Contents

Chapter 1

Introduction (draft)

Subsurface scattering (SS) is a physical phenomenon that naturally occurs in a wide range of natural materials. Some of the materials that exhibit a strong SS effect in everyday life are milk, human skin and marble. Subsurface scattering is that phenomenon that occurs when light is partially absorbed by an object, bounces inside (”scatters”) and finally exits the surface on another point of the material (see Figure 1.1). The phenomenon that results is generally known as *translucency*. We can see some examples of translucency in Figure 1.2

Since the beginning of computer graphics, various attempts have been performed in order to physically model subsurface scattering. Some of these models involve Monte Carlo simulations of the light entering the medium [Pharr and Hanrahan, 2000], other focus on approximating the diffusion of light within the material using an analytical approach [Jensen et al., 2001].

The first model that proposed and analytical approach was the one by Jensen et al. [2001], as an approximation of the radiative transfer equation. This approximation has then been exploited by different authors, in order to account for multi-layered materials [Donner and Jensen, 2005], heterogeneous materials [Wang et al., 2010] and thin surfaces[Wang et al., 2010]. A recent analytical approximation, proposed by Frisvad et al. [2013], extends the approximation in order to account for the directionality of the incoming light.

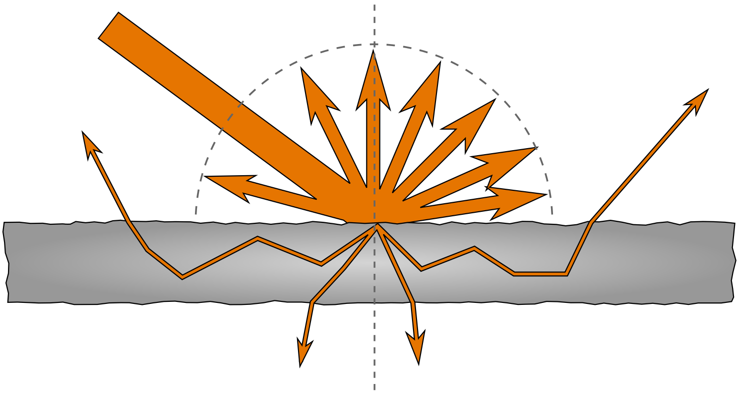


Figure 1.1: Diagram of subsurface scattering. Most of the incoming light gets reflected, but some of it enters the material and leaves it at a different point.

In recent years, with the advent of programmable graphics cards (GPU), it has become possible to exploit these algorithms and bring them to interactive frame rates, and in some cases even to real time rendering. Jensen and Buhler [2002] were the first to propose an efficient implementation (though not real time and on CPU) for rendering subsurface scattering using an octree. More recently, several methods have been proposed, including image-based splats, sum-of-Gaussians filtering, and grid-propagation based methods.

In this thesis we want to employ some cutting edge GPU techniques, with the aid of the programmable pipeline, to implement Frisvad et al. directional model in a real-time fashion. This method should achieve real time results (i.e. in the range of 30 to 60 frames per second) for a wide range of natural materials.

Figure 1.2: Some examples of translucent materials: milk, leaves and a candle. Images courtesy of Wikimedia Commons.

Chapter 2

Related Work

In rendering of subsurface scattering, all approaches rely on approximating correctly the *Radiative Transport Equation* (RTE). We identified two main approaches to the problem in literature:

Analytical One class of solutions consists of approximating the RTE or one of its approximations via an analytical model. These model can have different level of complexity and computation times, and are often adaptable to a wide range of materials. However, often they rely on assumptions on the scattering parameters that limit their applicability.

Numerical In this other class of solutions, a numerical solution for the RTE is actually computed. While providing an exact solution, the computation times are longer. When interactivity is needed, generally some heavy pre computation must be used.

2.1 Analytical techniques

In the analytical techniques, two different areas of research must be distinguished. The first area is the research on the actual models, while the second is research on how the actual models can be implemented efficiently. Each model is usually represented by a specific function called BSSRDF (*Bidirectional Subsurface Scattering Reflectance Distribution Function*), that describes how light propagates between two points on the surface. This function in the general case must be calculated between all the couple of points on the surface and then integrated over each point. Implementation techniques focus on efficiently implementing this integration step, often making assumptions for which points the computation can be avoided.

2.1.1 Models

Regarding the models, the first and most important is the dipole developed by Jensen et al. [2001]. The models relies on an approximation of the RTE called the *diffusion approximation*, that relies on the assumption on highly scattering materials. In this case, a BSSRDF for a planar surface in a semi-infinite medium can be obtained. The BSSRDF needs only the distance between two points to be calculated, and with some precautions can be also extended to arbitrary geometry. This model does not include any single scattering term, that needs to be evaluated separately. The model was then further extended in order to account for multi-layered materials[Donner and Jensen, 2005].

A significant improvement on the model was later given by D'Eon [2012], that improved the model to better fit path traced simulations without any extra computation cost. A more advanced model based on quantization was proposed by D'Eon and Irving [2011], that introduced a new physical foundation in order to improve the accuracy of the original diffusion approximation. Finally, some higher order approximation exist [Frisvad et al., 2013], in order to account for the directionality of the incoming light and single scattering. This allows a more faithful representation of the model at the price of extended computation times.

Finally, for real-time critical applications (such as games), translucency is often estimated as a function of the thickness of the material, that is used to modify a lambertian term [Tomaszewska and Stefanowski, 2012]. While not physically accurate, this technique allows to have a fast translucency effect that can be easily added to existing deferred pipelines.

2.1.2 Implementations

Most research on efficient implementations of a subsurface scattering analytical model has been made on the original model by Jensen et al. [2001]. The first efficient implementation was proposed by Jensen and Buhler [2002], based on a two-pass hierarchical integration approach. Samples on the model are organized in an octree data structure, that then is used to render the object. In the first step, the radiance from the light is stored in the points. In the second pass, using the octree, the contribution from neighboring points is computed, clustering far points in order to speed up calculations. In the original paper, the single scattering term is approximated with as a simple BRDF approximation.

Lensch et al. [2002] approached the problem by subdividing the subsurface scattering contribution into two: a direct illumination part and a global illumination part (i.e. the light shining through the object). The global illumination part is pre-computed as vertex-to-vertex throughput and then summed to the direct illumination term in real-time. Translucent shadow maps [Dachsbacher and Stamminger, 2003] use an approach similar to standard shadow maps: they render the scene from the light point of view, and then calculate the dipole contribution in one point only from a selected set of points, according to a specified sampling pattern. As in Lensch et al. [2002], the contribution is split into global and local to permit faster computations. Mertens et al. [2003b] propose a fast technique based on radiosity hierarchical integration techniques, that unlike the previous implementation can handle deformable geometry.

Another important category of methods is screen space methods. Mertens et al. [2003a] propose an image space GPU technique that pre-computes a set of sample points for the area integration and then performs the integral over multiple GPU passes. d'Eon et al. [2007] proposes a method in image-space, interpreting subsurface scattering as a sum of images to which a gaussian filter has been applied. The gaussians are then summed with weights that make them fit the diffusion approximation. Jimenez et al. [2009] improves further the technique, giving more precise results in case of skin. Shah et al. [2009] present a fast technique that render the object as a series of splats, using GPU blending to sum over the various contributions.

Regarding more advanced models, the better and the quantized dipole can be applied to any of the previous implementations, since they do not require additional information that the standard dipole. On the other hand, the directional dipole requires the direction of the incoming light as part of its calculations, so it is generally not applicable to the mentioned implementations.

2.2 Numerical techniques

Numerical techniques for subsurface scattering are often not specific, but come for free or as an extension of a global illumination numerical approximation, since the governing equations are essentially the same. Given their generality, they are usually slower that their analytical counterpart, and often rely on heavy pre-computation steps in order to achieve interactive framerates. Jensen's Photon Mapping[Jensen and Christensen, 1998] was originally developed to render anisotropic subsurface scattering. Classical approaches as a full Monte-Carlo simulation implementation of the light-material interaction[Dorsey et al., 1999], and finite-difference methods exist in literature[Stam, 1995].

Some less general methods have been introduced in order to devise more efficient approximations when it comes to the specific problem of subsurface scattering. Stam [1995] uses the diffusion approximation with the finite difference method on the object discretized on a 3D grid. Fattal [2009] uses as well a 3D grid, that is swept with a structure called light propagation map, that stores the intermediate results until the simulation is complete.

Wang et al. [2010], instead of performing the simulation on a discretized 3D grid, makes the propagation directly in the mesh, converting it into a connected grid of tetrahedrons called *QuadGraph*. This grid can be optimized to be GPU cache friendly, and provide a real-time rendering of deformable heterogeneous objects. The problem in this method is that the QuadGraph is slow to compute (20 minutes for very complex meshes) and has heavy memory requirements for the GPU.

Precomputed radiance transfer methods is another class of general global illumination methods, that generally pre-compute part of the lighting and store it in tables[Donner et al., 2009], allowing to retrieve it efficiently with an additional memory cost.

A recent method called SSLPV - Subsurface Scattering Light Propagation Volumes [Børlum et al., 2011] extends a technique originally developed by Kaplanyan and Dachsbacher [2010] to propagate light efficiently in a scene using a set of discretized directions on a 3D grid. The method allows real-time execution times and deformable meshes with no added pre-computation step, with the drawback of not being physically accurate.

Chapter 3

Theory

Chapter 4

Implementation

In this chapter, we describe the implementation details of our technique, using the approximation of the rendering equation introduced in the previous chapter. We start by giving a rather generic introduction of our algorithm, introducing then all the implementation details of the implementation. We will also dewscribe which artifacts we identified and how we deal with them.

4.1 Algorithm overview

Our algorithm, in order to be generic, must meet some requirements. Our first requirement is that our algorithm must be as generic as possible, relying on the fact that only the geometry of the object will be provided. This means we cannot rely on a UV mapping on the object, but only on the positions and the normals. Secondly, our algorithm must deal in real time with dynamic lighting and object deformations. So no baking of lighting or geometry form factors is possible. Finally, we wanted to create an algorithm that progressively improves, converging to a finer and finer result while there are no changes in the scene.

By keeping this limitations in mind, we introduce our three pass algorithm.

Step 1 - Light buffer
In the first step, positions and normals of the object are rendered into a texture from the light point of view. In addition, for each light a conversion matrix is computed and stored, in order to convert the position from world space to texture space.

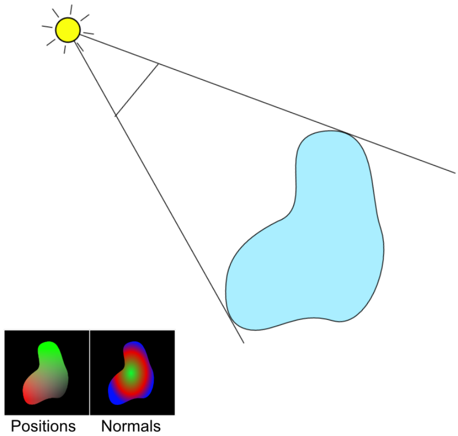


Figure 4.1: Render to G-buffer. The appearance of the G-buffers is shown below.

Step 2 - Render to cubemap
In the second step, we render the object on a cubemap. The center of the cubemap is places on the center of the object bounding box. Since the model we are using is view-independent (apart from a Fresnel term) we can combine the results of the cubemap in a final combination step.

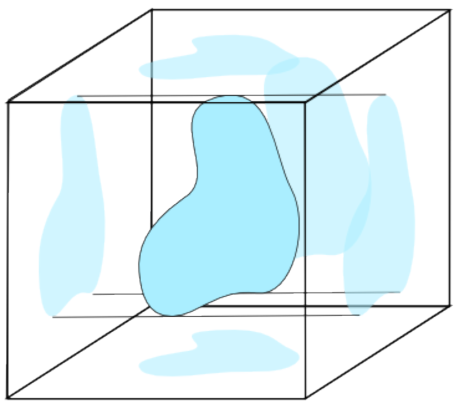


Figure 4.2: Render to cubemap.

When we are rendering a point from the orthographic camera that represents a side of the cubemap, we do as illustrated in Figure 4.3. For each fragment, we calculate the closest point to the light, sampling the texture calculated in the previous step. In Figure 4.3 we have two examples, of when the two points coincide (directly lit) and when the two points does not (light passing through the object).

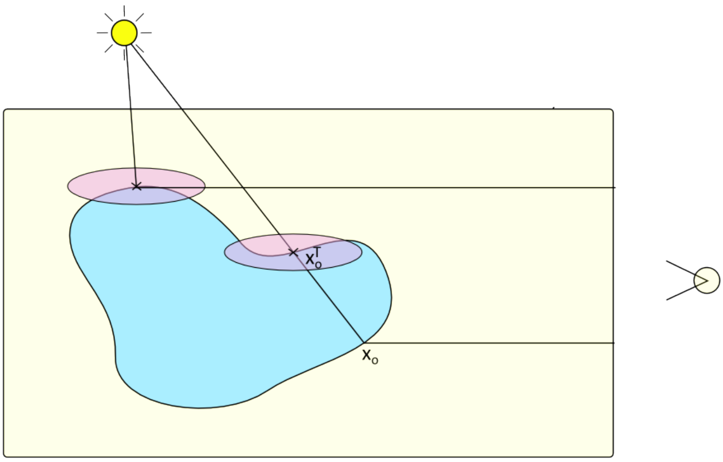


Figure 4.3: Render to cubemap, side view. Note that the fragment $\mathbf{x}_o^T$ is not rendered in this step, but only the point $\mathbf{x}_o$ is.

Then, we place a disk in the texture and accumulate the BSSRDF from the neighboring points, as shown in Figure 4.4. The points are chosen on the disk according to a pre-determined sampling scheme (discussed later). In order to accumulate the points and perform the right area integral, we need to assume that all the points on the disk cover the same area. So, we accumulate the point according to this formula:

$$C^f(\mathbf{x}_o) = \sum_{i=1}^{k} L_i(\mathbf{x}_i, \vec{\omega}_i) S_i(\mathbf{x}_i, \mathbf{x}_o, \vec{\omega}_i, \vec{\omega}_o)\ (\vec{n_i} \cdot \vec{\omega}_i)\ F_t(\vec{n_i}, \vec{\omega}_i)$$

where $\mathbf{x}_o$ is the exiting point C^f is the cubemap on face f, L_i is the incoming radiance, S_i is the BSSRDF, $\mathbf{x}_i$ and $\vec{n_i}$ are the position and the normal sampled from a point of the disc, k is the number of samples, and F_t is the incoming Fresnel term.

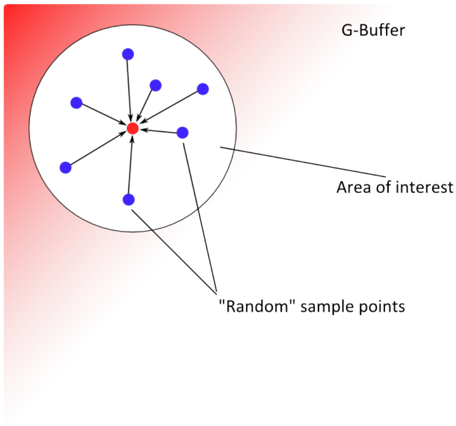


Figure 4.4: Render to cubemap, gbuffer view.

Step 3 - Combination

In this step, for each fragment on the surface we sample all the six cubemap sides as illustrated in Figure 4.5. In order to do this, we need a depth cubemap that inform us if the fragment was visible when we rendered the cubemap face. Then, each point is divided by the number of visible faces to average it. In formulas, to get the final luminance:

$$L(\mathbf{x}) = \frac{\sum_{i=1}^{6} V_i C(\mathbf{x}^i_{proj})}{\sum_{i=1}^{6} V_i}$$

where V_i is a visibility function that is zero if the point is not visible on the face i and 1 if it is visible. $C(\mathbf{x})$ is the sample from the cubamap obtained in the previous step, and $\mathbf{x}^i_{proj}$ is the point $\mathbf{x}$ projected on the i-th cubemap face.

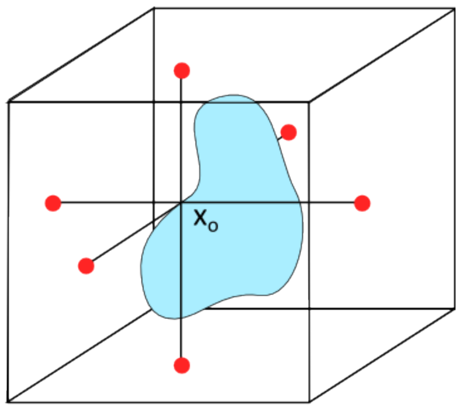


Figure 4.5: Final combination step. Note that the point is generally not visible from all the cubemap faces.

4.2 Implementation details

4.3 Artifacts

A simple implementation of the method described until now is not completely correct. In fact, since we are discretizing the surface on a texture, some sampling artifacts are inevitable. During our implementation we identified three different types of artifacts:

- Incorrect sampling of the G-buffer
- Incorrect sampling of the cubemap
- Shadow bias (when sampling the depth of the texture).

That are described in detail in the following sections.

4.3.1 Incorrect sampling of the G-buffer

In order to sample the G-buffer correctly, we need to modify the world coordinate of the point $\mathbf{x}_o$ with normal $\vec{n}_o$ in order to "shrink" a little bit towards the inside of the object according to the light direction $\vec{\omega}_l$:

$$\mathbf{x}'_o = \mathbf{x}_o - \epsilon_g(\vec{n}_o - \vec{\omega}_l(\vec{\omega}_l \cdot \vec{n}_o))$$

4.3.2 Incorrect sampling of the cubemap

Since we are sampling a cubemap, we do not need to account for the light direction in this case. In addition, the cubemap needs a 3D vector to be sampled with. So, instead of using $\mathbf{x}_o$, we use a point slightly intruded (i.e. displaced along the normal) in the calculations, according to:

$$\mathbf{x}'_o = \mathbf{x}_o - \epsilon_c\vec{n}_o$$

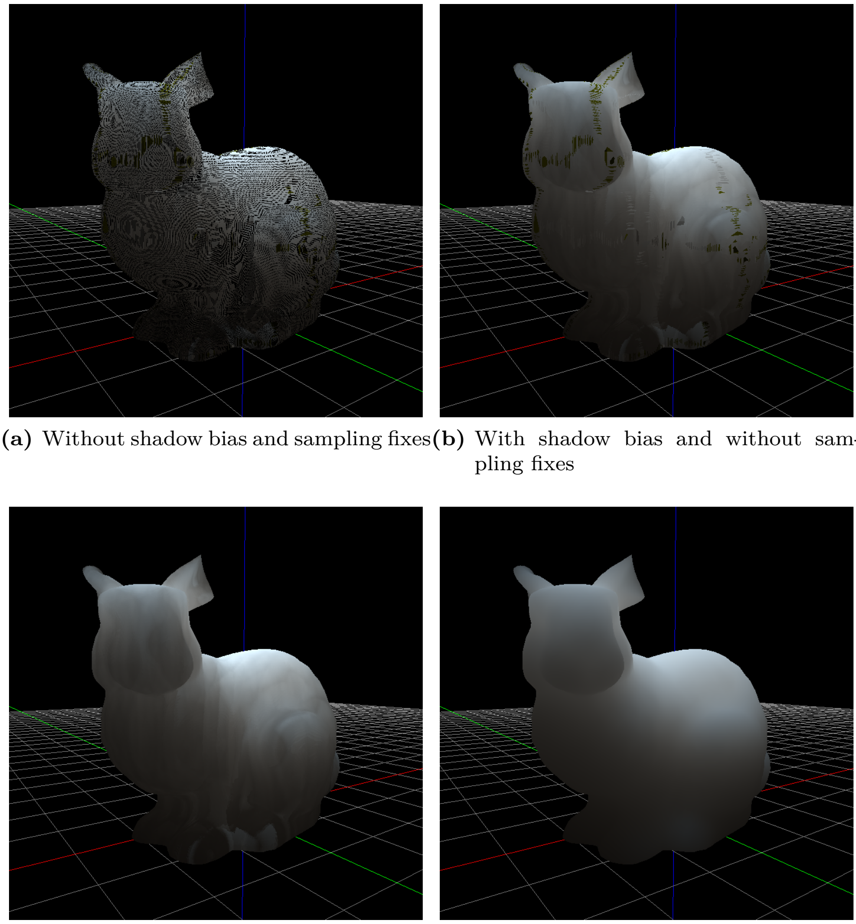
4.3.3 Shadow bias

In order to avoid artifacts such as shadows acne, we use a bias when comparing the z values of a point to determine if the point is in shadow or not. This implies that we need to convert the depth value from texture space ($\mathbf{z}_{tex}$) to world space again ($\mathbf{z}_{world}$). Since we are using an orthographics camera, the z value is the same in clip coordinates and in normalized device coordinates. Then, we simply use the camera projection properties ($\mathbf{z}_{far}$, $\mathbf{z}_{near}$) to convert the depth into the camera local space, in order to finally add the camera position transformed z value ($\mathbf{z}_{camera}$) and reconstruct the depth in world space:

$$\mathbf{z}_{world} = \mathbf{z}_{camera} - \frac{\mathbf{z}_{far} - \mathbf{z}_{near}}{2} \left(2\mathbf{z}_{tex} - 1 + \frac{\mathbf{z}_{far} + \mathbf{z}_{near}}{\mathbf{z}_{far} - \mathbf{z}_{near}} \right)$$

And finally compare the obtained z with the z position in world space of the point ($\mathbf{z}$) using the bias ϵ_b, so a point is lit iff:

$$\mathbf{z}_{world} - \epsilon_b < \mathbf{z}$$



(a) Without shadow bias and sampling fixes **(b)** With shadow bias and without sampling fixes

(c) With both shadow bias and sampling fixes **(d)** Reference

Figure 4.6: Progressively removing artifacts to get to the final image.

Chapter 5

Results

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