The function then returns true if the outgoing ray hit anything. The end result look like this:



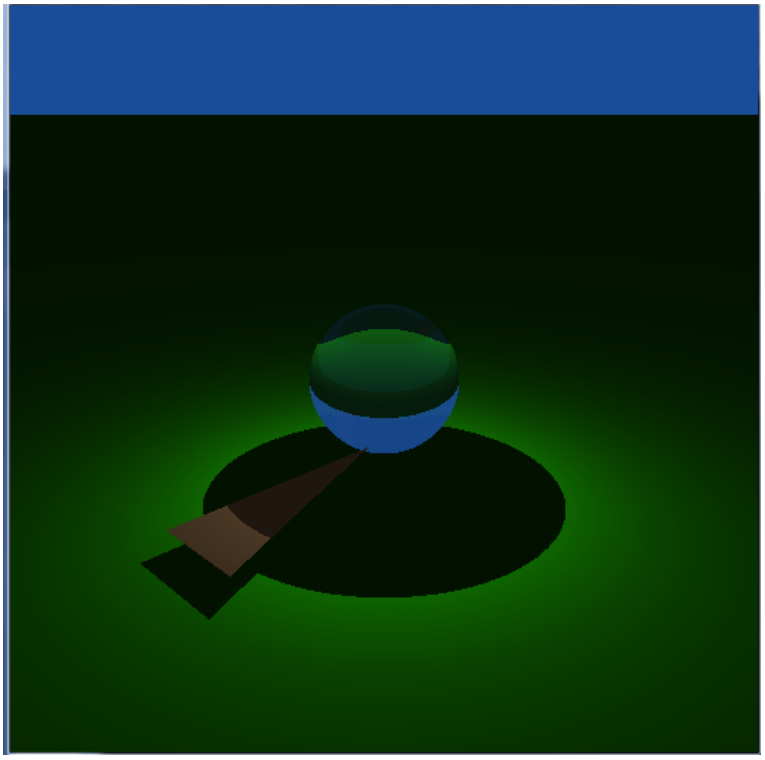
```
Building acceleration structure...(time: 0.001)
Building photon maps...
Unable to store enough particles.
Particles in caustics map: 0
Building time: 0.314
Generating scene display list
Switched to shader number 1
Generating scene display list
Raytracing.......... - 2.15 secs
```

Part 3 - Refraction

```
1  bool RayTracer::trace_refracted(const Ray& in, const HitInfo& in_hit, Ray&
       out, HitInfo& out_hit) const
2  {
3    float3 outDirection;
4    float3 outNormal;
5    float inTheta;
6
7    out_hit.ray_ior = get_ior_out(in, in_hit, outDirection, outNormal,
         inTheta);
8
9    float3 refractedDirection;
10
11   if(optix::refract(refractedDirection, -outDirection, outNormal, out_hit.
         ray_ior / in_hit.ray_ior))
```

```
12    {
13      out.ray_type = 0;
14      out.direction = refractedDirection;
15      out.origin = in_hit.position;
16      out.tmin = 0.001f;
17      out.tmax = 99999;
18
19      if(this->trace_to_closest(out, out_hit))
20      {
21        out_hit.trace_depth = in_hit.trace_depth + 1;
22
23        return true;
24      }
25    }
26    return false;
27  }
```

We first declare two variables of the type float3 to hold the direction and normal of the outgoing ray along with one to hold the theta value. The theta value is not used for anything in this piece of code but is needed in order to call the index of refraction helper function. This is the next thing to be called. This function checks if the ray will go out of the object it is currently in, if that is the case the normal of the incoming hit is reverted along with theta and an index of refraction of 1 is returned which means the ray is traveling in air. Otherwise the function finds the index of refraction based on the incoming ray's hit's material reference. Next we check if the outgoing ray will refract. This is done by calling the optix refract function that also calculates the refraction vector. optix functions in general assume that the ray direction they get in still is the original direction so we have to invert the direction that was inverted in the helper function. If no internal refraction occurs, we initialize the outgoing ray with direction of the refraction, with start in the incoming hit, and tmin and tmax set to sensible values. We then trace the ray and if we hit anything, add one to the trace depth of the outgoing hit and return true. The end result look like this:



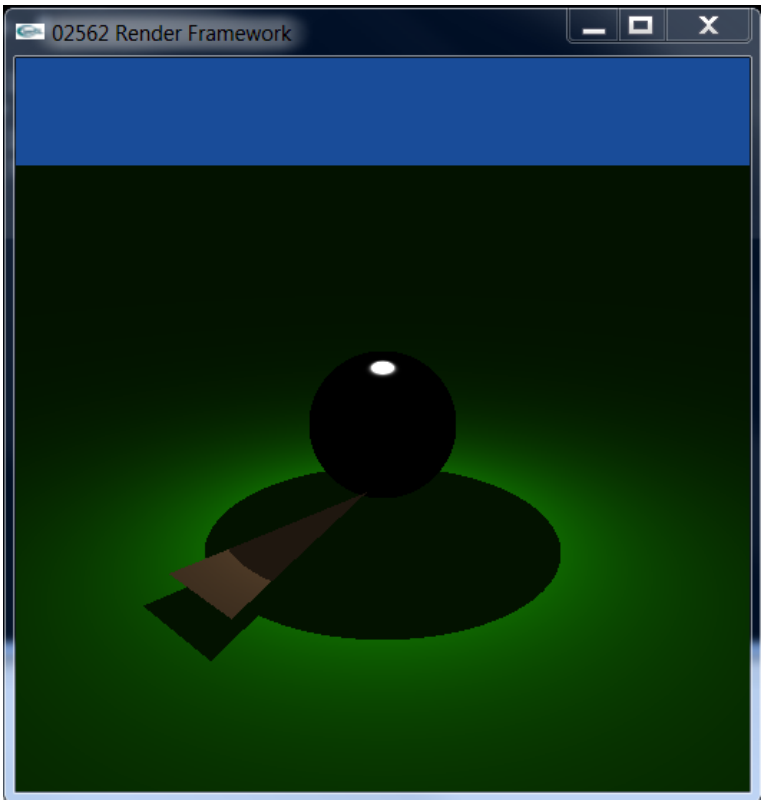
```
Building acceleration structure...(time: 0)
Building photon maps...
Unable to store enough particles.
Particles in caustics map: 0
Building time: 0.311
Generating scene display list
Switched to shader number 1
Generating scene display list
Raytracing.......... - 3.552 secs
```

Part 4 - Phong Illumination

```
1  float3 Phong::shade(const Ray& r, HitInfo& hit, bool emit) const
2  {
3    float3 rho_d = get_diffuse(hit);
4    float3 rho_s = get_specular(hit);
5    float s = get_shininess(hit);
6
7    float3 result = make_float3(0);
8
9    for(int i = 0 ; i < lights.size() ; i++)
10   {
11     float3 L;
12     float3 dir;
13     if( lights[i]->sample(hit.position, dir, L) )
14     {
15       float3 R = optix::reflect(-dir,hit.shading_normal);
```

```
16          unsigned int sInt = (int)s;
17
18          result += rho_d*L* optix::fmaxf(optix::dot(hit.shading_normal, dir),
                0) + rho_s*L* int_pow(optix::fmaxf( optix::dot(R, -r.direction),
                0), sInt);
19      }
20    }
21    return result;
22  }
```

We start by getting the material specific parameters of the phong equation and declare a variable to store the result of the shading. Then we loop over the lights in the scene. If the light hits the surface we use the returned direction to the light source and its intensity in the phong equation. We also calculate the reflected light ray in order to implemented specular reflection. To make the calculation of the specular reflection faster we also convert the shininess of the material to an int so we can use the int pow function. The end result look like this:

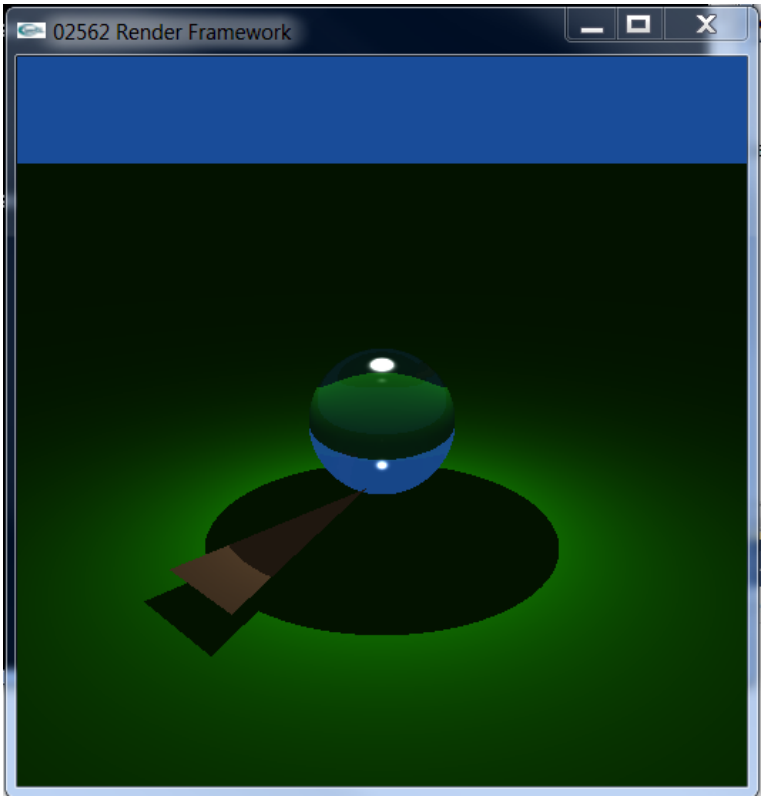


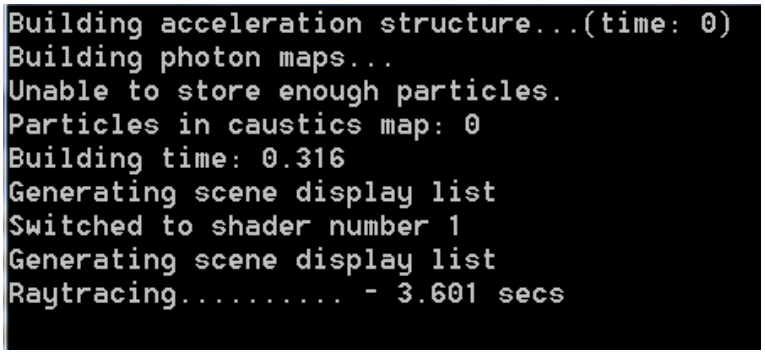

```
Building acceleration structure...(time: 0)
Building photon maps...
Unable to store enough particles.
Particles in caustics map: 0
Building time: 0.341
Generating scene display list
Switched to shader number 1
Generating scene display list
Raytracing.......... - 2.19 secs
```

Part 5 - Combining it all

```
1  float3 Glossy::shade(const Ray& r, HitInfo& hit, bool emit) const
2  {
3    if(hit.trace_depth >= max_depth)
4      return make_float3(0.0f);
5
6    Ray reflected, refracted;
7    HitInfo hit_reflected, hit_refracted;
8    tracer->trace_reflected(r, hit, reflected, hit_reflected);
9    tracer->trace_refracted(r, hit, refracted, hit_refracted);
10
11   return 0.1f * Phong::shade(r, hit, emit) +
12         0.1f*shade_new_ray(reflected, hit_reflected) +
13       0.9f* shade_new_ray(refracted, hit_refracted);
14 }
```

The first part is to check if the hit given to the function has reached the maximum trace depth, if that is the case the shader returns black. Since the shader implements both refraction and reflection we need to declare a ray and hit info for each of these phenomena. Each of these rays is then calculated. And used to shade the surface with the shade new ray method. These can then again create a new call to the glossy shader as the light bounces around inside the sphere. It is therefore we have the trace depth. The end result is also added together with the phong reflection of the material. Since the ball is made of glass it only has a specular component which gives the highlights on the ball. This highlight is multiplied with the reflectance since it produces the reflection of the lightsource. The end result look like this:





As we can see, the more rays a method generates the longer it takes to calculate.

Rendering assignment three

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December 19, 2012

Introduction

This is my answers to the three handin in the Rendering course. The formulation of the exercises is given in italic.

Part 1

small 25W light bulb has an efficiency of 20%. How many photons are approximately emitted per second? Assume in the calculations that we only use average photons of wavelength 500 nm.

$$f = \frac{c}{\lambda} = \frac{3 * 10^8 \frac{m}{s}}{500m * 10^{-9}} = 6 * 10^1 4s^{-1}$$

$$q[500nm] = hf = 6.626 * 10^{-34} Js * 6 * 10^1 4s^{-1} = 3.976 * 10^{-19} J$$

$$N_{photon}[25W * 0.2] = \frac{25W * 0.2}{3.976 * 10^{-19} J/photon} = 1.258 * 10^{19} photon/s$$

Part 2

A light bulb (2.4 V and 0.7 A), which is approximately sphere-shaped with a diameter of 1 cm, emits light equally in all directions. Find the following entities (ideal conditions assumed)

Radiant flux

This is equal to the effect of the bulb. This can be obtained from the voltage and amperage:

$$W = A * V = 2.4V * 0.7A = 1.68J/s$$

Radiant intensity

Radian intensity is how much power is emitted per solid angle. Since we are to take the whole sphere of the lightbulb into consideration the solid angle is equal to four pi:

$$I = W/sr = \frac{1.68J/s}{4\pi sr} = 0.42\frac{J}{s * sr}$$

Radiant exitance

Radiant exitance is the power divided by the surface area. Since the bulb is a unit sphere the area of it is equal to 4 pi and the result is therefore the same as before but with different units:

$$M = W/m^2 = 0.42W/m^2$$

Emitted energy in 5 minutes

This is simply taking the flux effext of the bulb and multiply it with 5*60 seconds:

$$Q = W/s = 1.68J/s * 5 * 60s = 504J$$

Part 3

The light bulb from above is observed by an eye, which has an opening at the pupil of 6 mm and a distance of 1 m from the light bulb. Find the irradiance recieved in the eye
We use the inverse square law:

$$E = \frac{W}{4\pi r^2}$$

where E is irradiance, W is radiant flux and r is distance from light source. When we use the value of radiant flux calculated earlier and set r to 1m we get:

$$E = \frac{1.68J/s}{4\pi(1m)^2}$$

$$E = \frac{0.13J/s}{m^2}$$

Part 4

We start by calculating the flux of the bulb:

$$\Phi = P * \eta = 200W * 20$$

I assume the task is to calculate the irradiance at the closest point on the table. I can then use the inverse square law again:

$$E = \frac{W}{4\pi r^2}$$

$$E = \frac{40W}{4\pi(2m)^2}$$
$$E = \frac{40W}{4\pi 4m^2}$$

The irradiance is therefore:

$$E = 0.80\frac{W}{m^2}$$

To calculate the illuminance we use the relationship between radiometric and photometric quantities:

$$Photometric = radiometric * 685 * V(\lambda)$$

At 650 nm the luminous efficiency curve has the value 0.1. The illuminance at the table is therefore equal to:

$$Lux = E * 685 * V(\lambda)$$
$$Lux = 0.80\frac{W}{m^2} * 685 * 0.1L/W$$
$$Lux = 54.8L/m2$$

Part 5

We have the values:

$$I_{known} = 40\frac{lm}{sr}$$
$$r_{known} = 0.35m$$
$$r_{unknown} = 0.65m$$

If we asumme that the light sources are isotropic and spherical we can use the inverse square law:

$$E = \frac{I}{r^2}$$

So we have that:

$$E_{known} = \frac{I_{known}}{r^2_{known}}$$
$$E_{unknown} = \frac{I_{unknown}}{r^2_{unknown}}$$

since we know that:

$$E_{unknown} = E_{known}$$

We can derive the unkonwn irradiance:

$$\frac{I_{unknown}}{r^2_{unknown}} = \frac{I_{known}}{r^2_{known}}$$
$$I_{unknown} = I_{known}\frac{r^2_{unknown}}{r^2_{known}}$$
$$I_{unknown} = 40\frac{lm}{sr}\frac{0.65m^2}{0.35m^2}$$
$$I_{unknown} = 138\frac{lm}{sr}$$

Part 6

The relationship between flux and radiance and radiosity and radiance for a diffuse emitter is:

$$\Phi = LA\pi$$

$$B = L\pi$$

The flux is therefore equal to:

$$\Phi = 5000\frac{W}{m^2 sr} * (0.1m)^2 * \pi = 157W$$

and the radiosity:

$$B = 5000\frac{W}{m^2 sr}\pi = 1.570 * 10^4\frac{W}{m^2}$$

Part 7

The relationship between radiance and radiosity is equal to:

$$B = \int_\Omega Lcos\theta d\omega$$

We have that the projected solid angle is equal to:

$$\int_\Omega \cos\theta d\omega = \int_0^{2\pi}\int_0^{\pi} cos\theta sin\theta d\theta d\phi = \pi$$

The radiosity is therefore:

$$B = L\pi = 6000\pi\frac{W}{m^2}$$

To calculate the flux we use the relationship:

$$\Phi = B * A$$

$$\Phi = 6000\pi\frac{W}{m^2}(0.1m)^2 = 60\pi W$$

Rendering assignment week 5-6

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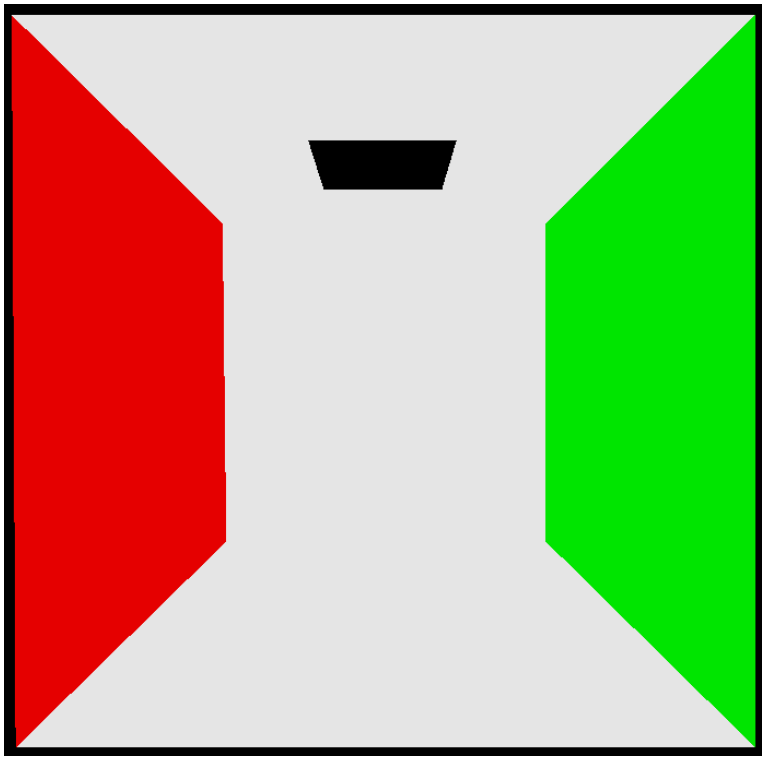
December 17, 2012

Introduction

This is my handin for week 5 and 6 of the Rendering course. The handin concerns the Radiosity method, which is specifically suited to do render LD*E paths.

Part 1 - Basic Setup & Meshing

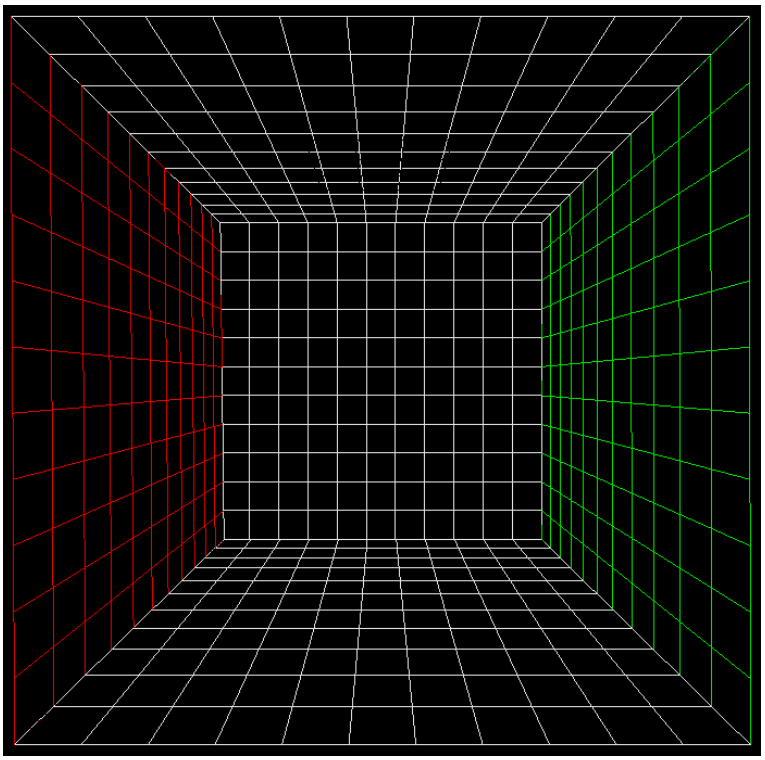
When the radiosity framework is first compiled and run it produces the following flat shaded image:



The next part is to implement tesselation of the scene geometry. This is done with the Mesher library and the code for doing this is the following:

```
1   //output variables
2   vector<MyPolygon*> tesselated_polygons;
3   vector<MyVertex*> tesselated_vertices;
4
5   //patch sizes
6   const float faceSize = 20;
7   const float lightSize = 20;
8
9   //tesselation
10  Mesher::mesh(loaded_vertices,loaded_polygons,tesselated_vertices,
        tesselated_polygons, faceSize, lightSize);
11
12  polygons = tesselated_polygons;
13  vertices = tesselated_vertices;
```

And the result looks like this:



Part 2 - The Progressive Refinement Method

Progressive refinement is a method to do radiosity that is designed to over time produce a better and better result. This way the process can be cancelled if the artist finds that the result generated is not satisfactory. In the normal formulation of the radiosity method each patch gathers light from each other. In the progressive refinement method the radiosity is shot from the "brightest" patch, the patch with most unshot radiosity, to all the other patches in the scene. A patch thus has to fields, one that stores how much radiosity it has recieved overall, and another that stores how much radiosity it has recieved that it has not distributed out to other patches yet. The field for overall radiosity is used to

calculate the color of the patch.

The first part is to calculate the form factor between the patches based on the following analytical formula:

$$F_{dAidAj} = \int_{Aj} \frac{\cos \Phi i \cos \Phi j}{\pi r^2} \mathrm{d}A_j$$

If the patches are sufficiently small we do not need to take the integral over the patch since the form factor does not change that much when it is sufficiently small The function can therefore be calculated in the following way:

```
1  MyPolygon* calcAnalyticalFF()
2  {
3    // Reset all form factors to zero
4    for(unsigned int i = 0; i < polygons.size(); i++)
5      polygons[i]->formF = 0.0f;
6
7    // Find the patch with maximum energy
8    MyPolygon* maxEnergyPatch = maxenergy_patch();
9
10    //for all patches
11   for(unsigned int i = 0; i < polygons.size(); i++)
12   {
13       //find the vector between the two patches
14     Vec3f lineBetweenPatches = maxEnergyPatch->center - polygons[i]->center
         ;
15       //and the normalized version of it
16     Vec3f normalizedLine = lineBetweenPatches;
17     normalizedLine.normalize();
18
19     //calculate phi for each patch
20
21     float phi1 = dot(normalizedLine, polygons[i]->normal);
22
23     if(phi1 < 0)
24       phi1 = 0;
25
26     float phi2 = dot(-normalizedLine, maxEnergyPatch->normal);
27
28     if(phi2 < 0)
29       phi2 = 0;
30
31     //finally calculate the form factor
32     polygons[i]->formF = polygons[i]->area * phi1*phi2 * M_1_PI / pow(
         lineBetweenPatches.length(), 2 );
33   }
34   // Return the maximum patch
35   return maxEnergyPatch;
36 }
```

The next part is the function that distributes the unshot radiosity from the patch with most unshot radiosity to the other patches. This is based on the formula:

$$B_j = R_j B_i F_i j \frac{A_i}{A_j}$$

Where i refers to the patch being shot from and j refers to the patch being shot at. The code for doing this is shown below:

```
bool distributeEnergy(MyPolygon* maxP)
{
  //if a null pointer is given, return false
  if(maxP == 0)
    return false;

  // Distribute energy from the maximum patch to all other patches.
  for(unsigned int i = 0; i < polygons.size(); i++)
  {
    //we do not distribute energy from the max energy patch onto itself
    if(polygons[i] == maxP)
    continue;

      //calculate the radiosity recieved by patch i
    Vec3f radiosity = polygons[i]->diffuse * polygons[i]->formF * ( maxP->
        area / polygons[i]->area) * maxP->unshot_rad;

    //add this to patch i's radiosity and unshot radiosity
    polygons[i]->unshot_rad += radiosity;
    polygons[i]->rad += radiosity;
  }

  // Set the unshot radiosity of the maximum patch to zero and return true
  maxP->unshot_rad = Vec3f(0);

  return true;
}
```

The function is quite simple. First it is tested if the function is passed a null pointer, if that is the case it returns false. Next it loops over all patches, skips the patch with max energy since a patch cannot distribute energy onto itself. Then the above formula is calculated and the result added to the current patch's radiosity and unshot radiosity.

Next, we need a function to calculate the color of each patch. The color is equal to the radiance of the patch. The relationship between radiosity and radiance for a diffuse reflector is:

$$B = L\pi$$

So this means the color is obtained by dividing the radiosity with phi.

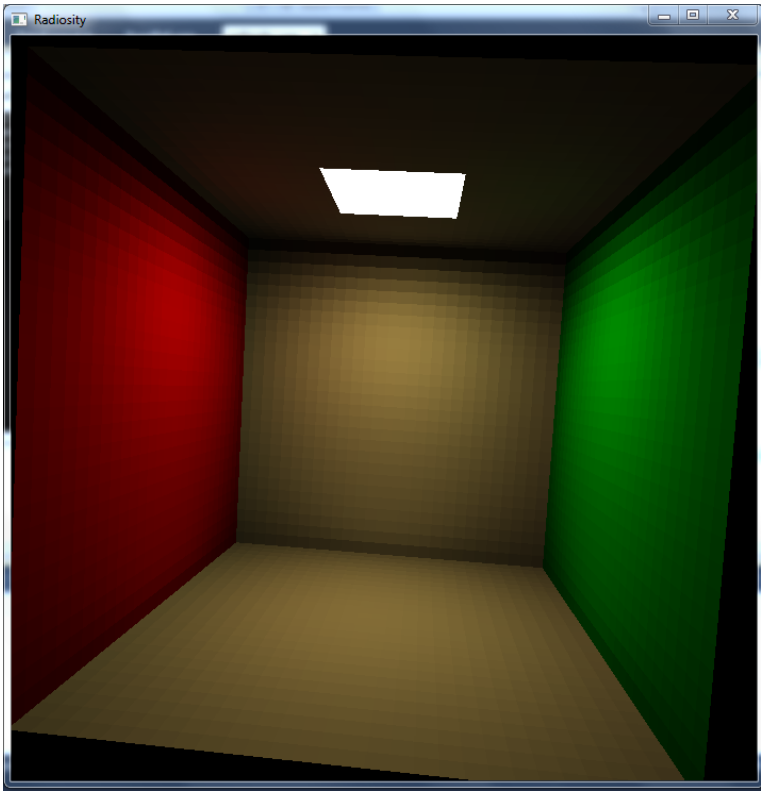
```
void colorReconstruction()
{
  for(unsigned int i = 0; i < polygons.size(); i++)
  {
    polygons[i]->color =  polygons[i]->rad * M_1_PI;
  }
}
```

The last thing in this part is to call the function from inside the display function:

```
void display()
{
```

```
3       MyPolygon* maxP = calcAnalyticalFF();
4
5       distributeEnergy(maxP);
6
7       colorReconstruction();
8
9       glViewport(0,0,screen_size,screen_size);
10      ball->do_spin();
11      glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);
12      glColor3f(1.0,0.0,0.0);
13      glLoadIdentity();
14      ball->set_gl_modelview();
15      displayMyPolygons();
16    glutSwapBuffers();
17  }
```

The result looks like this:



Part 3 - Smoothing via Nodal averaging

The main task here is to compute the color of each vertex based on the color of the patches that it is a part of. The strategy used it to first reset the colors of all the vertices, then go trough all the patches and add the color of that patch to the vertices it is connected to. To obtain the color of a vertex we then divide with the number of patches it is connected to thus finding the mean color value. The function to calculate color is therefore changed to:

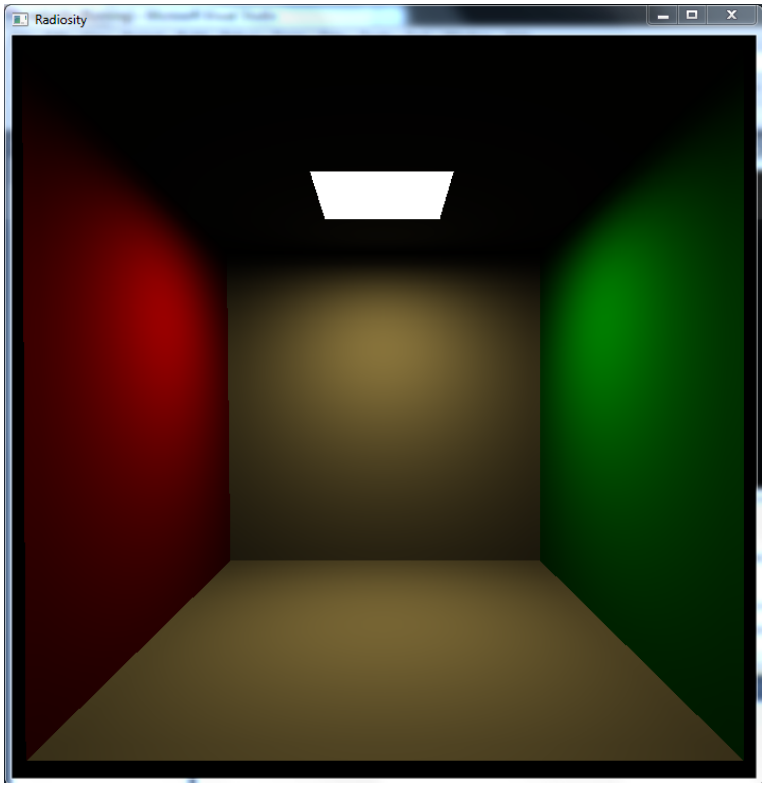
```
1  void colorReconstruction()
```

```
2  {
3    for(unsigned int i = 0 ; i < vertices.size() ; i++)
4    {
5      vertices[i]->color = Vec3f(0);
6      vertices[i]->colorcount = 0;
7    }
8
9    for(unsigned int i = 0; i < polygons.size(); i++)
10   {
11     polygons[i]->color =  polygons[i]->rad * M_1_PI;
12
13     for(unsigned int k = 0 ; k < polygons[i]->vertices ; k++)
14     {
15       vertices[polygons[i]->vertex[k] ]->color += polygons[i]->color;
16       vertices[polygons[i]->vertex[k] ]->colorcount += 1;
17     }
18   }
19
20   for(unsigned int i = 0 ; i < vertices.size() ; i++)
21   {
22     vertices[i]->color =  vertices[i]->color / vertices[i]->colorcount;
23   }
24 }
```

Next we need to change the DisplayMyPolygons function so it uses the vertex colors instead of the patch's color:

```
1
2  void displayMyPolygons()
3  {
4    for(int i=0;i<polygons.size();i++)
5    {
6      if (4==polygons[i]->vertices)
7        glBegin(GL_QUADS);
8      else if (3==polygons[i]->vertices)
9        glBegin(GL_TRIANGLES);
10     else
11       assert(false); // illegal number of vertices
12
13     for (int j=0;j<polygons[i]->vertices;j++)
14     {
15       glColor3f(vertices[ polygons[i]->vertex[j] ]->color[0],vertices[
             polygons[i]->vertex[j]]->color[1],vertices[ polygons[i]->vertex[j
             ]]->color[2]);
16
17       Vec3f position = vertices[polygons[i]->vertex[j]]->position;
18       glVertex3f(position[0], position[1], position[2]);
19     }
20     glEnd();
21   }
22 }
```

Since OpenGL's fixed function pipeline is based on Garroud shading and the shading is already set to be smooth we do not have to do more. The result looks like this:



Part 4 - Occlusion via the Hemicube Method

There is two functions that need to be implemented in order to use the hemicube method, the first is renderPatchIDs that prepares the scene to be rendered to the hemicube by setting the color of each patch to its index (plus one to avoid that areas where there are no patches are considered as the first patch in the vector). The main task is therefore to change what is done in the DisplayMyPolygons function to use the index of the patch instead. The index therefore needs to be changed into a RGB value. This is done with bit masks and bit shifting:

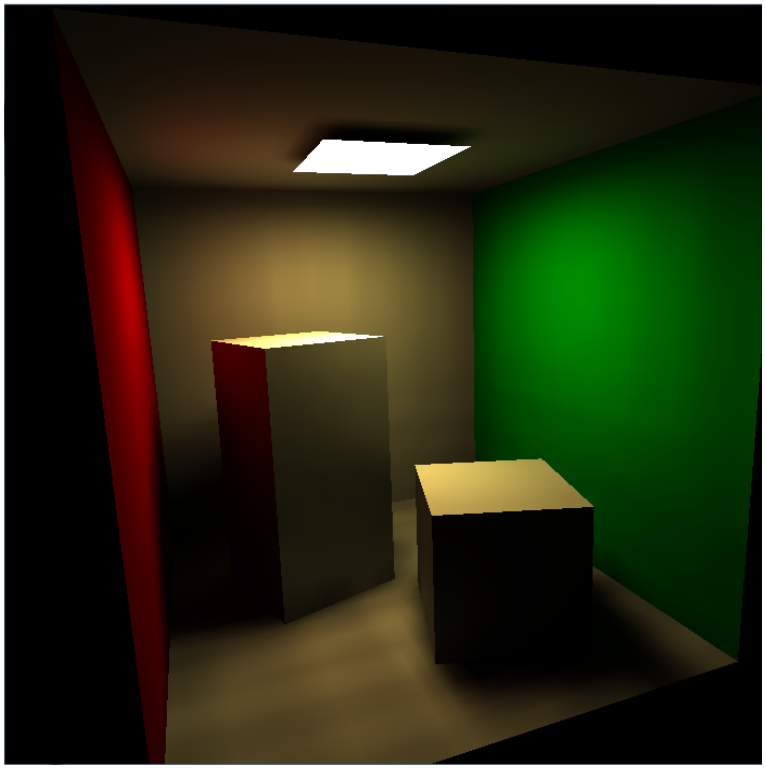
```
1  void renderPatchIDs()
2  {
3    // Render all polygons in the scene as in displayMyPolygons,
4    // but set the colour to the patch index using glColor3ub.
5    // Look at the Hemicube::getIndex function to see how the
6    // indices are read back.
7
8    for(int i=0;i<polygons.size();i++)
9    {
10     if (4==polygons[i]->vertices)
11     //if(4==polygons[i]->vertices)
12       glBegin(GL_QUADS);
13     else if (3==polygons[i]->vertices)
14       glBegin(GL_TRIANGLES);
15     else
16       assert(false); // illegal number of vertices
17
18     unsigned int index = i + 1;
```

```
19
20      unsigned char r = ( index & 0xff0000 ) >> 16;
21      unsigned char g = ( index & 0x00ff00 ) >> 8;
22      unsigned char b = ( index & 0x0000ff );
23
24      glColor3ub(r, g, b);
25
26      for (int j=0;j<polygons[i]->vertices;j++)
27      {
28        Vec3f position = vertices[polygons[i]->vertex[j]]->position;
29        glVertex3f(position[0], position[1], position[2]);
30      }
31      glEnd();
32      }
33  }
```

Next, the form factors can be calculated. Here the hemicube class is used. This requires that a virtual camera is set up which looks in the direction of the max energy patch's surface normal, has its eye point in the plane of the patch and the up vector also lying in the same plane. When the scene has been rendered the indexes are read from the frame buffer and then used to calculate the form factor of each patch. The function looks like this:

```
1  MyPolygon* calcFF(Hemicube* hemicube)
2  {
3     for(unsigned int i = 0; i < polygons.size(); i++)
4     {
5      polygons[i]->formF = 0;
6     }
7
8      MyPolygon* maxP = maxenergy_patch();
9
10   Vec3f up = vertices[ maxP->vertex[0] ]->position - maxP->center;
11
12   hemicube->renderScene(maxP->center, up, maxP->normal, renderPatchIDs);
13
14   hemicube->readIndexBuffer();
15
16   for(unsigned int i = 0 ; i < hemicube->rendersize ; i++)
17   {
18     for(unsigned int k = 0 ; k < hemicube->rendersize ; k++)
19     {
20       unsigned int index = hemicube->getIndex(i,k);
21
22       if(index > 0)
23       {
24         float f = hemicube->getDeltaFormFactor(i,k);
25
26         polygons[index - 1]->formF += f;
27       }
28     }
29   }
30   // Return the maximum patch
31   return maxP;
32 }
```

With the hemicube the cornell box looks like this:



Part 5 - Answers to Questions

What is the effect of changing the subdivision level of the light source?
if the level is too low banding or aliasing artifacts appear. This is because the hemicube method is an approximation to calculating the form factor between two patches.

What happens when you change the size of the hemicube? And why does it happen? What can be done in order to avoid this problem?
If the size of the hemicube is to small aliasing will mean that artefacts will be present in the final image. The cause of this is that the projection of the patches down on the hemicube cannot be represented properly if the hemicube's resolution is to low. The mean way to fix this problem is therefore to use the right resolution that produces an image without artefacts but which does not take to long time to evaluate.

What are the advantages and disadvantages of radiosity as compared to ray tracing?
The advantages are:

- viewpoint independent which means that for a static scene it only needs to be calculated once and the viewport can then be moved around where it is only the projection of the geometry that is needed to be calculated. This is probably also an advantage in architectural visualisations.

- Color bleeding. A surface with one color will project that color onto nearby surfaces.

- Soft shadows.

The disadvantages are:

- slower than for example basic ray tracing, and not much research has gone into how it can be optimized.
- Light and shadow leakage can occur if patch boundaries does not coresspond to boundaries of the geometry
- only LD*E paths can be simulated with the radiosity method.
- if only Garraud interpolation is used between patches, mach banding can occur if the patches are large enough.
- insufficient meshing strategies can cause discontinuities in the radiosity across a surface. This can for example be seen on my rendering of the cornell box where the box most in the front does not have shadow in its left lower corner where it should have.

Week 7 Report

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December 19, 2012

1 INTRODUCTION

The purpose of this week's set of exercises is to introduce anti-aliasing to the previously developed ray casting. This is done to make edges in the render look more smooth.

2 DESCRIBTION

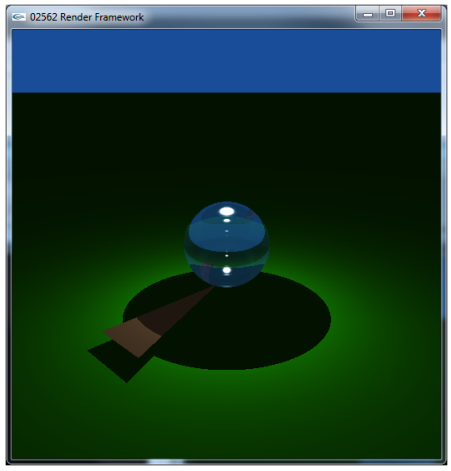
- *Describe how the pixel subdivision level is changed while the program is running*
  The `subdivs` variable is incremented and `compute_jitters` function is called, which fills the `jitter` array.
- *Explain what the function `compute_jitters` stores in the vector array `jitter`.*
  The `jitter` array stores coordinates of random points inside subpixels, which are calculated based on coordinates of the pixel and number of its subpixels.
- *Explain how many subpixels we get for each pixel when the pixel subdivision level is `subdivs = s`.*
  Each dimension of a pixel is divided into `s` parts, therefore the number of subpixels equals s^2.

3 CODE

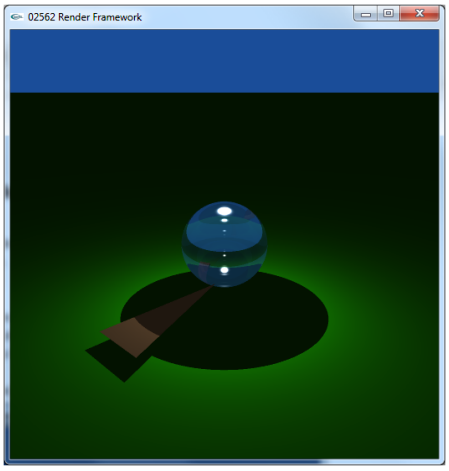
Listing 1: Part of the displayMyPolygons function from radiosity.cpp file

```
float3 RayCaster::compute_pixel(unsigned int x, unsigned int y)
     const
{
  float2 viewportCoords = optix::float2();

  viewportCoords.x = lower_left.x + win_to_ip.x*x;

  viewportCoords.y = lower_left.y + win_to_ip.y*y;

  float3 result = make_float3(0);

  // for each subpixel
  for(int i = 0; i < subdivs; i++)
       for(int j = 0; j < subdivs; j++)
       {
          // create a ray and hit
          optix::Ray ray = scene->get_camera()->
               get_ray(viewportCoords + jitter[i*subdivs + j]);

          HitInfo info;

          // and then trace it
          if(scene->closest_hit(ray, info))
          {
               result +=  get_shader(info)->shade(ray,info);
          }
          else
          {
               result += get_background(ray.direction);
          }

       }

       // when all rays have been traced, divide by the
       // number of subpixels to get the correct result

  return result/(subdivs*subdivs);
}
```

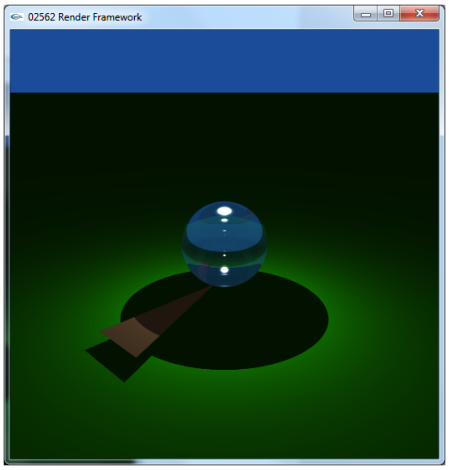
4 Render Results



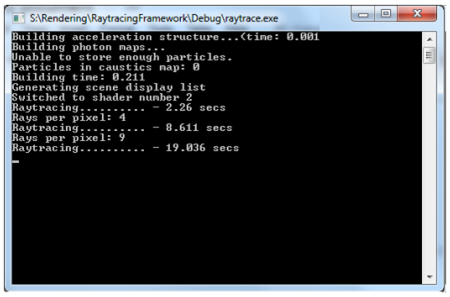
(a) subdivs = 1



(b) subdivs = 2



(c) subdivs = 3



(d) render output

Figure 4.1: screenshots of render results

5 Final Questions

- *What is the relationship between the pixel subdivision level and the render time?*
  The time is proportional to squared subdivision level.
- *What is the relationship between the pixel subdivision level and the aliasing error in the render result?*
  Using a higher number of rays per pixel decreases the aliasing error. High number of rays shot through one pixel means that the resulting color of the pixel is calculated as an average of bigger number of values and therefore produces a more accurate result.
- *At what pixel subdivision level would you say that the improvement is no longer visible?*
  We cannot see any improvement between subdivision level 2 and 3.
- *At what pixel subdivision level would you say that the improvement is no longer worth the increase in render time?*
  It depends on the situation, for a test render we can say that there is no point using subdivision, for the final render it's worth waiting for render with subdivision level 2, but not more as there is no further improvement visible.

Weeks 8-9 Report

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December 16, 2012

1 INTRODUCTION

The purpose of this set of exercises is to add photon mapping to the previously implemented ray tracing solution. As a result, caustics should be included in the renderings.

2 EMITTING PHOTONS FROM LIGHT SOURCE

In order to emit photons we first create a random direction vector that is inside the unit sphere. This is done through rejection sampling. Then we cast a ray in that direction with origin at the light's position. If it hits something we calculate the irradiance the photon. Since we have the intensity of the light which unit is W/sr we just have to multiply the intensity with 4 pi in order to get the radiant flux:

Listing 1: emit function from PointLight.cpp file

```
bool PointLight::emit(Ray& r, HitInfo& hit, float3& Phi) const
{
    // Sample ray direction with rejection sampling
    // and create ray
    float x,y,z;
    do
    {
        x = randomizer.mt_random() * 2 - 1;
        y = randomizer.mt_random() * 2 - 1;
        z = randomizer.mt_random() * 2 - 1;
    }while(x*x + y*y + z*z > 1);
```

```
    float3 dir = normalize(make_float3(x, y, z));

    r.direction = dir;
    r.origin = light_pos;
    r.tmin = 1e-5;
    r.tmax = 9999;

    // Trace created ray
    // If a surface was hit, compute Phi and return true
    if (tracer -> trace_to_closest(r, hit))
    {
        Phi = intensity * 4 * M_PIf;
        return true;
    }

    return false;
}
```

3 TRACING AND STORING PHOTONS

The next step is to emit photons and storing them. First we check if we have enough photons, if not we continue with the function. The first step is to declare the necessary variables to shooting a ray and storing the radiant flux of the photon it casts. We then emit it and bounce the photon around until it reaches a difuse surface. If it hits a trnasparent surface we first trace the refracted ray. From that we get the reflectance of the surface and use it to calculate with russian roulette if we should trace the reflected ray instead. After the while loop we check if the ray has been traced more than once which means the created photon has been produced by a caustic. If that is the case it is stored in the caustics photon map.

Listing 2: trace_particle function from ParticleTracer.cpp file

```
void ParticleTracer::trace_particle(const Light* light, const unsigned int caust
{
  if(caustics_done)
    return;

  Ray r;
  HitInfo hit;
  float3 phi;

  // Shoot a particle from the sampled source
  light -> emit(r, hit, phi);

  // Forward from all specular surfaces
  while(scene -> is_specular(hit.material) && hit.trace_depth < 500)
  {
    switch(hit.material->illum)
    {
    case 3:  // mirror materials
      {
        // Forward from mirror surfaces here
        return;
      }
      break;
    case 11: // absorbing volume
    case 12: // absorbing glossy volume
      {
        // Handle absorption here (Week 11)
      }
    case 2:  // glossy materials
    case 4:  // transparent materials
      {
        // Forward from transparent surfaces here
          Ray r_out;
          HitInfo hit_out;
          float reflectance;
          trace_refracted(r, hit, r_out, hit_out, reflectance);
```

```
            if (mt_random() < reflectance && !trace_reflected(r, hit, r_out, hit_o
                return;
            else if(!hit_out.has_hit)
                return;

            r = r_out;
            hit = hit_out;
        }
        break;
      default:
        return;
      }
    }
    // Store in caustics map at first diffuse surface
    // The depth check is added to make sure that
    // no photons coming directly from a light source
    // are stored.
    if (hit.trace_depth > 0)
       caustics.store(phi, hit.position, -r.direction);
}
```

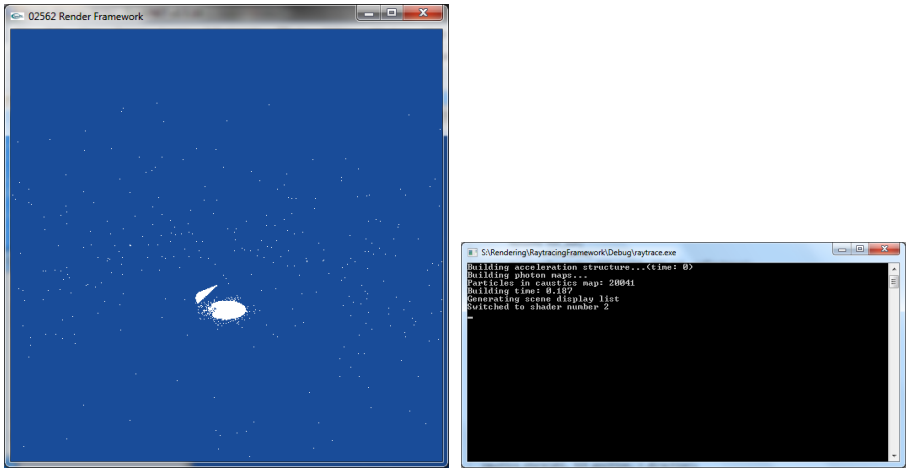

Figure 3.1: photon map preview

4 WRITING A SHADER

When we render caustics we need to convert from irradiance to radiance since the photon map gives us radiant flux over the surrounding area. The formula for calculating radiance from the photon map is given as:

$$L_r(x,\vec{w}) = \sum_{p=1}^{n} f_r(x,\overrightarrow{w_p},\vec{w})\frac{\Delta\Phi_p(x,\overrightarrow{w_p})}{\Delta A}$$

Since we are only storing the caustics photon map on difuse surfaces we can simplify the expression. Since a diffuse surface scatters light in all direction and radiance is equal to the irradiance that is reflected from the surface the solution is just to calculate the amount of photons that is inside the sphere and multiply it with the reflectivity of the surface and the BRDF of diffuse surfaces which is one over pi. In order to render the surface with normal diffuse shading we also add the result of a lambertian shading.

Listing 3: shade function from PhotonCaustics.cpp file

```
float3 PhotonCaustics::shade(const Ray& r, HitInfo& hit, bool emit) const
{
  float3 rho_d = get_diffuse(hit);
  float3 irradiance = tracer -> caustics_irradiance(hit, max_dist, photons);

  return irradiance * rho_d * M_1_PIf + Lambertian :: shade(r, hit, emit);
}
```

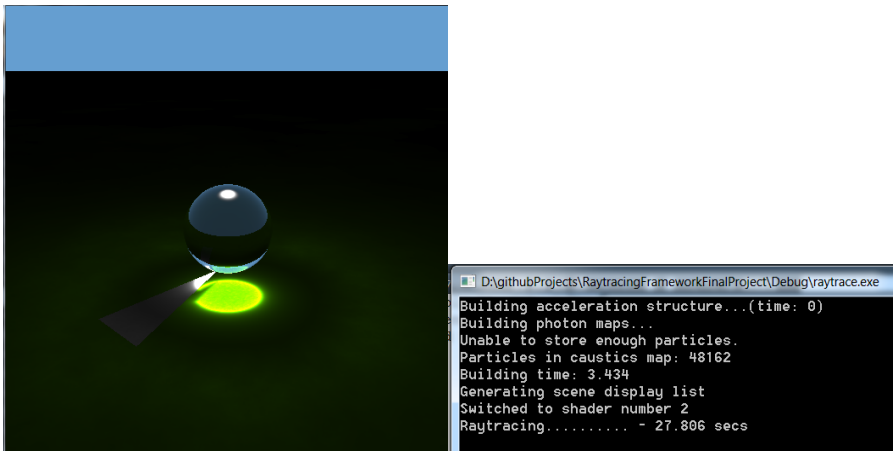

Figure 4.1: a render using caustics illumination only

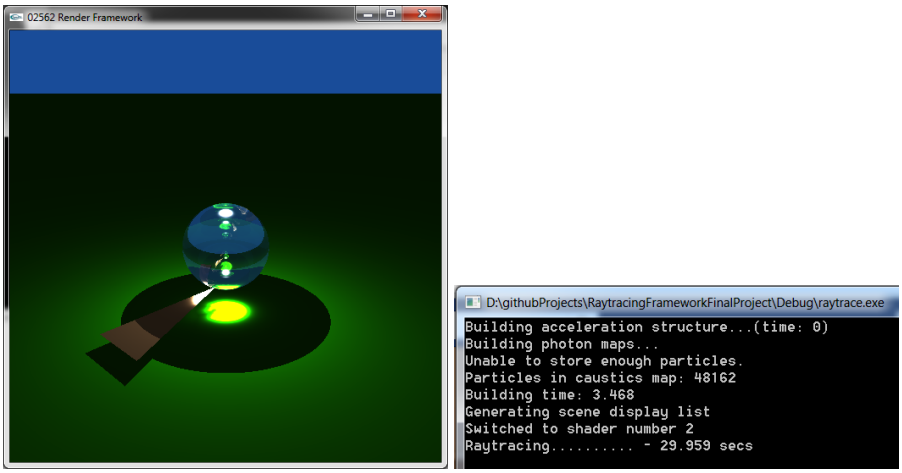

Figure 4.2: a complete render of the scene

Weeks 10 Report - Texture Mapping

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December 19, 2012

1 INTRODUCTION

The purpose of these exercises was to add texture mapping to the raytracing framework.

2 LOADING OF IMAGE FILES

The loading of textures is first started when the plane is loaded with the following line in RenderEngine.cpp:

```
1  scene.add_plane(make_float3(0.0f, 0.0f, 0.0f), make_float3(0.0f, 1.0f, 0.0f), "../models
       /default_scene.mtl", 1, 0.02f);
```

The add_plane function in In Scene.cpp is passed the path to the default scene material desription file. The add_plane function looks like this.

```
1  void Scene::add_plane(const float3& position, const float3& normal, const string&
       mtl_file, unsigned int idx, float tex_scale)
2  {
3    vector<ObjMaterial> m;
4    if(!mtl_file.empty())
5      mtl_load(mtl_file, m);
6    if(m.size() == 0)
7      m.push_back(ObjMaterial());
8    Plane* plane = new Plane(position, normal, idx < m.size() ? m[idx] : m.back(),
         tex_scale);
9    planes.push_back(plane);
10 }
```

First a vector is created to store all the materials in the file. The file is then passed with the call to mtl_load and all the materials in the file is put into the vector. A plane is then created and assigned a copy of the created material that corresponds to its index. An improvement to the parsing would be to only parse the mtf file once before the scene is created. As it is right now the mtf file is parsed each time a primitive is loaded. For each material the following three variables are defined: In ObjMaterial.h:

```
1    bool has_texture;
2    std::string tex_path, tex_name;
3    int tex_id;
```

They are set by the material's constructor. After the path to the the texture has been stored in the material by the call to load_files the init_textures in the render_engine is called afterwards. This in turn calls the function load_texture for all the planes, spheres and other meshes in the scene.

```
1  void Scene::load_texture(const ObjMaterial& mat, bool is_sphere)
2  {
3    if(mat.has_texture && textures.find(mat.tex_name) == textures.end())
4    {
5      Texture*& tex = textures[mat.tex_name];
6      tex = is_sphere ? new InvSphereMap : new Texture;
7      string path_and_name = mat.tex_path + mat.tex_name;
8      tex->load(path_and_name.c_str());
9    }
10 }
```

If the material has a texture the Texture::load function gets called:

```
1  void Texture::load(const char* filename)
2  {
3    SOIL_free_image_data(data);
4    data = SOIL_load_image(filename, &width, &height, &channels, SOIL_LOAD_AUTO);
5    if(!data)
6    {
7      cerr << "Error: Could not load texture image file." << endl;
8      return;
9    }
10   int img_size = width*height;
11   delete [] fdata;
12   fdata = new float4[img_size];
13   for(int i = 0; i < img_size; ++i)
14     fdata[i] = look_up(i);
15   tex_handle = SOIL_create_OGL_texture(data, width, height, channels, tex_handle,
         SOIL_FLAG_INVERT_Y);
16   tex_target = GL_TEXTURE_2D;
17 }
```

This function utilizes the Simple OpenGL Image Library that does all the more low level work like reading the compressed data in the texture into the data variable that can be accessed by the rest of the program. In order to use the data of the texture in the rest of the framework we also need to convert it into floating point format. This is done in the next section.

3 TEXTURE COLOUR'S USE IN RENDERING

In the load function an array called fdata is declared and filled with normalized floating point values of each pixels. This is done with the functions look_up and convert:

```
1  float4 Texture::look_up(unsigned int idx) const
2  {
3    idx *= channels;
4    switch(channels)
5    {
6    case 1:
7    {
8      float v = convert(data[idx]);
9      return make_float4(v, v, v, 1.0f);
10   }
11   case 2:
12     return make_float4(convert(data[idx]), convert(data[idx]), convert(data[idx]),
           convert(data[idx + 1]));
13   case 3:
14     return make_float4(convert(data[idx]), convert(data[idx + 1]), convert(data[idx +
           2]), 1.0f);
15   case 4:
16     return make_float4(convert(data[idx]), convert(data[idx + 1]), convert(data[idx +
           2]), convert(data[idx + 3]));
17   }
18   return make_float4(0.0f);
19 }
20
21 float Texture::convert(unsigned char c) const
22 {
23   return (c + 0.5f)/256.0f;
24 }
```

In look_up the index it is passed is first divided with the number of channels in the texture. This is done since the texture's data is stored in a flat array and the number of channels thus specifies how many bytes each pixel fills. The channel variable is also used in a switch case to determine how the floating data returned should be formatted. If it is a monocromatic texture then a greyscale color is returned. If the texture also contains an alpha channel this is also used in the calculation as well. If the texture has the three colour channels but no alpha channel then the alpha value returned is set to the default opague value of 1.0f. The last case is if the texture contains an alpha channel, then this is also converted and returned as well.

The convert function takes an char value in the range of 0 to 255 and remaps it to the range 0 to 1 in floating point format. What is weird is that the maximum value that can be mapped to is 255 + 0.5f / 256 = 0.998046875. A more correct way would be to add 1.0f insteaf of 0.5f.

4 COMPUTATION OF TEXTURE COORDINATES & TEXTURE LOOKUP

We add the following lines to the plane's intersect function:

```
    if(material.has_texture)
    {
      float3 vector = hit.position - position;

      // to get a basis change matrix we need an inverse matrix of [tangent, binormal, normal]
      // as the vectors in the basis are orthogonal, we can use transposed matrix instead

      float3 transposed1 = make_float3(onb.m_tangent.x, onb.m_binormal.x, onb.m_normal.x);
      float3 transposed2 = make_float3(onb.m_tangent.y, onb.m_binormal.y, onb.m_normal.y);
      float3 transposed3 = make_float3(onb.m_tangent.z, onb.m_binormal.z, onb.m_normal.z);

      hit.texcoord = (vector.x * transposed1 + vector.y * transposed2 + vector.z * transposed3) * tex_scale;
    }

    return true;
```

What we do here is to remap the hit position in world coordinates into coordinates relative to the plane's center. This is done by first finding the vector that goes from the positon of the plane in world coordinates and to the hit also in world coordinates. We then use the ortonormal basis of the plane to transform this vector into the coordinate system of the plane. We then scale it with tex_scale in order to be able to control the tiling of the texture.

The next step is to implement basic point sampling. This is done via the function sample_nearest:

```
float4 Texture::sample_nearest(const float3& texcoord) const
{
  if(!fdata)
    return make_float4(0.0f);

  int a = floor((texcoord.x - floor(texcoord.x)) * (width - 1) + .5);
  int b = floor((1 - (texcoord.y - floor(texcoord.y))) * (height - 1) + .5);

  return fdata[a + b * width];
}
```

The texel coordinates is found by first remapping the texcoord into a value between 0 and 1. This is done by substracting the floor'ed value. This normalized value is then multiplied with the width (or height respectively) minus one to make sure we do not go over the length of the pixel array. at the end we add 0.5 in order to take the pixel whose center is closest to the specified uv coordinates. At the end the texel coordinates is used to look into the flat array and return the correct pixel value.

5 THE ROLE OF THE PIXEL SUBDIVISION LEVEL

The next task was to render the image with different subdivisions where nearest neighbour sampling was used. The result can be seen on figure 5.1. As it can be seen the quality of the texture lookup goes up when more samples are introduced. However because the samples originate from the image plane and is not performed in the texture lookup the quality only goes up when the jittered rays has had some distance to scatter or said in another way when the rays have traveled farther. In order to improve the quality of the texture no matter how close it is we need to introduce more samples directly in the texture lookup.

6 BILINEAR SAMPLING

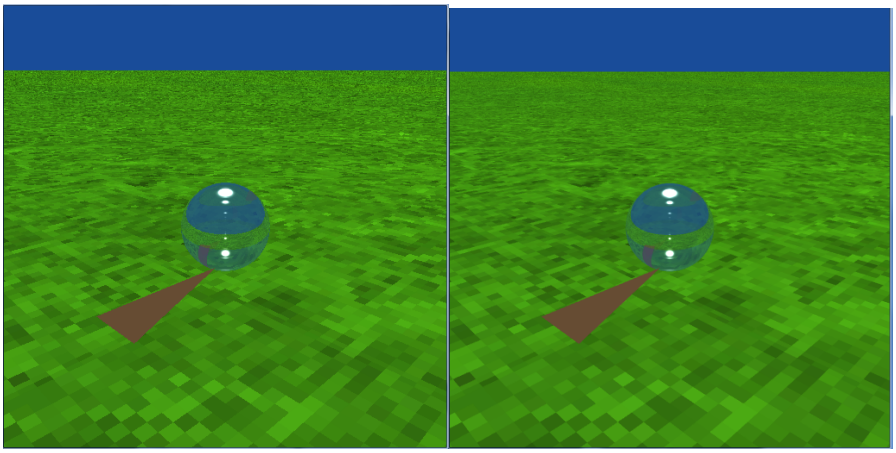
The next step is to implement bilinear sampling:

```
1  float4 Texture::sample_linear(const float3& texcoord) const
2  {
3    if(!fdata)
4      return make_float4(0.0f);
5
6    float a = (texcoord.x - floor(texcoord.x)) * width;
7    float b = (texcoord.y - floor(texcoord.y)) * height;
8
9    float2 alpha, beta, gamma, delta;
10
11   alpha = make_float2(floor(a), floor(b));
12   beta = make_float2(fmodf(ceil(a),width), floor(b));
13   delta = make_float2(fmodf(ceil(a),width), fmodf(ceil(b),height));
14   gamma = make_float2(floor(a), fmodf(ceil(b), height));
15
16   float4 c = lerp( fdata[ (int)alpha.x + (int)alpha.y * width ]      , fdata[ (int)beta.
         x + (int)beta.y * width ], a - floor(a) );
17   float4 d = lerp( fdata[ (int)gamma.x + (int)gamma.y * width ] , fdata[ (int)delta.x +
         (int)delta.y * width ], a - floor(a) );
18
19   return lerp(c, d, b - floor(b));
20 }
```

We first start by finding the texel coordinates of the sample. We then find the four pixels that are closest to this sample. After this is the bilinear interpolation performed. This is done by first doing a linear interpolation between the two sets of pixels that lies on top of each other. At the end another interpolation is done between the two points to produce the final result. The bilinear sampling produces the result seen on figure **??** As it can be seen this produces a much better result than point sampling. This is especially noticable when the texture gets magnified - is closer to the viewer. There is still aliasing farther ahead but it comes at a greater distance. When this happens the only way to improve the quality is to introduce more samples through stocastic sampling. Still the bilinear sampling does give a better result at a lover amount of jittered rays but

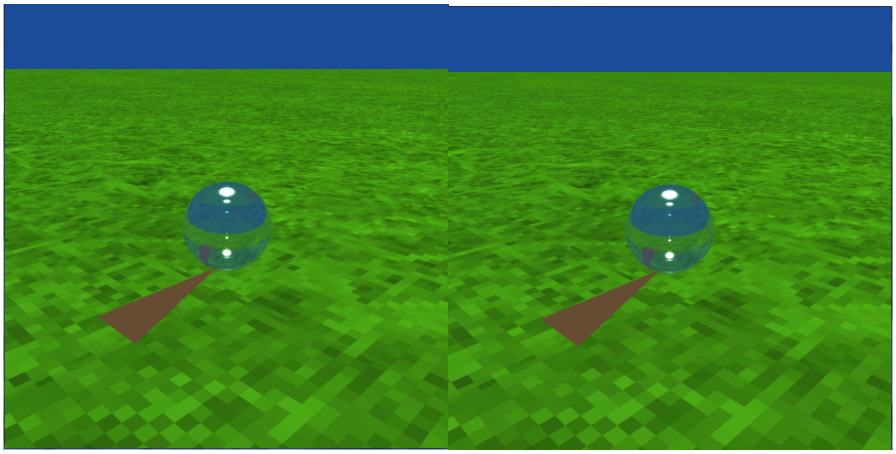
7 SCALING OF TEXTURE COORDINATES

When the texture scaling is increased to 10 it means the texture will repeat 10 times as often since the uv coordinates changes 10 times faster than if the scaling was set to 1. This results in figure 7.1



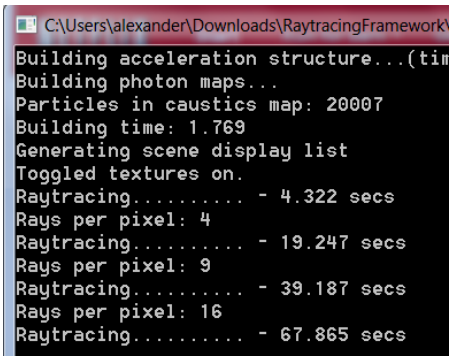
(a) Subdivision 0

(b) Subdivision 1



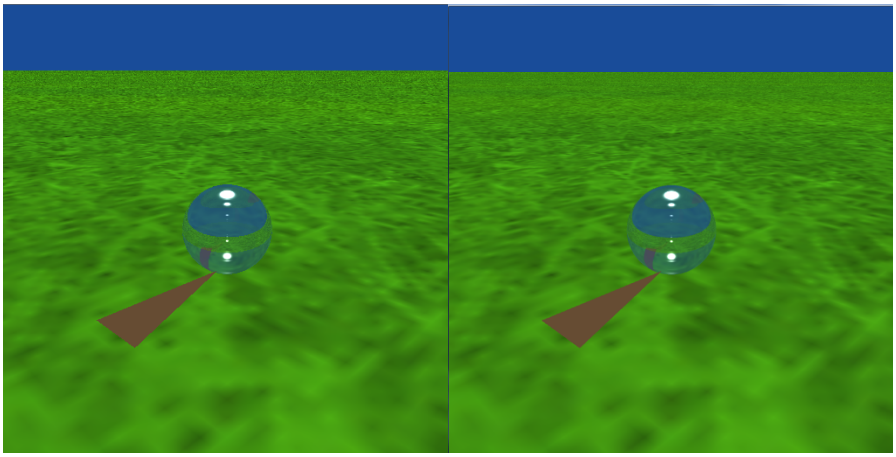
(c) Subdivision 2

(d) Subdivision 3

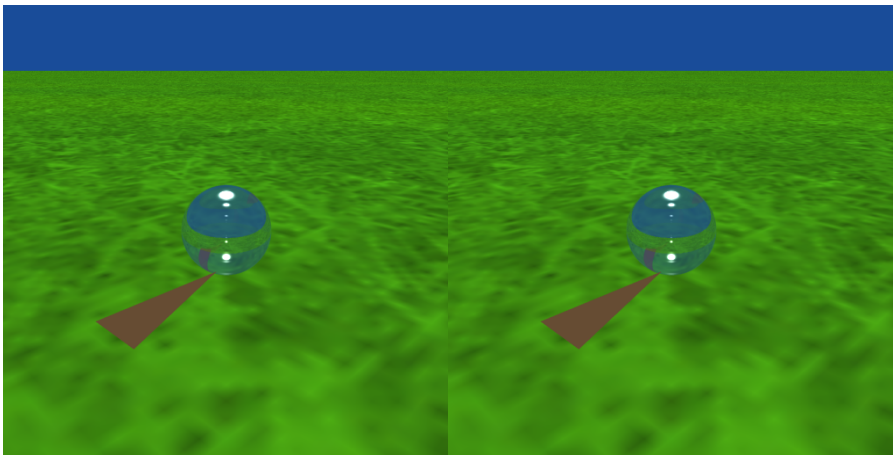


(e) Console output of subdivision

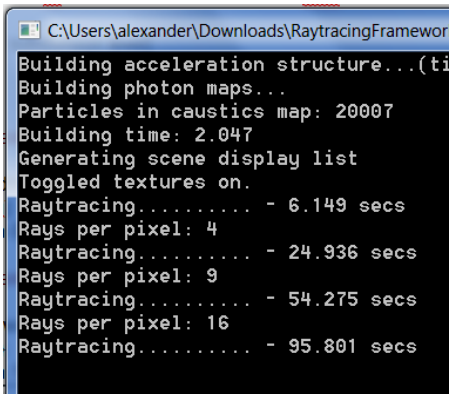
Figure 5.1: Renderings of default scene with nearest neighbour sampling



(a) Subdivision 0 (b) Subdivision 1



(c) Subdivision 2 (d) Subdivision 3



(e) Console output of subdivision

Figure 6.1: Renderings of default scene with linear interpolation sampling

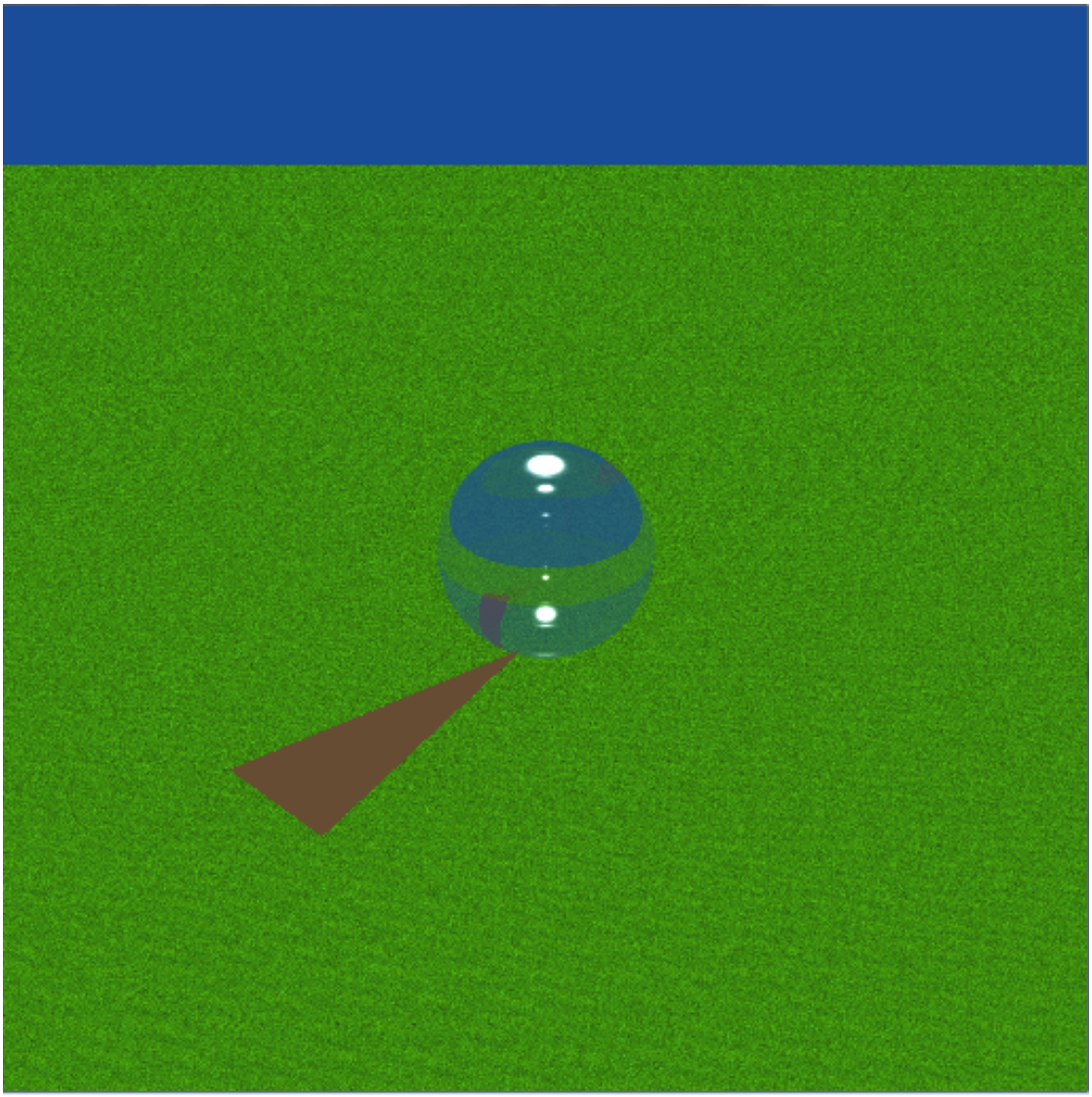


Figure 7.1: Image where texture is scaled with a factor of 10

Week 11 Report

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December 16, 2012

1 INTRODUCTION

The point of this week's set of exercises is to introduce a physically based reflectance and absorbtion models to the raytracing framework. This is done using Fresnel equations and Bouguer's law.

2 FRESNEL REFLECTANCE

First part of the assignment focuses on calculating reflectance depending on angle.

Listing 1: the fresnel equations implemented in `fresnel.h` file

```
inline double fresnel_r_s(double cos_theta1, double cos_theta2,
    double ior1, double ior2)
{
  // Compute the perpendicularly polarized component of the
     Fresnel reflectance
  return (ior1*cos_theta1 - ior2*cos_theta2) / (ior1*cos_theta1 +
      ior2*cos_theta2);
}

inline double fresnel_r_p(double cos_theta1, double cos_theta2,
    double ior1, double ior2)
{
  // Compute the parallelly polarized component of the Fresnel
     reflectance
```

```
  return (ior2*cos_theta1 - ior1*cos_theta2) / (ior2*cos_theta1 +
      ior1*cos_theta2);
}

inline double fresnel_R(double cos_theta1, double cos_theta2,
    double ior1, double ior2)
{
  // Compute the Fresnel reflectance using fresnel_r_s(...) and
     fresnel_r_p(...)
  return 0.5 * ( pow( fresnel_r_s(cos_theta1, cos_theta2, ior1,
     ior2), 2) + pow( fresnel_r_p(cos_theta1, cos_theta2, ior1,
     ior2), 2) );
}
```

Then the `Fresnel_R` function is used to compute reflectance as shown in listing below. In case of a total internal reflection (when `optix::refract` returns false), reflectance is set to 1.

Listing 2: `trace_refracted` function from `RayTracer.cpp` file

```
bool RayTracer::trace_refracted(const Ray& in, const HitInfo&
    in_hit, Ray& out, HitInfo& out_hit, float& R) const
{
     float3 outDirection;
     float3 outNormal;
     float inTheta;

     out_hit.ray_ior = get_ior_out(in, in_hit, outDirection,
        outNormal, inTheta);

     float3 refractedDirection;

     if(optix::refract(refractedDirection, -outDirection,
        outNormal, out_hit.ray_ior / in_hit.ray_ior))
     {
          out.ray_type = 0;
          out.direction = refractedDirection;
          out.origin = in_hit.position;
          out.tmin = 0.001f;
          out.tmax = 99999;

          double cos_theta1 = inTheta;
          double cos_theta2 = optix::dot( refractedDirection, -
             outNormal);
          R = fresnel_R(cos_theta1, cos_theta2, in_hit.ray_ior,
             out_hit.ray_ior);
          if(this->trace_to_closest(out, out_hit))
          {
               out_hit.trace_depth = in_hit.trace_depth + 1;
```

```
                return true;
            }
        }
        else
            R = 1.0f;

        return false;
}
```

3 Absorption

The second part of the assignment focuses on handling absorbtion of light in a medium. This is done by using Bouguer's law.

The function listed below calculates transmittance from diffuse reflectance using Bouguer's law. The conditions comparing against small values are introduced to handle division by zero.

Listing 3: `get_transmittance` function from `Volume.cpp`

```
float3 Volume::get_transmittance(const HitInfo& hit) const
{
  if(hit.material)
  {
    // Compute and return the transmittance using the diffuse
       reflectance of the material.
    // Diffuse reflectance rho_d does not make sense for a
       specular material, so we can use
    // this material property as an absorption coefficient. Since
        absorption has an effect
    // opposite that of reflection, using 1/rho_d-1 makes it more
        intuitive for the user.
    float3 rho_d = make_float3(hit.material->diffuse[0], hit.
       material->diffuse[1], hit.material->diffuse[2]);

     float3 at;

     if(rho_d.x < 0.000001f)
          at.x = 99999999.0f;
     else
          at.x = (1.0f / rho_d.x) - 1;

     if(rho_d.y < 0.000001f)
          at.y = 99999999.0f;
     else
          at.y = (1.0f / rho_d.y) - 1;

     if(rho_d.z < 0.000001f)
```

```
            at.z = 99999999.0f;
        else
            at.z = (1.0f / rho_d.z) - 1;

        return optix::expf(-at*hit.dist);
    }

    return make_float3(1.0f);
}
```

Listing 4: `shade` function from `Volume.cpp`

```
float3 Volume::shade(const Ray& r, HitInfo& hit, bool emit) const
{
  // If inside the volume, Find the direct transmission through
      the volume by using
  // the transmittance to modify the result from the Transparent
      shader.

      if(dot(r.direction, hit.shading_normal) > 0)
        return Transparent::shade(r, hit, emit) *
            get_transmittance(hit);
      else
            return Transparent::shade(r, hit, emit);
}
```

After changing the parameters of the glass ball in `default_scene.mtl` file (`illum` set to 12 and `Kd` to `(0.8, 0.1, 0.3)`) the function listed below is implemented.

Listing 5: `shade` function from `GlossyVolume.cpp`

```
float3 GlossyVolume::shade(const Ray& r, HitInfo& hit, bool emit)
    const
{
  // Compute the specular part of the glossy shader and attenuate
      it
  // by the transmittance of the material if the ray is inside (
      as in
  // the volume shader).

      float3 transmittance = make_float3(1);

      if(dot(r.direction, hit.shading_normal) > 0)
      {
            transmittance = get_transmittance(hit);
      }

      float3 rho_s = get_specular(hit);
```

```
15      float s = get_shininess(hit);

            float3 result = make_float3(0);

            for(int i = 0 ; i < lights.size() ; i++)
20          {
                float3 L;
                float3 dir;
                if( lights[i]->sample(hit.position, dir, L) )
                {
25                  float3 R = optix::reflect(-dir,hit.
                        shading_normal);
                    unsigned int sInt = (int)s;

                    result += ( rho_s*L* int_pow(optix::dot(R, -r
                        .direction), sInt));
                }
30          }

            return Volume::shade(r, hit, emit) + result *
                transmittance;
}
```

Next step is to copy `get_transmittance` function from Listing 3 to the function of the same name in `ParticleTracer.cpp`.

Listing 6: `trace_particle` function from `ParticleTracer.cpp`

```
void ParticleTracer::trace_particle(const Light* light, const
    unsigned int caustics_done)
{
  if(caustics_done)
    return;

  // Shoot a particle from the sampled source
  Ray r;
  HitInfo hit;
  float3 phi;

  light -> emit(r, hit, phi);

  // Forward from all specular surfaces
  while(scene -> is_specular(hit.material) && hit.trace_depth <
     500)
  {
    switch(hit.material->illum)
    {

     ...

    case 12: // absorbing glossy volume
      {
            if(dot(r.direction, hit.shading_normal) > 0)
            {
                 float3 transmittance = get_transmittance(hit);
                 float P = (transmittance.x + transmittance.y +
                    transmittance.z ) / 3;

                 if (mt_random() < P)
                 {
                    phi *= transmittance / P;
                 }
                 else
                     return;
            }
      }

     ...

  }
  if (hit.trace_depth > 0)
     caustics.store(phi, hit.position, -r.direction);
}
```

Implementing glossy absorption shown in listing 6 is the last part of this assignment. Here

it is first checked if we are are inside the object before the absorption is calculated. This is done by taking the dot product between the ray's direction and the surface normal.

4 Results

The renderings below show the result of implementing absorption and Fresnel reflectance together with a render of non Fresnel reflectance.

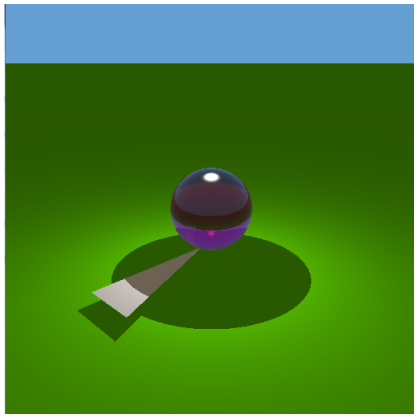


Figure 4.1: Fresnel reflectance and absorption without caustics

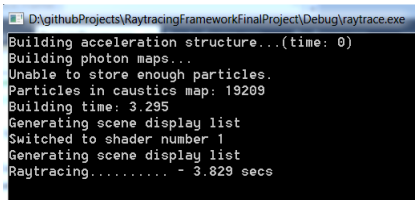


Figure 4.2: Log for fresnel reflectance without caustics

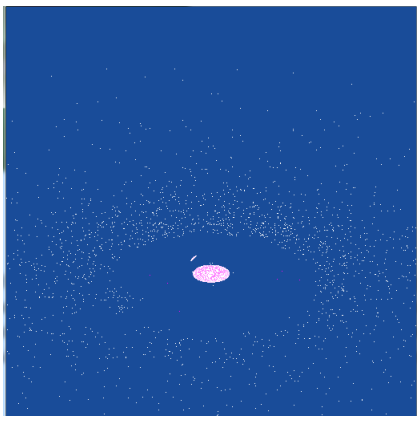


Figure 4.3: Photon map with fresnel reflectance

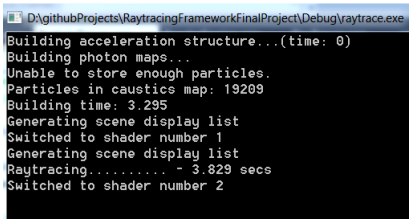


Figure 4.4: Log for fresnel reflectance and aborption without caustics

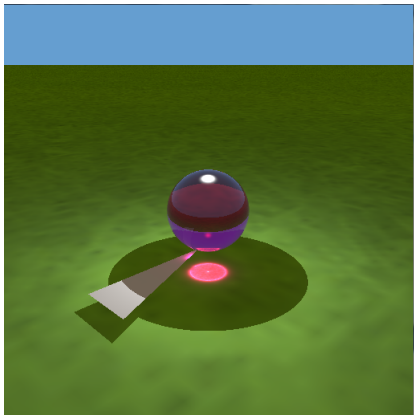


Figure 4.5: Final render result

5 Comparison to old glossy shader

If we compare the final rendering result to a render of the glossy shader without fresnel reflectance we can see that the reflection of the sky is shaped a bit differently.

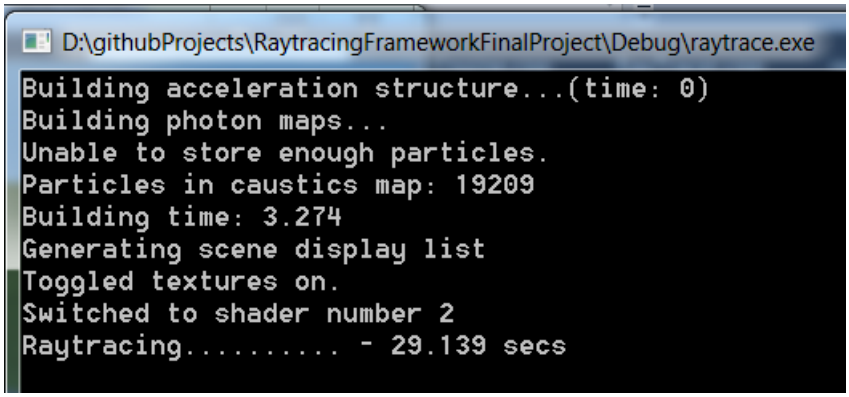
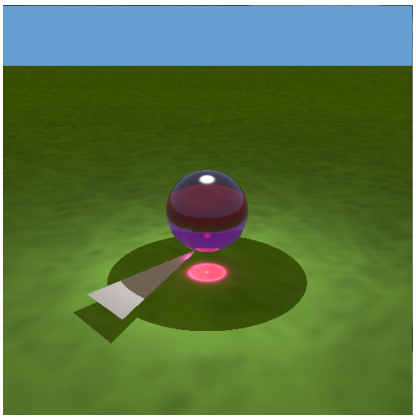
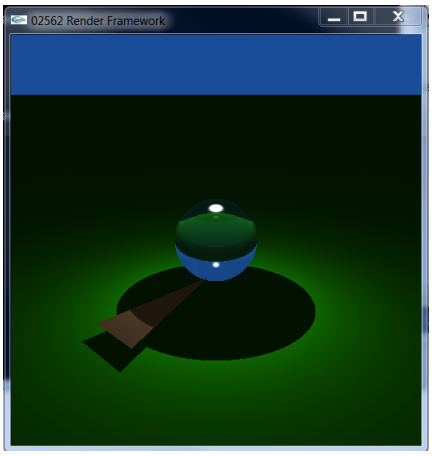


Figure 4.6: Log for final render result



(a) Absorption and Fresnel reflectance



(b) old glossy shader

Technical University of Denmark

02562 - Introduction to Rendering

Ambient Occlusion & Environment Mapping

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December 19, 2012

Contents

Chapter 1

Motivation

Even though global illumination techniques have come a long way they still have many limitations. One of them is the often long render times they require. Ambient occlusion is a rather simple technique that allows indirect lighting from an environment to be simulated cheaply. The technique was originally developed by Hayden Landis and colleagues at Industrial light and Magic to accomodate the needs they had for production ready global illumination [5]. Ambient occlusion together with environment mapping has since then often been used in the industry. The reason for this is that ambient occlusion besides being faster also allows for easy compositing of synthetic 3D images into live video footage[5]. The technique is also often sought implemented in a realtime context since its cheap evaluation lends itself well to realtime graphics[4, 9, 8].

We will in this report present an implementation of Ambient Occlusion into the Raytracing framework used for the course "02562 - Rendering Introduction" at Technical University of Denmark.

Chapter 2

Theory

This section will explain the basic theory and concept behind Ambient Occlusion. Besides covering the basic concept and math behind ambient occlusion it will also be covered how texture lookup into light probe images are performed. The chapter will conclude with a discussion of the disadvantages of ambient occlusion.

2.1 The Basic Concept

Ambient Occlusion works by seeing how much of an external environment can be seen from each surface point on the object or scene to be rendered. The more of the external environment that can be seen, the more ambient lighting that point will recieve. This type of illumination is therefore often called "sky light" in production, because it simulates how a model would be lighted on an overcast day, since the light from ambient occlusion is incident on the point from all directions due to the scatering of the clouds.

When ambient occlusion is calculated two factors are obtained. The first is the accessibility term. This is the measure of how much of the environment that is accessible from the surface point. The other is the "bent normal", which is the average direction of the incident light from the environment. The bent normal can then be used to look up into a light probe, which is a special type of image, in order to give more realistic lighting without the added cost of a global illumination algorithm. These two concepts is illustrated on figure 2.1 that illustrates how these two variables are calculated in a ray tracer. The accessibility at point P is determined by shooting rays out from the hemisphere

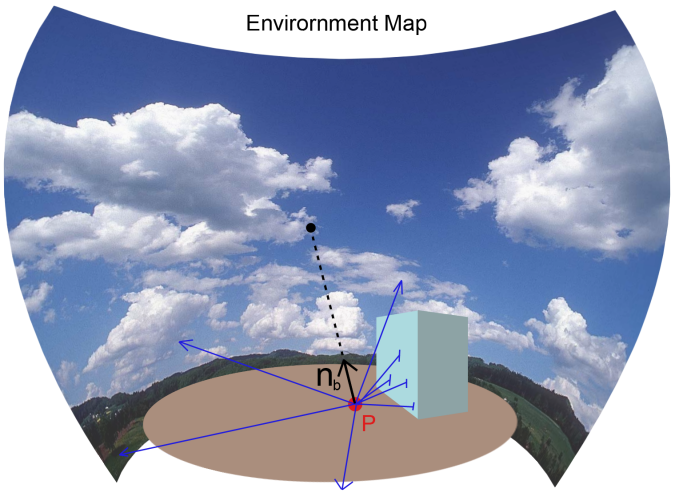


Figure 2.1: Overview of ambient occlusion.

surrounding the surface around P. The number of rays that does not hit other objects determines the accesibility. The average of the unoccluded rays is the bent normal that can be used to make a lookup into an environment map such as a light probe.

2.2 Mathemathical Foundation

Ambient Occlusion as all other realistic rendering methods tries to approximate the rendering equation:

$$L_o(\mathbf{x}, \overrightarrow{w}) = L_e(\mathbf{x}, \overrightarrow{w}) + \int_{2\pi} f_r(\mathbf{x}, \overrightarrow{w}', \overrightarrow{w}) L_i(\mathbf{x}, \overrightarrow{w}') \cos\theta dw'$$

We will aproximate this with the Monte Carlo estimator[2]:

$$L_o(\mathbf{x}, \overrightarrow{w}) = L_e(\mathbf{x}, \overrightarrow{w}) + \frac{1}{N} \sum_{i=1}^{N} \frac{f_r(\mathbf{x}, \overrightarrow{w}', \overrightarrow{w}) L_i(\mathbf{x}, \overrightarrow{w}') \cos\theta}{pdf(\overrightarrow{w}'_i)}$$

if we only consider diffuse reflectance then the BRDF is equal to the BRDF for Lambertian reflectance:

$$f_r(\mathbf{x}, \overrightarrow{w}', \overrightarrow{w}) = \frac{R_d}{\pi}$$

Then the expression becomes:

$$L_o(\mathbf{x}, \overrightarrow{w}) = L_e(\mathbf{x}, \overrightarrow{w}) + \frac{1}{N} \sum_{i=1}^{N} \frac{\frac{R_d}{\pi} L_i(\mathbf{x}, \overrightarrow{w}') \cos\theta}{pdf(\overrightarrow{w}'_i)}$$

This expression can be evaluated directly by rejection sampling the hemisphere. Since the probability density function for this sampling method is[2]:

$$PDF : p(\Theta) = \frac{1}{2\pi}$$

This means the above Monte Carlo Estimator end up being:

$$L_o(\mathbf{x}, \overrightarrow{w}) = L_e(\mathbf{x}, \overrightarrow{w}) + \frac{1}{N} \sum_{i=1}^{N} \frac{\frac{R_d}{\pi} L_i(\mathbf{x}, \overrightarrow{w}') \cos\theta}{pdf(\frac{1}{2\pi})}$$

$$L_o(\mathbf{x}, \overrightarrow{w}) = L_e(\mathbf{x}, \overrightarrow{w}) + \frac{2}{N} R_d \sum_{i=1}^{N} L_i(\mathbf{x}, \overrightarrow{w}') \cos\theta$$

However a better approach would be to simplify the expression even more. A good probability density function would therefore be[2]:

$$pdf((\overrightarrow{w}'_i)) = cos\theta/\pi$$

The goal is therefore to find a sampling method that has this probability density function. One is[2]:

$$\overrightarrow{w}'_i = (\theta, \phi) = (\cos^{-1}\sqrt{r_1}, 2\pi r_2)$$

Where r1 and r2 are random numbers between 0 and 1. When this sampling method and a visibility function denoted V is used to describe incident illumination the equation finaly becomes:

$$L_o(\mathbf{x}, \overrightarrow{w}) = \frac{1}{N} \sum_{i=1}^{N} \frac{\frac{R_d}{\pi}) V(\mathbf{x}, \overrightarrow{w}') \cos\theta}{cos\theta/\pi}$$

$$L_o(\mathbf{x}, \overrightarrow{w}) = \frac{1}{N} \sum_{i=1}^{N} R_d V(\mathbf{x}, \overrightarrow{w}')$$

$$L_o(\mathbf{x}, \overrightarrow{w}) = \frac{R_d}{N} \sum_{i=1}^{N} V(\mathbf{x}, \overrightarrow{w}')$$

Where V is equal to 1 if the direction is unoccluded and 0 otherwise. In a raytracer this is normally done by casting N rays with origin in the surface point being sampled with a cosine weighted random direction in the point's hemisphere, and divide the result by N. A similar approach is used to calculate the bent normal. This is the sampling method used in Landis' paper[5] but other papers choose not to include the cosine term in the ambient occlusion integral to start with [3]. Some also choose to let V return a value between 0 and 1 depending on the distance to the occluder where V returns 1 if the occluder being hit is farther away than a certain treshold [6].

2.3 Environment maps & High Dynamic Range Imaging

As mentioned earlier the bent normal can be used to do a lookup into an image. Most often this image comes in the form of a light probe, which is an omnidirectional image that stores incident light at a certain point in space. Since the human visual perception is able to detect a high range of luminosity values, a high dynamic range format such as RGBE is often used. In RGBE the fourth byte stores an exponential value used to modify the RGB value. This allows the format to have the same range as floating point values. This way it can handle both very bright and dark pixels. The formula for converting RGBE value is simply:

$$R_w = \frac{R_m + 0.5}{256} 2^{E-128}$$

$$G_w = \frac{G_m + 0.5}{256} 2^{E-128}$$

$$B_w = \frac{B_m + 0.5}{256} 2^{E-128}$$

When the light probe is used to illuminate a diffuse surface the most used method is to sample the image in a region around the point sample from the bent normal. This way the lookup becoems blured which gives a more realistic look when used to color a diffuse surface[5].

2.4 Lightprobe lookup

A lightprobe is stored as a latitude longitude map as shown on figure 2.2.

Figure 2.2: Example of a light probe from St Peter's Basilica, Rome. Source[1]

When sampling a light probe it is therefore necessary to convert the 3 dimensional direction of the bent normal into a set of uv coordinates. We will now derive how. Since it is custom to have the center of the lightmap be the upwards direction we get that the base of the uv coordinates should be:

$$(u, v) = (\frac{1}{2}, \frac{1}{2})$$

the next part is to determine at what distance and in what direction from the center of the texture we should sample. Since we start from the middle of the texture the distance should go from 0 to 0.5. We can obtain this range by taking the arccos of the z value and divide by two pi:

$$dist = \frac{arccos(D_z)}{2\pi}$$

The x and y values tells us in what direction from the center we should go out to get to the right position. We therefore have to get the normalized xy vector:

$$direction = \frac{1}{\sqrt{D_x^2 + D_y^2}}(D_x, D_y)$$

At the end we can rearange to end up with the following:

$$r = \frac{arcos(-D_z)}{2\pi\sqrt{D_x^2 + D_y^2}}$$

$$(u, v) = (\frac{1}{2}) + rD_x, \frac{1}{2}) + rD_y)$$

Where D_x, D_y and D_z is the lookup direction. Here it is assumed that the z-axis is upwards. One has also to take care of the event where Dx and Dy is close or equal to zero in which case the function should return (0.5 , 0.5).

2.5 Disadvantages of Ambient Occlusion

The main problem with Ambient Occlusion is from the fact that it reduces the problem of finding incident light, to using the calculated bent normal to do a texture lookup in an environment map. Since the bent normal is the average direction of incident light, it can in certain cases point in a direction that is actually occluded as illustrated by figure 2.3.

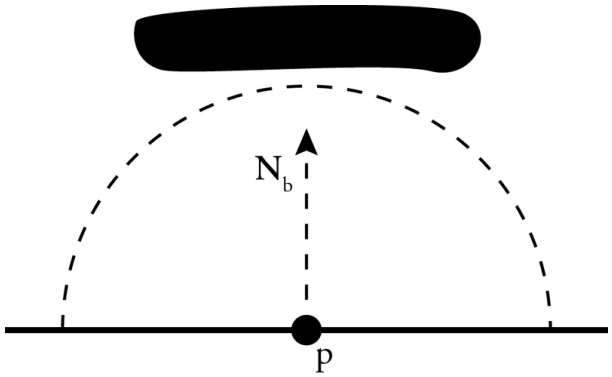


Figure 2.3: The problem of using a bent normal Nb to find the irradiance at point P.

However since ambient occlusion is used to calculate the diffuse term the lookup into the environment map is usually blured which means this error is not so noticable.

The next section will cover our implementation of Ambient Occlusion.

Chapter 3

Implementation

3.1 Ambient Occlusion Shader

To implement ambient occlussion in the ray tracing framework, it was necessary to create a new shader which can be found in `Shaders\DiffuseAmbientOccluded.cpp`. Later we implemented the functions that were needed to add support of HDR environment maps to our solution. This chapter will explain how different methods needed to achieve it were implemented.

3.1.1 Rejection Sampling

First, we implemented a basic ambient occlusion shader which uses simple rejection sampling to generate rays to be traced from each point. The function called in `DiffuseAmbientOccluded::shade()` can be seen in Listing 3.1 while Listing 3.2 shows the function `sampleHemisphere` responsible for the rejection sampling itself.

```
1  optix::float3 DiffuseAmbientOccluded::doRejectionSampling(const optix::Ray& r, HitInfo
       & hit, bool emit) const
2  {
3    float3 rho_d = get_diffuse(hit);
4
5    float3 avgUoccluded = make_float3(0,0,0);
6    float numOfUnoccluded = 0;
7
8    // define number of rays that are sampled
9    int numOfRays = 300;
10   for(int i = 0 ; i < numOfRays ; i++)
11   {
12     Ray hemiRay = r;
13     HitInfo hemiHit;
14     if(sampleHemisphere(hemiRay, hemiHit, hit))
15     {
16       avgUoccluded += hemiRay.direction;
17       numOfUnoccluded += dot(hemiRay.direction, hit.shading_normal);
18     }
19   }
20   //compute the average direction of unoccluded rays and accesability value at given
         point
21   float3 averageNormal = normalize(avgUoccluded / numOfUnoccluded);
22   float accessability = ((float)numOfUnoccluded) / numOfRays;
23
24   return 2 * accessability * rho_d;
25 }
```

Listing 3.1: Ambient occlusion shader with rejection sampling.

The function in Listing 3.1 shoots a number of rays over the hemisphere as described in [7]. It calls the function from Listing 3.2 to sample directions on the hemisphere.

```
bool DiffuseAmbientOccluded::sampleHemisphere(Ray& r, HitInfo& hemiHit, HitInfo&
    surfaceHit) const
{
  float x,y,z;
  while(true)
  {
    // get a random point in a unit cube around the point
    x = randomizer.mt_random() * 2 - 1;
    y = randomizer.mt_random() * 2 - 1;
    z = randomizer.mt_random() * 2 - 1;

    // reject those outside of a unit sphere
    if(x*x + y*y + z*z > 1)
      continue;
    // reject the lower hemisphere
    if(dot(make_float3(x,y,z), surfaceHit.shading_normal) < 0)
      continue;

    break;
  }

  // create a ray in the sampled direction
  float3 dir = normalize(make_float3(x, y, z));

  r.direction = dir;
  r.origin = surfaceHit.position;
  r.tmin = 0.001f;
  r.tmax = 99999;

  // return false if it hit anyting
  if (tracer -> trace_to_any(r, hemiHit))
    return false;

  return true;
}
```

Listing 3.2: Rejection sampling.

3.1.2 Cosine Weighted Hemisphere

In order to improve performance and result of our solution we introduced the method of sampling ray directions from a cosine weighted hemisphere instead of the rejection sampling method used in the previous subsection. This provides a much more efficient way of generating rays distributed over a hemisphere and allows us to save computations. The relevant code is shown in Listing 3.3.

```
bool DiffuseAmbientOccluded::sampleCosineWeightedHemisphere(Ray& ray, HitInfo& hemiHit
    , HitInfo& surfaceHit) const
{
  // get an orthonormal basis at the given point
  optix::Onb onb = optix::Onb(surfaceHit.shading_normal);
```

```
5
6   // get a random point from a unit circle around the point using polar coordinates
7   float phi, r;
8   phi = randomizer.mt_random() * M_PIf * 2;
9   r = randomizer.mt_random();
10
11  // "raise" the point from the circle to the hemisphere above it
12  float x = r*cos(phi);
13  float y = r*sin(phi);
14  float z = sqrt(1-r*r);
15
16  // transform the coordinates to the onb coordinate system
17  float3 dir = x*onb.m_tangent + y*onb.m_binormal + z*onb.m_normal;
18
19  dir = normalize(dir);
20
21  ray.direction = dir;
22  ray.origin = surfaceHit.position;
23  ray.tmin = 0.001f;
24  ray.tmax = 99999;
25
26  // trace the ray in the sampled direction, return false if it hit anything
27  if (tracer -> trace_to_any(ray, hemiHit))
28    return false;
29
30  return true;
31 }
```

Listing 3.3: Cosine weighted hemisphere sampling

3.2 Environment Sampling

The next part of our project is to add sampling of light from the environment in form of HDR light probes. To do this we had to extend the framework to handle conversion from RGBE to floating point RGB as well as implement the projection of direction to texture coordinates. Then we could use them in our ambient occlusion solution.

3.2.1 HDR Image Conversion

The first part focuses on conversion of RGBE format used in HDR images to floating point RGB. This is done with the function from Listing 3.6.

```
1 float HDRTexture::convert(unsigned char c, int e)
2 {
3   return ((float)c + .5) * pow(2.0f, e - 8);
4 }
```

Listing 3.4: RGBE to RGBA conversion.

3.2.2 Spherical Texture Lookup

Furthermore we needed to implement a function which returns coordinates in a spherical texture by converting direction from which the environment should be sampled to uv coordinates. This is done in Listing 3.5.

```
void SphereTexture::project_direction(const float3& d, float& u, float& v) const
{
  // handling denominator = 0
  float dxdy = sqrt(d.x * d.x + d.y * d.y);
  if (dxdy < .001f)
  {
    u = v = .5;
    return;
  }

  float r = .5 * M_1_PIf * acos(-d.z)/dxdy;

  u = .5 + r * d.x;
  v = .5 + r * d.y;
}
```

Listing 3.5: Conversion to texture coordinates

In the end we could modify our shader code to include the contribution coming from the lookup in the spherical texture as shown in Listing 3.6.

```
optix::float3 DiffuseAmbientOccluded::doWeightedCosineSamplingWithEnvironmentSampling(
    const optix::Ray& r, HitInfo& hit, bool emit) const
{
  float3 rho_a = get_emission(hit);
  float3 rho_d = get_diffuse(hit);

  float3 avgUnoccluded = make_float3(0,0,0);
  int numOfUnoccluded = 0;

  const int numOfRays = 200;
  for(int i = 0 ; i < numOfRays ; i++)
  {
    Ray hemiRay = r;
    HitInfo hemiHit;
    if(sampleCosineWeightedHemisphere(hemiRay, hemiHit, hit))
    {
      avgUnoccluded += hemiRay.direction;
      numOfUnoccluded++;
    }
  }

  float3 averageNormal = normalize(avgUnoccluded / numOfUnoccluded);
  float accessability = ((float)numOfUnoccluded) / numOfRays;

  // sample the environment in the average unoccluded direction
  float3 hdrValue = tracer -> get_background(averageNormal);

  return M_1_PIf * accessability * rho_d * hdrValue;
}
```

Listing 3.6: RGBE to RGBA conversion.

Chapter 4

Results & Discussion

In the following chapter we will try to summarise the results we got from our ambient occlusion solution as well as compare the two implemented sampling methods and their efficiency with regard to the number of used samples.

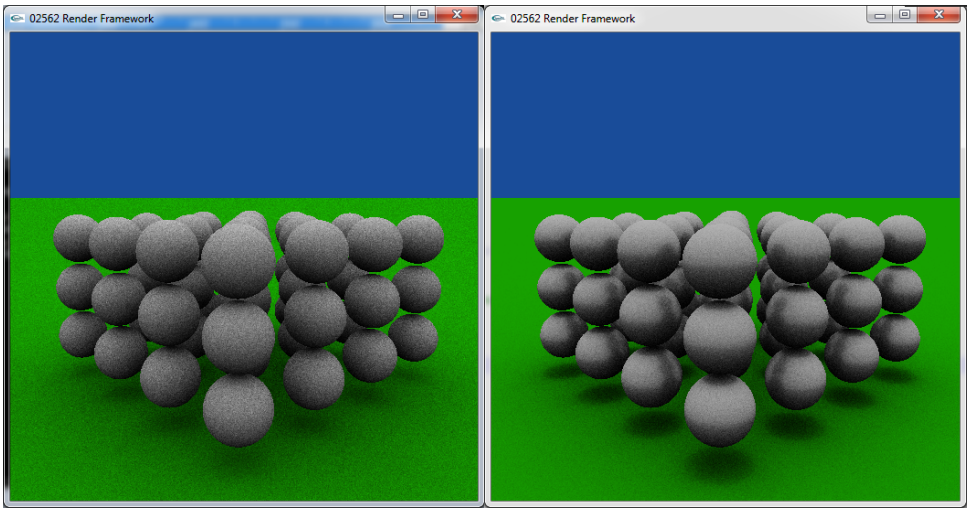
4.1 Comparison of ambient occlusion results

This section contains comparison of results using rejection sampling (described in subsection 3.1.1) to the use of cosine weighted hemisphere sampling (subsection 3.1.2). The renders were run with 100, 200 and 300 sample rays and the results can be seen in Figure 4.1.

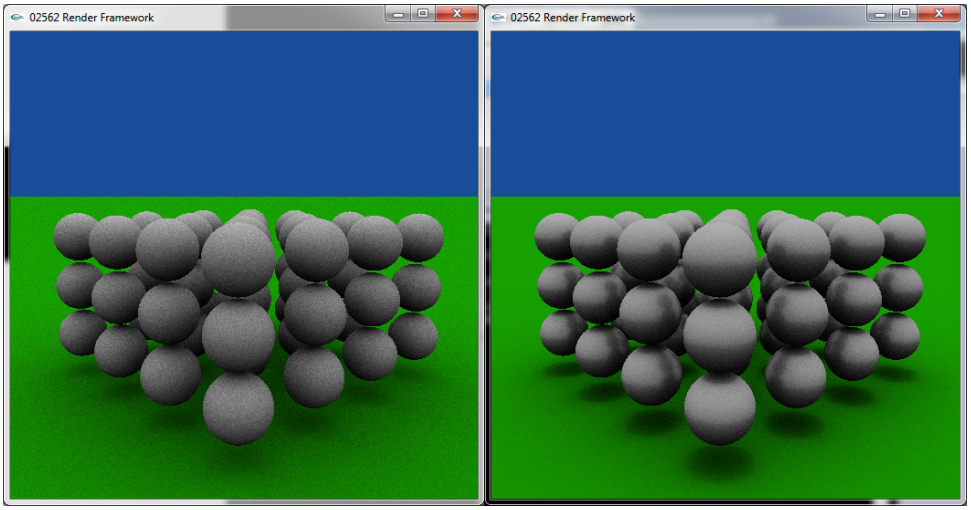
The result clearly show that the cosine weighted hemisphere sampling performs much better than the simple rejection sampling. This may be accounted to higher efficiency of sampling the directions of rays.

4.2 HDR environment map

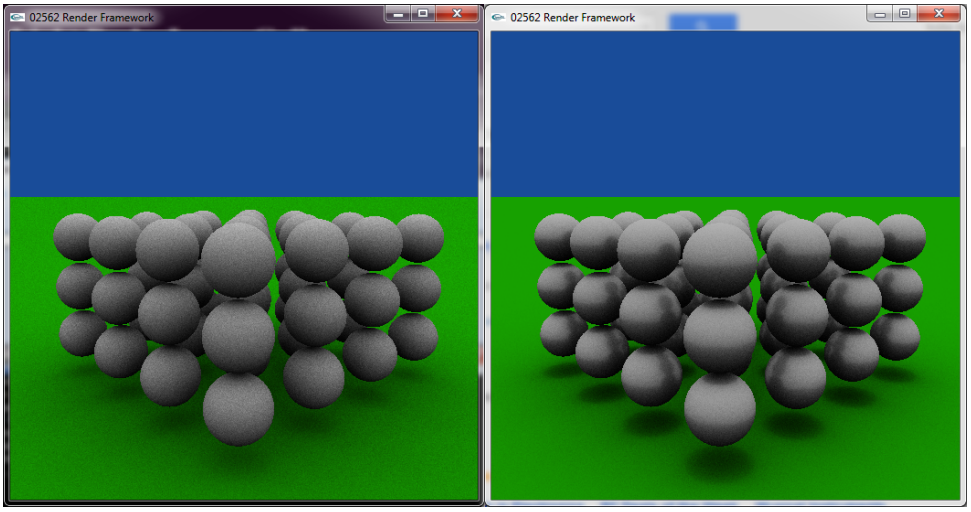
The final feature that we included in our ambient occlusion solution is environment mapping from HDR textures (as seen in section 2.3). The renders in Figure 4.3 use the cosine weighted hemisphere sampling method implemented in the previous chapter. The HDR images used in renders in Figure 4.3 come from [1]



(a) 100 samples, rejection sampling (b) 100 samples, cosine weighted sampling

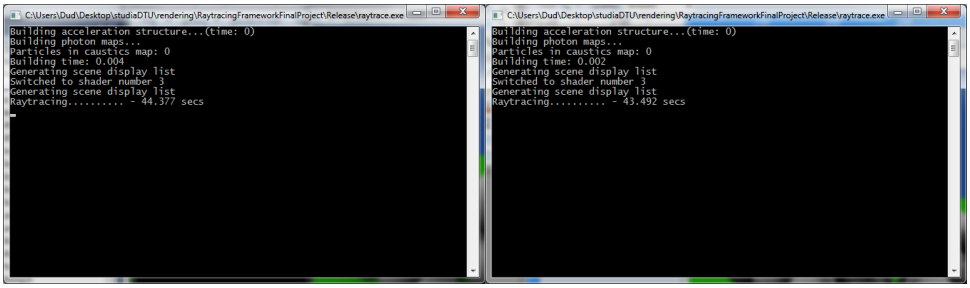


(c) 200 samples, rejection sampling (d) 200 samples, cosine weighted sampling

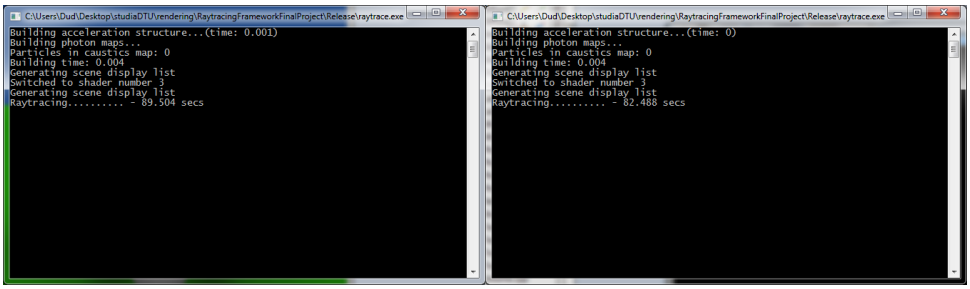


(e) 300 samples, rejection sampling (f) 300 samples, cosine weighted sampling

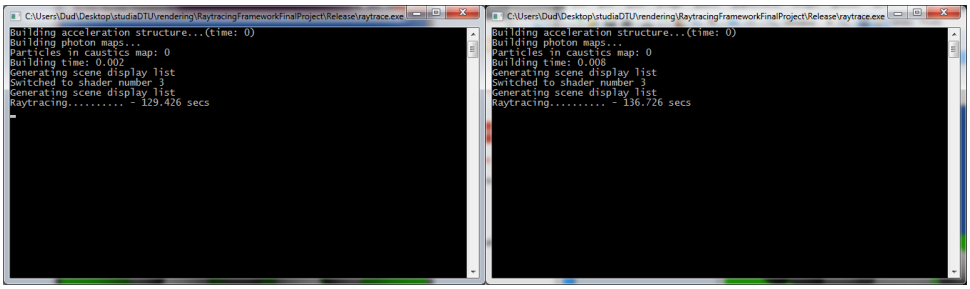
Figure 4.1: Comparison of sampling methods if different number of samples



(a) 100 samples, rejection sampling (b) 100 samples, cosine weighted sampling

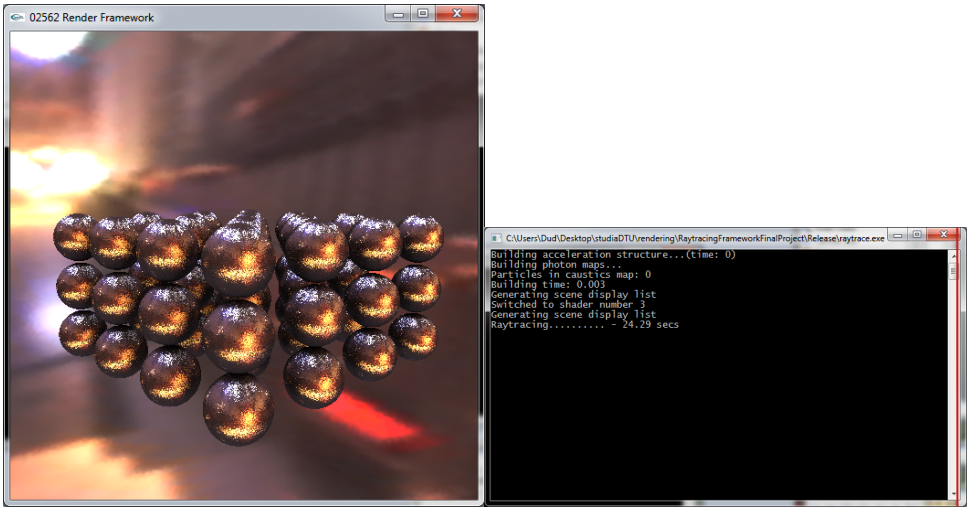


(c) 200 samples, rejection sampling (d) 200 samples, cosine weighted sampling



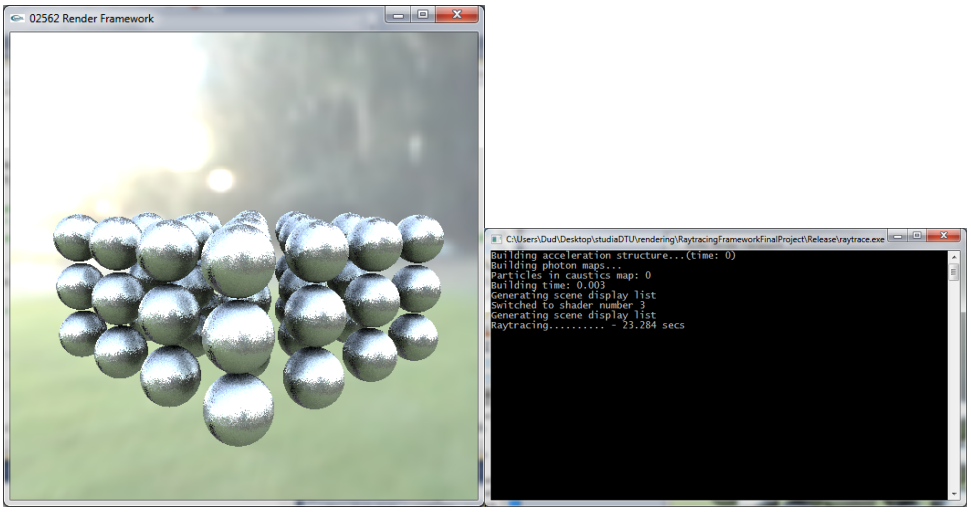
(e) 300 samples, rejection sampling (f) 300 samples, cosine weighted sampling

Figure 4.2: Render logs for the renders in Figure 4.1.



(a) Render with Grace Cathedral texture.

(b) Render log.



(c) Render with Campus at Sunset texture.

(d) Render log.

Figure 4.3: Environment mapping results.

Chapter 5

Conclusion

We have demonstrated two different ways of performing the sampling for ambient occlusion that produced two different visual results. From the litterature it seems that both methods are acceptable so it is a matter of what visual style that fits the desired result the best. That the two different methods produce two overall different levels of brightness. A likely candidate is the lack of a modification with the probability density function in the rejection sampling method but it does not seem to be something that other papers take into consideration [7]. The lookup into the light probe image and conversion from the RGBE format to floating point RGB seems to work in a satisfactory way. Here a better mapping to values the screen can show could also improve the result.

The two most obvious improvements to our method would be to change the weight of each occluded ray based on how far away the hit on the occluder are. Another improvement would be to implemnt a blurred lookup into the environment map.

Bibliography

[1] P. Debevec, *Light probe image gallery*, December 2012.

[2] P. Dutré, *Global Illumination Compendium*, Program of Computer Graphics, Cornell University, Sept. 2003.

[3] O. Klehm, T. Ritschel, E. Eisemann, and H.-P. Seidel, *Bent normals and cones in screen-space*, in Vision, Modeling and Visualization Workshop, 2011.

[4] J. Kontkanen and S. Laine, *Ambient occlusion fields*, in Proceedings of the 2005 symposium on Interactive 3D graphics and games, I3D '05, New York, NY, USA, 2005, ACM, pp. 41–48.

[5] H. Landis, *Production-Ready Global Illumination*, in Siggraph Course Notes, vol. 16, 2002.

[6] M. McGuire, *Ambient occlusion volumes*, in Proceedings of the Conference on High Performance Graphics, HPG '10, Aire-la-Ville, Switzerland, Switzerland, 2010, Eurographics Association, pp. 47–56.

[7] M. Pharr and S. Green, *Chapter 17. ambient occlusion*, in GPU Gems, Pearson Education Inc., 2004.

[8] P. Shanmugam and O. Arikan, *Hardware accelerated ambient occlusion techniques on gpus*, in Proceedings of the 2007 symposium on Interactive 3D graphics and games, I3D '07, New York, NY, USA, 2007, ACM, pp. 73–80.

[9] T. Umenhoffer, B. Tóth, and L. Szirmay-Kalos, *Efficient methods for ambient lighting*, in Proceedings of the 25th Spring Conference on Computer Graphics, SCCG '09, New York, NY, USA, 2009, ACM, pp. 87–94.