Project - Pathtracer

Introduction

In this lab we will implement and improve a simple path-tracer. Path-tracing is a way of rendering global illumination images that has recently become quite popular in off-line renderers. You will start from some simple code that renders an image with direct lighting only. From there we will add some basic functionality and then you will do one larger assignment (suggestions at the end) on your own.

The rendering Equation

We will begin by describing the basic math behind what we are going to do, but very briefly. Refer to lecture notes, your textbook (chapters 7 and 9) and the internet for details. We start out with *The Rendering Equation*. This equation is actually all we have to solve to create glorious photo-realistic images:

$$L_o(\boldsymbol{p},\omega) = L_e(\boldsymbol{p},\omega) + \int_\Omega f(\boldsymbol{p},\omega,\omega')L_i(\boldsymbol{p},\omega')\cos(\boldsymbol{n},\omega')\,d\omega'$$

It says that the *radiance* (Watt per unit solid angle and unit area) L_o that leaves a point **p** in the direction ω can be found from the:

- **Emitted Light**, $L_e(\boldsymbol{p},\omega)$ – If the surface at point **p** emits radiance in direction ω
- **BRDF**, $f(\boldsymbol{p},\omega,\omega')$ - This is a function that describes how the surface at point **p** reflects light that comes from direction ω' in direction ω. Some details below.
- **Incoming radiance**, $L_i(\boldsymbol{p},\omega')$ - This is the incoming light from direction ω', which we typically find by evaluating this same equation at the first intersection point in that direction.
- **Cosine term,** $\cos(\boldsymbol{n},\omega')$ - This will attenuate the incoming light based on the incident angle.

This equation is recursive (since L_i depends on L_o) and there is no analytical solution to it. We can however estimate it using what is called *Monte Carlo integration*:

$$L_o(\boldsymbol{p},\omega) \approx L_e(\boldsymbol{p},\omega) + \frac{1}{2\pi N}\sum_{i=0}^{N} f(\boldsymbol{p},\omega,\omega_i)L_i(\boldsymbol{p},\omega_i)\cos(\boldsymbol{n},\omega_i)$$

and that is exactly what we are going to do. The directions ω_i above are N random directions uniformly distributed over the hemisphere. We will discuss better sampling later.

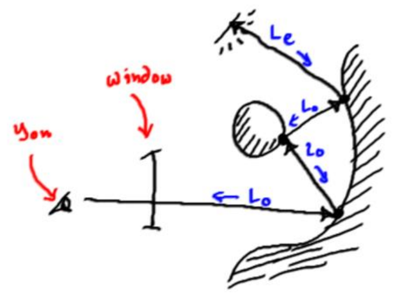
The BRDF and Materials

In our discussion and code we will talk about BRDFs and Materials. The *Bidirectional Reflectance Distribution Function* (BRDF) is a four-dimensional function that says how much of the energy that comes from direction ω will be reflected in some direction ω'. The BRDF is *reciprocal*, i.e. $f(\boldsymbol{p},\omega,\omega') = f(\boldsymbol{p},\omega',\omega)$ and *energy-conserving*. This second property means that unless energy is absorbed and turned into heat, the total energy reflected will equal the total incoming energy over the hemisphere.

In this tutorial, a Material can "contain" one BRDF or a combination of several BRDFs, and various settings that describe the material (e.g. reflectance, index-of-refraction and so on…).

Path-tracing

Let's move on to something more practical and find out how we can use all this to generate pretty images. We will use a method called path-tracing to solve the equation above and in this



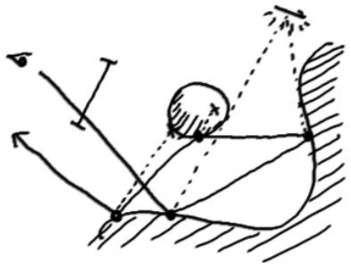
section we will briefly cover how that works, before we go on to actually implement one.

For starters, we will shoot one ray per pixel (the ray starts at the camera and goes "through" the pixel and into the scene). We find the first intersection-point with the scene and there we want to estimate the outgoing radiance.

We do so by shooting *one single ray* to estimate the incoming radiance. At the first intersection point for that ray, we again shoot a single ray and so on, forming a *path* that goes on until there is no intersection (or we terminate on some other criteria). At each vertex of the path we will evaluate the emitted light, the BRDF and the cosine term to obtain the radiance leaving the point. When the recursion has terminated and we have obtained L_o for the first ray shot, we record this radiance in the framebuffer.

This is all we need to do to create a mathematically sound estimation of the true global illumination image we sought! It's probably all black though, unless we were lucky and hit an emitting surface with some rays in which case it might be black with a little bit of noise. But if we keep running the algorithm, and accumulate the incoming radiance in each pixel (and divide by the number of samples) we would eventually end up with a correct image. This will take more time than is left for this course though, so let's speed things up a bit.

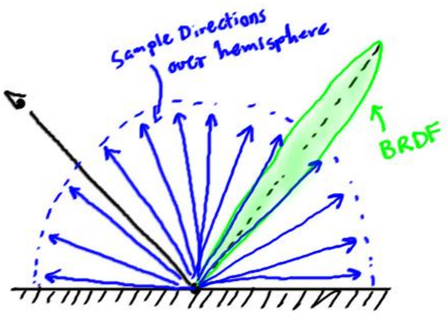
Direct Illumination



The first step is to separate *indirect* and *direct* illumination. At each vertex of the path we will first shoot a *shadow-ray* to each of the light-sources in the scene. If there is no geometry blocking the light we will multiply the radiance from the light with the BRDF and cosine term and *then* add the incoming indirect light by shooting a single ray as before. For this to be correct, we just have to make sure that the surfaces we have chosen to be light-sources do not contribute emitted radiance if sampled by an indirect ray.

There! That's a path-tracer and it generates correct images. It's still painfully slow if any of our materials have a narrow brdf though. We will remedy this with what is called *importance sampling*.

Importance sampling

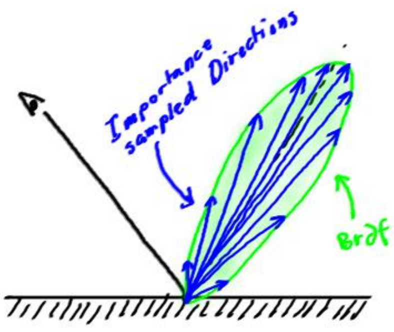


The problem is illustrated in the image to the right. Say that our BRDF represents a near mirror direction. That means that all sample directions that are not close to the perfect specular reflection direction will contribute almost nothing.

With importance sampling we will instead pick samples from a distribution that looks more like the BRDF we are trying to sample, for which we know the *Probability Density Function* (PDF), $p(\omega_i)$.

$$L_o(\boldsymbol{p},\omega) \approx L_e(\boldsymbol{p},\omega) + \frac{1}{N}\sum_{i=0}^{N}\frac{f(\boldsymbol{p},\omega,\omega_i)L_i(\boldsymbol{p},\omega_i)\cos(\boldsymbol{n},\omega_i)}{p(\omega_i)}$$

This new equation is no different from the previous one, except that we now allow for varying PDFs (Before the pdf was a constant $\frac{1}{2\pi}$ since we sampled uniformly on the hemisphere). We will now pick samples with a probability that is much higher where the BRDF is large. We then have to divide the resulting radiance of each sample by the PDF in the sample direction to account for this. So we will have more samples where the brdf is high, but if we happen to pick a sample where the PDF is low, its contribution will be increased.



Note that we rarely can find a sampling scheme that exactly matches the brdf and that the sampling scheme must be carefully chosen so that it will not occasionally sample directions with very low probability where the BRDF is not correspondingly low. If we do, then we can get very strong samples in some random pixels that take a very long time to converge.

Let's look at a simple (perhaps the simplest) example. Say that our surface has a gray perfectly diffuse material. The surface absorbs 30% of the incoming light and reflects the rest. A diffuse material reflects equally in all directions.

$$\boldsymbol{color} = (0.7, 0.7, 0.7)$$

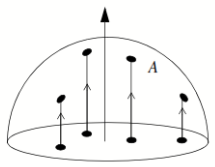
$$f(\boldsymbol{p}, \omega, \omega_i) = \frac{1}{\pi}\boldsymbol{color}$$

Well… If it reflects equally in all directions, wouldn't sampling the hemisphere uniformly be the best choice? No because what we are sampling is not just an integral over the brdf. We trying to find a solution to the integral:

$$\int_{\Omega} f(\boldsymbol{p}, \omega, \omega')L_i(\boldsymbol{p}, \omega')\cos(\boldsymbol{n}, \omega')\,d\omega'$$

So ultimately we would like to importance sample with a sample distribution that matches *this* integral as well as possible. But the incoming light is rarely known in advance, and is expensive to evaluate. We can however importance sample on the cosine-term.

In fact, there is a simple way to choose a direction with a pdf that is $p(\omega_i) = \frac{\cos(\boldsymbol{n},\omega')}{\pi}$. All you have to do is to generate points uniformly on a disc, then project these points on the hemisphere. You can find a number of useful sampling methods with pdfs and other good stuff in the *Global Illumination Compedium*:



http://people.cs.kuleuven.be/~philip.dutre/GI/TotalCompendium.pdf

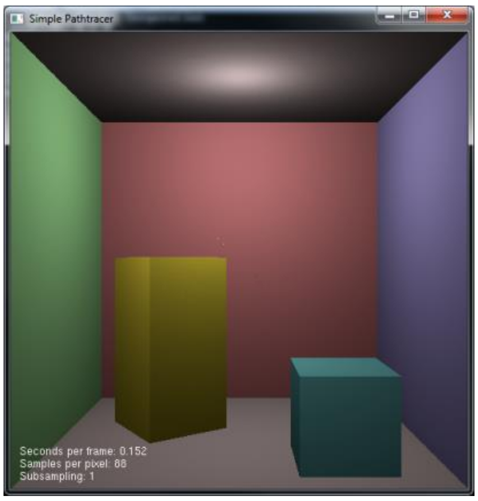
Now let's use this:

$$\frac{1}{N}\sum_{i=0}^{N}\frac{f(\boldsymbol{p},\omega,\omega_i)L_i(\boldsymbol{p},\omega_i)\cos(\boldsymbol{n},\omega_i)}{p(\omega_i)} = \frac{1}{N}\sum_{i=0}^{N}\frac{\frac{1}{\pi}\boldsymbol{color}L_i(\boldsymbol{p},\omega_i)\cos(\boldsymbol{n},\omega_i)}{\frac{\cos(\boldsymbol{n},\omega')}{\pi}} = \frac{1}{N}\sum_{i=0}^{N}\boldsymbol{color}\;L_i(\boldsymbol{p},\omega_i)$$

How about that? Just by changing the directions you sample, the expression becomes a lot simpler *and* you get a better result.

Implementing a basic path-tracer

That's enough theory for now. Open the Visual Studio solution file ("Pathtracer.sln"), make sure you have "Release" build activated and run the program. (If you open the solution in VS2012, it will prompt you to "update" the projects. Do this and everything should work the same.)



Seconds per frame: 0.152
Samples per pixel: 88
Subsampling: 1

Yikes! That's not pretty at all. Well, don't worry. You will have many opportunities to improve on this image. But first, let's examine what the program does.

Open the file `pathtracer_main.cpp`. This should look quite familiar by now. It is a simple OpenGL program that loads an OBJ model (in the main function towards the end) and then starts a GLUT main loop.

Every time the display() function runs, it will trace one ray per pixel (by calling `g_pathtracer.tracePrimaryRays()`). This is where all the interesting stuff happens. When this is done, the PathTracer object will contain an updated framebuffer and that will be copied to a texture and rendered as a full-screen quad in the window.

You will spend very little time in this file, but look it through and make sure you understand what goes on. Then look at the very top where you can find these lines

```
#ifdef _DEBUG
int g_subsample = 8;
#else
int g_subsample = 1;
#endif
```

This is a variable you may want to change at times. The g_subsample variable lets you raytrace a smaller image than the size of the window while showing a magnified version. This is very useful while debugging or just trying something new. Set g_subsample to 2 for now.

Pathtracer::tracePrimaryRays()

Now take a look at this function to make sure you understand it. It takes the currently selected camera and generates one ray for each pixel. It then calls `Scene::intersect` for this ray. This method will find the first intersection between the ray and the scene and fills in an `Intersection` object. This object contains the position, normal and a pointer to the Material of the surface that was intersected. Or, the method returns false if there was no intersection.

Then, if there was an intersection, we need to evaluate the radiance that reaches us from that point. This is calculated in `Pathtracer::Li`. If there was no intersection `Pathtracer::Lenvironment` is called instead, which currently just returns a constant radiance.

Assignment:
Let's do a little something to improve the quality of the image already. The code currently samples the lower left corner of the pixel every single iteration. Modify this so that it chooses a random position within the pixel instead, to get some nice super-sample antialiasing.

Tip: There is a randf() helper function in the file MCSampling.h which returns a random float value between 0.0 and 1.0

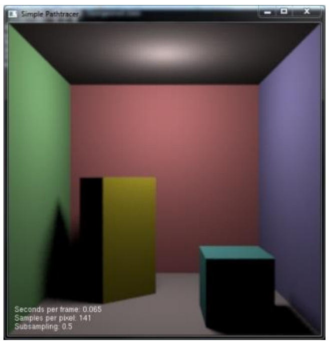
Cameras and lights

A quick intermission about cameras and lights. The pathtracer reads OBJ files, which look just as they always have, but the corresponding MTL files look nothing like real MTL files. Take a look at cornell.mtl. You need not care about the material definitions just yet, but note that we can define lights and cameras in these files that our program will respect.

You can have any number of lights and any number of cameras. The lights are all used at once, and you can change the chosen camera with the 'c' key. Give it a try. The arguments for lights and cameras should be self-explanatory, but if not, ask an assistant.

Pathtracer::Li()

This is where all the interesting stuff happens. Or doesn't happen as it stands, but you will soon take care of that. The current code just iterates over all lights and chooses one position on each light to sample. It then evaluates $f(\boldsymbol{p}, \omega, \omega_i) L_i(\boldsymbol{p}, \omega_i) \cos(\boldsymbol{n}, \omega_i)$, where L_i is the radiance from the light, and returns the sum of all light contributions.



```
Seconds per frame: 0.065
Samples per pixel: 141
Subsampling: 0.5
```

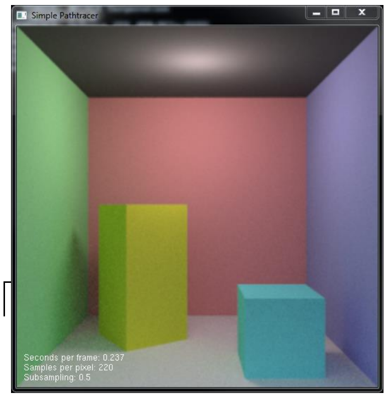
Assignment:
The least thing we can do is to include light visibility so we get some shadows. Create a shadow-ray and intersect it with the scene to see if the light should contribute or not. When you are done you should see a lovely soft shadow like the image to the right.

Tip #1: The Scene class has an `intersectP()` method that may suit your needs. What is the difference between this and the `intersect()` method?
Tip#2: There is a value **`PT_EPSILON`** defined. This might come in handy here.

Well, that was easy. Now for the tricky part. The current program is not a path-tracer. Because it doesn't trace a path. It's time to rewrite it so that it does not only look at the direct lighting but also shoots a ray to gather indirect illumination.

We could (and you may) implement this as a recursive algorithm, but in practice this is often a lot slower so in the pseudo code below we will instead suggest an iterative approach. Read the pseudo code below and make sure you understand it, then roll up your sleeves and implement it in C++:

```
L                    <- (0.0, 0.0, 0.0)
pathThroughput       <- (1.0, 1.0, 1.0)
currentRay           <- primary ray
isect                <- primary intersection
for bounces = 0 to PT_MAX_BOUNCES
{
      // Direct illumination
      for each Light
             sample a point on light
             L += pathThroughput * [direct illumination from light if visible]

      // Sample an outgoing direction, the brdf and pdf
      (wo, brdf, pdf)  <- material.sample_f(wi)

      // If the pdf is too close to zero, break to avoid instability
      if pdf < PT_EPSILON return L

      cosineterm = abs(dot(wo, isect.normal)

      pathThroughput = pathThroughput * (brdf * cosineterm)/pdf

      // If pathThroughput is too small there is no need to continue
      if max(pathThroughput) < PT_EPSILON return L

      // Create next ray on path
      currentRay <- new ray from intersection point in outgoing direction

      // Bias the ray slightly to avoid self-intersection
      currentRay.o += PT_EPSILON * isect.normal

      // Trace the new ray
      isect <- m_scene.intersect(currentRay)

      if no intersection
             return L + pathThroughput * Lenvironment(currentRay)
}
```



Seconds per frame: 0.237
Samples per pixel: 220
Subsampling: 0.5

Allright. If you get it right, you should have something like the image to the left. Isn't life better with GI? Now we will add some importance sampling. In your pathtracer, the direction in which to sample indirect illumination is chosen by the `Material::sample_f()` method.

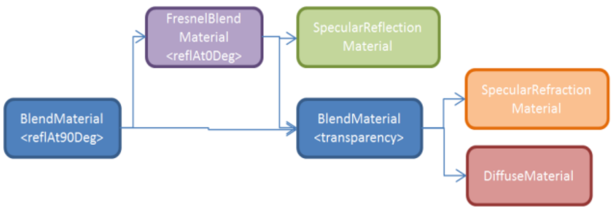
Assignment:
These cubes all have a simple diffuse material so far. Change the `DiffuseMaterial::sample_f()` method so that it importance samples the cosine term.

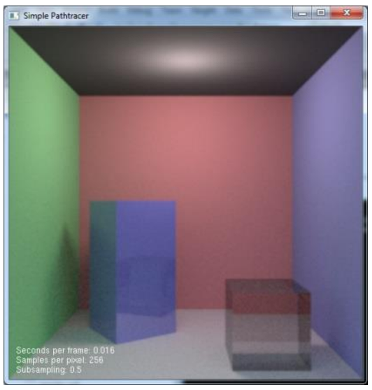
Tip: In MCSampling.h we have already provided a `cosineSampleHemisphere()` method for you.

Now compare the non-importance sampled image and the importance sampled after the same number of samples per pixel (you can set the `MAX_SAMPLES_PER_PIXEL` pixel in pathtracer_main.cpp).

Materials

Take a look at `Material.h`. Besides the `DiffuseMaterial` with which you are already acquainted there are a number of others. When we read an OBJ/MTL file from disc we actually build a little material tree that looks as to the right.


FresnelBlend Material <reflAt0Deg>
SpecularReflection Material
BlendMaterial <reflAt90Deg>
BlendMaterial <transparency>
SpecularRefraction Material
DiffuseMaterial



```
Seconds per frame: 0.016
Samples per pixel: 256
Subsampling: 0.5
```

Now uncomment the additional arguments to the materials in cornell.mtl. You should end up with something like the image to the left.

Then play with the material settings and have fun. For exactly one hour. Then choose a project from below and show your work to an assistant.

Project

Now that you know the ins and outs of the path-tracer, choose a project from one of the suggested ones below, or if you want to do something else suggest it to an assistant.

1. **Microfacet BSDF –** The BRDFs available in the pathtracer so far are quite simple. You can represent much more realistic looking materials if you add a BRDF that supports glossy reflections (not perfect mirror reflections). One good paper that presents a physically plausible Microfacet based BRDF that also handles rough refractions is:
   http://www.graphics.cornell.edu/~bjw/microfacetbsdf.pdf
   Extend the path-tracer to use one of the models presented in this paper instead of our perfect specular reflection BRDF.
   Optional: Also allow rough refractions.

2. **BVH –** Examine the Scene class. You will find that the triangles are all stored in one list and that when intersect is called, we will simply iterate through this list of triangles and intersect them one by one to find the closest intersection. This works decently for the simple scene we have looked at so far which only has 32 triangles, but for anything more complex it will be extremely slow.

   Implement an acceleration structure (a fairly simple, still powerful suggestion is an AABB tree). You should be able to get below 4 seconds per frame for the scene "cornellbottle2.obj" (on the lab machines).

   Optional: The acceleration structure is not the only thing that is slow in this path-tracer. Try to profile the code and make it as fast as you possibly can.

3. **HDRI lighting –** Currently when a ray misses all geometry, the environment will return a single constant radiance. You can get much more interesting lighting of an outdoor scene if you instead fetch radiance from an HDRI environment.

   Either load and use an HDRI environment map *or* (trickier) implement a Sun&Sky model, for example this one:
   http://www.cs.utah.edu/~shirley/papers/sunsky/sunsky.pdf

   Optional: If you use a tricky HDRI environment map you may find that it takes a long time for your render to converge.This can be greatly improved if you treat your environment as a light instead and importance sample the direction you sample.

4. **Textures –** Just as in realtime rendering, offline renderers frequently use textures to increase the level of detail in a scene. Add support for diffuse textures to the code.

   Optional: You will be able to get even more interesting images if you allow for other types of textures as well. Try to implement support for normal-maps or specular-maps or transparency-maps or whatever tickles your fancy.