Raytracer Project Report

DH2323 (DGI17)

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Contents

1 Preface: abbreviated project specification

This sections contains an abbreviated version of the project specification that we submitted on May 3rd.

1.1 Idea

The idea of the project is to explore more features common in ray tracing rendering in an effort to gain an increased understanding of conventional ray tracing in general. We will do this by adding a number of features to the baseline feature set defined by the ray tracer implemented in lab 2.

1.2 Project plan

The following section contains two sets of implementation goals. The first set (”Baseline”) is what we consider to be the minimum for project completion, while the second set (”Bonus”) contains ideas that are not essential but could improve the project should we find the time to implement them.

1.3 Baseline features

Fast wireframe view

The application should default to a wireframe renderer. From the wireframe mode the user should be able to initiate a single-frame high-quality render or simply a switch to continuous ray tracing, as well as be able to switch back to wireframe.

Multithreading

Rendering should be parallelized by partitioning the screen space and rendering each part in a separate thread. The number of threads should be configurable.

Back-face culling

Loading of models in the `.STL`[1] format

Loading of models in the Wavefront `.OBJ`[2] format

Features supported by the format that are outside the scope of basic triangle geometry (free-form curves, smoothing groups etc.) are not part of this goal.

Phong interpolation and the Phong reflection model

Materials

Primitives such as triangles should support being assigned a ”material”. The following properties should be implemented:

- **Phong properties (colors for ambient, specular, diffuse)**
- **Texture mapping**
- **Opacity**
- **Specular reflection and reflectivity**
- **Refraction**

[1] `https://en.wikipedia.org/wiki/STL_(file_format)`
[2] `http://www.martinreddy.net/gfx/3d/OBJ.spec`

Non-triangle based primitives: Spheres

The ray tracer should support rendering perfect spheres defined by position and radius. Spheres should support the same material settings as other primitives and should also be shown appropriately in the wireframe view.

Area lights and soft shadows

We will attempt to implement soft shadows by some method of simulating area lights (as opposed to the point light simulated in the labs).

1.4 Bonus features

- **Support the `.MTL` format as companion to `.OBJ`**
- **Anti-aliasing**
- **Fast flat-shaded view**
- **Normal mapping**

1.5 Implementation

The features will be implemented in a single executable application using C++ and SDL2.

1.6 Evaluation

The final application could be evaluated by comparing images created with other renderers to images created with our application. There are atleast a few commonly used scenes and objects (the Cornell box, the Stanford bunny) available for such comparisons.

2 Blog

Here is a link to our blog: `https://dybtracer.blogspot.se/`

3 Implementation

This section describes the work that has been done. The section begins with a short summary of the overall result followed by a short overview of the design of the code. We then go through the individual feature goals as defined by the project specification and describe implementation details along with notes on major problems and their solutions. Finally, the section ends with a short discussion on any planned features that where not implemented.

3.1 Summary

All baseline features except area lights were implemented. None of the bonus features mentioned in the specification were implemented. Three bonus features not mentioned in the specification have been implemented (bounding volume hierachies, metallic reflections and Lua scripting).

3.2 Design overview

The overall design is based on the simple pattern of concrete objects being used via a layer of interface abstraction. The most important interfaces and their implementations are listed below, along with one or two central methods of each interface:

Interface	Method(s)	Implementation(s)
`PixelSurface`	`setPixel(x, y, r, g, b)`	`SDLGui`
`GUI`	`createWindow(title, w, h)` `getEvents(vector&)`	`SDLGui`
`Texture`	`getColorAt(coords)`	`SDLTexture`
`Object`	`getIntersection(from,dir,Intersection&)` `getWireframe(vector&)`	`Mesh`, `Sphere`
`Renderer`	`renderScene(scene, w, h, PixelSurface&)`	`WireframeRenderer`, `RayTracingRenderer`

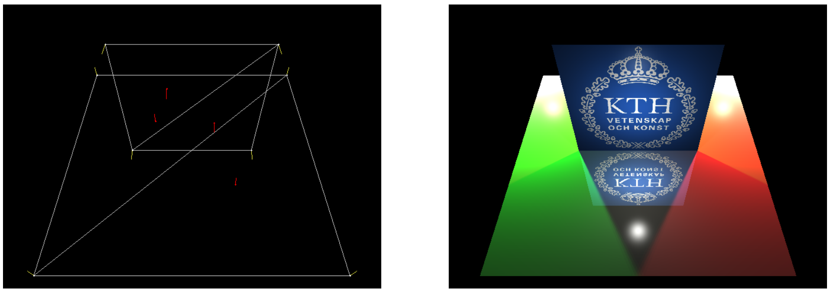
The pattern is then implemented throughout the code by having as much code as possible depend on the interfaces instead of the concrete classes. As an example, neither `WireframeRenderer` nor `RayTracingRenderer` knows anything about the specifics of the existing concrete objects (`Mesh` and `Sphere`) beyond what is exposed by the `Object` interface.

There are however several compromises to the pattern present in the current code. One example being the `SDLGui` class exposing a method `saveBMP` that is not part of the `GUI` interface, which means the client code using this method is tightly coupled to the `SDLGui` class. There are also several classes/structures that currently do not use an interface abstraction at all, such as `Intersection`, `Material` and `Light`.

3.3 Implemented baseline features

3.3.1 Switchable renderers

Switchable renderers were implemented by making use of the `Renderer` interface abstraction. The main application uses three pointers to instances of `Renderer`, two of which are initiated by constructing one `WireframeRenderer` and one `RayTracingRenderer`. The third pointer is the ”active” renderer, and is always set to equal one of the other pointers. Keyboard buttons are used to toggle the active renderer between the two possible values, where one button (R) is used to simply switch between renderers, and another button (T) is used to raytrace a single frame by switching specifically to the raytracing renderer and setting a flag to disable rendering until T is pressed a second time. While rendering is disabled the GUI will draw the last rendered frame repeatedly.



(a) Wireframe mode (b) Raytracing mode

Figure 1: Switchable renderer

3.3.2 Multithreading

Multithreading was surprisingly straightforward to implement despite never having done multithreading in C/C++ before. Multithreading is only implemented for the raytracer and consists the `renderScene` method setting up a number of threads that each run the private `renderingThread` method. Each thread has access to a pthread `thread_data` structure in which we store the screen space bounds (x_{from}, x_{to}, y_{from}, y_{to}) for the thread in question. The screen space is partitioned by setting different screen space bounds for each thread. There is also a progress counter implemented using a counter protected by a mutex. The progress counter simply reports the number of horizontal lines that have been completed.

At the moment, the screen is partitioned in full-width horizontal parts. This is not ideal since it often leads to large differences in workloads for different threads. As an example, picture rendering a complex model of a car sitting on a simple floor or in a void. The camera will probably be positioned so as to place the car more or less centered in frame with some room above and below it so the resulting image does not become cramped. This means that the first and last threads in particular will have a very small workload compared to threads that handle the areas closer to the center of the screen space, simply because most rays in the first and last threads will not intersect with the car model at all. The result of having unbalanced workloads is that some threads will exit early while others are still processing, often ending in a situation where the CPU becomes under-utilized because there are not enough active threads, making the rendering take longer to complete. With the progress counter enabled, the effect can be seen as progress slows down towards the end of the rendering.

The performance increase can be seen in a demo video we created for the blog:

`https://www.youtube.com/watch?v=u2EZAErKC1c`

The machine used in the demo has two physical cores and four logical cores, and as shown in the video the performance scales close to linearly going from one to two threads while not giving any substantial gains when the thread count is further increased.

3.3.3 Backface culling

We implemented the simplest possible form of backface culling in `Mesh::cullInvisibleParts`. The method takes the current position of the camera and sets a ”hidden” flag on every triangle for which the angle between the surface normal of the triangle and a vector from the the first vertex of the triangle to the camera position is larger than 90 degrees.

We had an issue with backface culling which in retrospect appears completely obvious. Backface culling was implemented before Phong interpolation. At that point, all vertex normals of all triangles were set to the triangle surface normal as computed by cross product on two edges of the triangle. After implementing Phong interpolation and using real, individual vertex normals on triangles the backface culling started behaving incorrectly, culling triangles that should not be culled. This is of course due to vertex normals rarely aligning with the surface normal as was expected by the backface culling code. The solution was to add storage of the computed cross product surface normal in each triangle and have the backface culling code use it.

Unfortunately, backface culling does not play nice with reflections without changing which faces are currently culled for each reflected ray. The fact that we render using several parallel threads means that fixing this is not entirely trivial, and so backface culling has been disabled in the code.

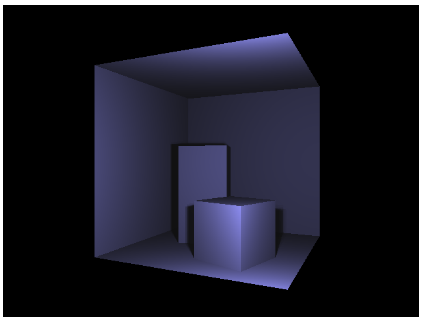


Figure 2: Culled wall in Cornell box

3.3.4 Loading .OBJ files

Mikael had written an `.OBJ` parser/loader while experimenting with lab 3 where it simply dumped triangles into a provided `vector<Triangle>` reference. Changing this code to instead generate a `Mesh` object was trivial. After Phong interpolation had been implemented the `.OBJ` parser was extended with the ability to read vertex normal entries as it had previously only cared about vertex and face entries.

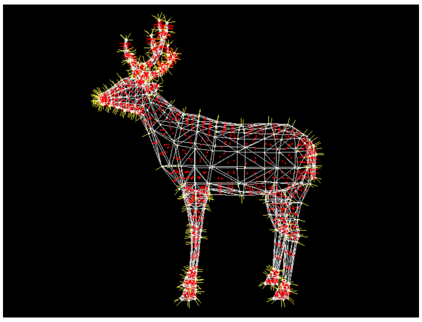


Figure 3: Geometry and normals loaded from an .OBJ file

3.3.5 Loading .STL files

We decided only to implement the binary version of the `.STL` format since the plain text version is an older version which takes up more space and is rarely used. Luckily there was pretty detailed information on how binary `.STL` files are represented on Wikipedia[3].

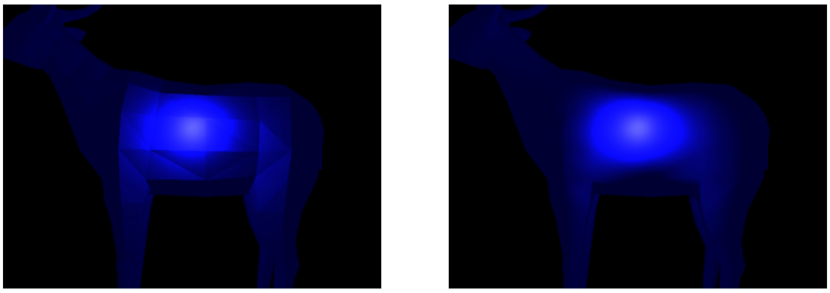
3.3.6 Phong interpolation

Phong interpolation was implemented in the `Mesh` class by computing barycentric coordinates for a point of intersection and using these as weighting for combining the three vertex normals. The code for barycentric coordinate computation was found on StackEx-

[3] `https://en.wikipedia.org/wiki/STL_(file_format)#Binary_STL`

change[4] where the post in question references the book Real-Time Collision Detection by Christer Ericson.

The research and addition of barycentric coordinate computation had actually been done for reasons of texture mapping, and so it was a happy discovery to be able to do the interpolation of normals without needing any new maths.



(a) No interpolation (b) Phong interpolation

Figure 4: Phong interpolation

3.3.7 Phong reflection model

The Phong reflection model was implemented using the exact formula as presented on Wikipedia[5]. Since the formula accounts for multiple light sources, this turned out to be an opportune time to implement support for multiple lights in the `Scene` class. Furthermore, the "Phong parameters" (k_s, k_d, k_a and α for specular, diffuse, ambient colors and shininess, respectively) were added to the `Material` structure at this time.

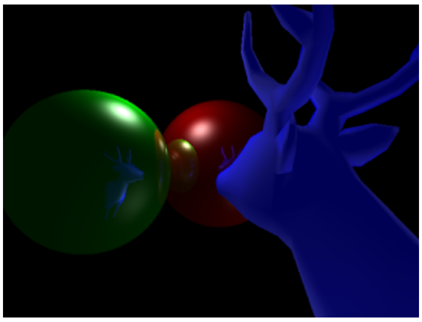


Figure 5: Phong reflection model with two lights

3.3.8 Materials

3.3.9 Texture mapping

Texture mapping was implemented by introducing three new properties for ambient texture, diffuse texture and specular texture to the `Material` structure, each holding a pointer

[4] https://gamedev.stackexchange.com/a/23745

[5] https://en.wikipedia.org/wiki/Phong_reflection_model#Description

to an instance of the `Texture` interface which exposes the method `getColorAt(vec2 texturecoords)`. Texture coordinates are computed as part of intersection testing in the object classes (`Mesh` and `Sphere`). For triangle meshes, texture coordinates of individual triangles are computed by combining the texture coordinate vectors of the vertexes weighted by the barycentric coordinates of the point of intersection. It is currently only possible to apply texture mapping to a mesh where the texture coordinates for each vertex have been set in advance. For spheres, texture coordinates are computed using a formula found on Wikipedia[6].

We had actually not considered the implications of using the Phong reflection model before starting our implementation of texture mapping. There was initially some confusion as to which color component(s) (ambient, specular and diffuse) should be replaced when a texture was present. The decision to have a separate texture slot for each color component came pretty quickly, and we also decided to let the base color components act as weights on the texture colors instead of just having texture colors replace the base colors.

In the current version of the raytracer we begin by taking copies of the base colors of the material before checking if the material has any textures set. We then check each texture pointer in turn, and for any that are set we multiply our copied color component by the color we get from the texture. This introduces a couple of extra branches to the raytracing code which is not a good thing from a performance perspective. A possible improvement to this will be discussed later in this document.

Figure 6: Texture mapping on a sphere

3.3.10 Opacity

Opacity was initially implemented by equipping the `Material` structure with a single `float` property for specifying opacity in the range of $[0, 1]$. The effect was then simulated in the raytracer. When a semitransparent material is hit, a new ray is cast from the point of intersection of the original ray in the same direction as the original ray, collecting the color from behind the semitransparent material and then mixing the two colors (the ”color yonder” and the color of the material itself) according to the opacity value.

[6] `https://en.wikipedia.org/wiki/UV_mapping#Finding_UV_on_a_sphere`

Later in the project timeline we decided to change the opacity property (as well as the reflection property, see below) to be per-component instead, going against the specification slightly. The opacity property was therefore changed from a `float` to a `vec3`, giving more flexibility to the material system.

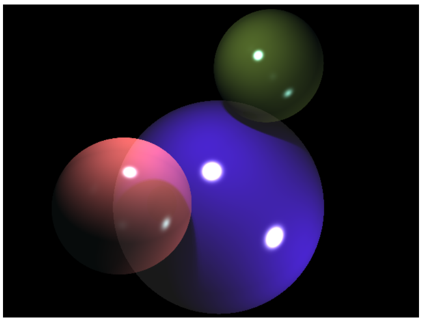


Figure 7: Opacity

3.3.11 Specular reflection

Mirror-like specular reflections were implemented in much the same way as opacity. The `Material` structure was equipped with a float property for specifying reflectivity in the range of $[0, 1]$ and the effect was added to the raytracer. Just like for opacity, when a reflective material is hit, a new ray is cast from the point of intersection of the original ray, but this time the new ray is given a new direction according to the law of reflection. The code for vector calculation of the new direction is heavily inspired by an article[7] found on the website 3dkingdoms.com.

As noted in the specification there is an obvious risk of infinite loops here. To avoid this problem, we introduced a `rayGeneration` counter parameter to the raycasting function along with an immediate function return when this value grows too large. Each recursive raycasting call simply adds one to the current generation value.

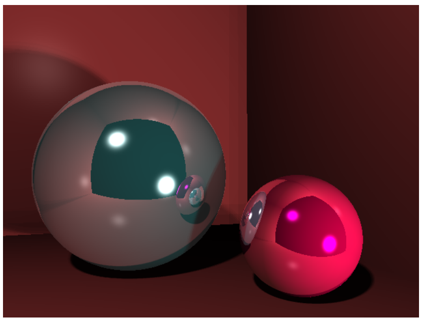


Figure 8: A couple of reflective spheres in a box

[7] `http://www.3dkingdoms.com/weekly/weekly.php?a=2`

3.3.12 Refraction

Refraction was implemented by introducing a new property for the `Material` structure called `refraction`. Standard refraction is used if no refraction has been set for the material and the standard refraction is set to 1 which is the refractive index for vacuum. Using Snell's law we cast a new refracted ray in the refracted direction coming out of the transparent material.

The refraction is represented as a `float` containing the refractive index of the material. Since refraction isn't something we see and think about every day it's kind of hard to evaluate if the refraction is realistic or not.

3.3.13 Spheres

Ray-sphere intersection testing was implemented using the "analytic solution" as presented by Scratch-a-Pixel[8] which consists of constructing and solving a quadratic equation. Spherical texture coordinates are covered in section 2.3.9 on texture mapping.

The original plan for rendering spheres in wireframe view involved drawing curved lines, but due to time constraints we opted for the simpler method of rough approximation by a set of points interconnected by straight lines. The code still contains the framework support for the original idea. The wireframe renderer collects a list of `WireframeElement` objects, each containing a set of points along with normals for each of the points and an indicator for which kind of "connector" function is to be used for drawing the connecting lines. At this time the only available connector is `Linear` which as the name implies performs linear interpolation between points and thus draws straight lines.

3.3.14 Soft shadows

A very basic variant of soft shadows was implemented by casting additional, slightly perturbed rays when doing the intersection test for shadows. Each of these N rays then contribute $1/N$ to a "shadow factor" value that is later multiplied with the lighting as computed by the Phong model. The effect is definitely an improvement on single-ray hard shadows, but is clearly not a particularly good solution as there is often visible color stepping in the penumbra even at expensive (in terms of rendering time) ray counts.

Sadly we did not manage to spend nearly as much time on soft shadows as we had planned. Area lights were sadly not implemented at all, and so the soft shadows really are just a trick, not taking the geometry of the light source into account at all.

[8] `https://www.scratchapixel.com/lessons/3d-basic-rendering/minimal-ray-tracer-rendering-simple-shapes/ray-sphere-intersection`

3.4 Implemented bonus features

None of the bonus features mentioned in the specification were implemented, but three previously unmentioned features did make it into the project. These features are described below along with some justification on why they were implemented.

3.4.1 Bounding volume hierarchy optimization for ray-mesh intersection

The `Mesh` class has been equipped with the ability to calculate a bounding box for its entire set of triangles and then recursively subdivide this box into a hierarchy of smaller and smaller bounding boxes, each box containing a list of pointers to the triangles that intersect it along with pointers to its two sub-boxes. The triangle-box intersection code[9] was published by Tomas Akenine-Möller on his website where he has also published a paper[10] on his algorithm, which is based on the separating axis theorem[11]. The subdivision of a particular box is canceled if the depth of recursion exceeds a set limit (5 in current version) or if the box does not contain enough triangles (minimum of 25 in current version). Empty boxes are deleted and their pointer in their parent box is set to nullptr.

This structure of boxes is then used to reduce the number of triangles that need to be tested for intersection by only testing those triangles that are contained in boxes at the deepest level that are intersected by a particular ray. The ray-box intersection code used was published by Tavian Barnes at his blog on tavianator.com[12]. Each box provides the guarantee that any triangle contained within it is also contained in one or both of its sub-boxes, should they exist. As such, when testing for ray intersection, if the current box has any sub-boxes it is safe to delegate intersection testing to them. In many cases, even if the box has two sub-boxes that contain triangles, the current ray will only intersect one of them, which means the triangles that are only contained in the other sub-box will not be tested for intersection.

The increase in performance is substantial. When rendering the following, reasonable (as in an image someone might realistically want to render) image of a car model the render time dropped from 119 seconds to 8.3 seconds (a speedup of about 14.3x)

[9] `http://fileadmin.cs.lth.se/cs/personal/tomas_akenine-moller/code/tribox3.txt`

[10] `http://fileadmin.cs.lth.se/cs/personal/tomas_akenine-moller/code/tribox_tam.pdf`

[11] `https://en.wikipedia.org/wiki/Hyperplane_separation_theorem`

[12] `https://tavianator.com/fast-branchless-raybounding-box-intersections/`

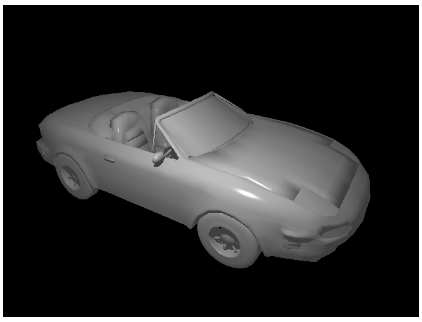


Figure 9: Car model (12819 triangles)

The justification for adding BVH is hopefully easy to see. After having implemented Phong shading and lighting we naturally wanted to see the result on some more complex models, and the poor performance became an issue. In addition, when reading about BVH and ray tracing one gets the impression that it is quite the important part of a good ray tracer. We did not know about this when planning the project and so did not include it in the specification.

3.4.2 Metallic reflection mode

The `Material` structure has been equipped with a property for indicating that reflections should be blended in a ”metallic mode”, which is to say that the reflected image should be heavily tinted by the color of the reflective material. The raytracer was then extended to handle such materials by computing a grayscale conversion (by RGB average) of the reflected color and multiplying it by the diffuse base color of the reflective material. This method has, as far as we know, no real basis in physics, but it works quite well to produce the desired effect. The idea for the metallic reflection mode came after having changed to per-channel reflectivity and having trouble trying to make a metallic material.

There is not much justification for including this feature, except that it was extremely quick to implement.

3.4.3 Lua scripting

Lua scripting support has been added to the main application. Upon pressing the F5 key, the program will try to load and run the file ”script.lua”. Pressing the key a second time will reset the Lua environment and re-run the file. It is also possible to select a new filename for loading with the F5 key by pressing the F key and selecting a new `.LUA` file in the file dialog. The following list describes what can be controlled from the script environment:

- Clearing the scene, removing all lights, objects, materials and textures
- Setting the ambient light power of the scene
- Setting the focal length, position, pitch and yaw of the camera

- Adding and positioning lights, plus setting diffuse and specular powers
- Loading textures
- Adding materials and setting material properties
- Adding spheres defined by position, radius and material
- Building meshes by constructing triangles
- Loading an .OBJ or .STL model, optionally applying a material to it
- Rendering a single frame using the raytracer
- Saving a screenshot

The Lua scripts can be thought of as the native file format for our raytracer, capable of storing a complete scene. Now, Lua being a turing-complete programming language this becomes quite an interesting file format, for example being capable of storing mathematically generated structures by simply writing a Lua program to generate the structure, including parameters for controlling the generator. In addition, the fact that Lua is able to request a single-frame render as well as saving a screenshot means we can render frame-by-frame animations.

The justification for adding Lua scripting is that we grew tired of editing the source code and recompiling just to, for example, increase the power of a light source in a test scene. The script support was added in a single afternoon and makes the program feel much more usable.

3.5 Missing features

This section lists the planned features that did not make it into the project along with short explanations for each missing feature.

3.5.1 Area lights

Due to the time constraints the implementation of area lights was never started. This could have been avoided with better planning, but we could also argue that the BVH feature is sophisticated and important enough to be a reasonable replacement.

3.5.2 Missing bonus features

None of the bonus features mentioned in the specification were implemented. The reason for this is likely to be that we treated them as not being required, while the bonus features that ended up being implemented were either out of necessity or just a quick addition.

4 Evaluation

Unfortunately we ran out of time while trying to create the planned comparison images. Alot of time was wasted trying to get hold of a Stanford bunny with precomputed vertex normals. We should obviously have started working on the comparison images much earlier.

5 Discussion/Reflection

5.1 What did we learn?

Mikael:

Besides what was learned from the labs and learning an awful lot of C++ during the project, I've learned about how simple it is (mathematically) to generate really incredible images using raytracing. More specifically, things that were new to me were ray-sphere intersections, barycentric coordinates and their applications for texture mapping (I did texture mapping as an experiment for lab 3 without barycentric coordinates, instead using the screen-space interpolation of vertex properties) and Phong interpolation. Also new were the full details of the combination of Phong interpolation and Phong illumination, and I've learned while researching that these days people are using less of Phong and more of a topic called BRDF, and that raytracing in general is moving (or has moved already) to more rigorously physically-based models and path tracing. I've also learned that raytracing without some form of search-space reduction is painfully slow, even on modern machines, and I've come up with a simple algorithm (surely a reinvention) for computing a BVH. Also new was the separating axis theorem and its use for triangle-box intersection, spherical texture coordinates, the .OBJ and .STL formats, and multithreading in C/C++ using pthreads.

Robin:

I've learned that I actually can code. No really, I've always thought that I needed help to do any coding at all but I see now that I can do it on my own. I've learned that raytracing is very straight forward, and I guess it should be since it's a digital interpretation of what happens in real life. I've also learned alot about reflection, refraction, alpha blending, stl format and BVH. Even though we didn't have time to implement normal mapping I've read up quite a bit about it and learned a lot about that too. If raytracing was faster, we'd have alot better looking computer games. This project has left me crawing more improvements for raytracing and I'll probably tinker a whole lot on this project over the summer.

5.2 Ideas for improvements

5.2.1 Reducing branching in raycasting function

Support for texture mapping added three new branches in the performance-critical raycasting function. An improvement could potentially be made by always performing the multiplication of base and texture colors and having materials be initialized with mock texture objects that simply return $(1, 1, 1)$ on calls to `getColorAt()`.

5.2.2 Proper handling of pixel formats in SDLTexture

`SDLTexture` currently assumes that the image data (loaded by `SDL_image`) is in the `RGBA8888` format. For many formats and files this is not the case, and scenes using such files for textures will not render correctly.

5.2.3 Access to methods for dealing with problematic normals when loading models in Lua scripts

Lua scripts are currently not able to specify a `VertexOrder` when loading models and is also not able call any of the various methods that are available for dealing with problematic model files such as `Mesh::flipY` and `Mesh::flipNormals`. These features were used quite heavily when testing by editing the source code directly, and it is a shame they were not exposed to lua in time for the deadline.

5.2.4 Object translation, rotation and scaling in Lua scripts

There is currently no support for translating, rotating or scaling an object from the Lua environment. Since scripts can be used to create animations, being able to move and rotate objects would be a useful improvement.

6 References

Please refer to the footnotes for references.

	Area	Mikael	Robin	
	.obj file reader			
	.stl file reader			
	3d camera			
	3d material abstraction			
	3d object abstraction			
	3d object mesh implementation			
	3d object sphere implementation			
	3d raytracing phong illumination			
	3d raytracing phong interpolation			
	3d raytracing renderer			
	3d raytracing renderer multithreading			
	3d raytracing renderer opacity			
	3d raytracing renderer refraction			
	3d raytracing renderer specular reflection			
	3d raytracing texture mapping			
	3d renderer abstraction			
	3d wireframe renderer			
	bounding volume hiearchy optimization			
	build system / environment			
	file dialog abstraction			
	file dialog gtk implementation			
	gui (2d graphics / input) abstraction			
	gui (2d graphics / input) sdl implementation			
	lua scripting support			
	project report			
	project specification			
	submission demo video			
	ui input abstraction			
	ui input implementation			