Real-time Rendering of Translucent Materials with Directional Subsurface Scattering

Alessandro Dal Corso

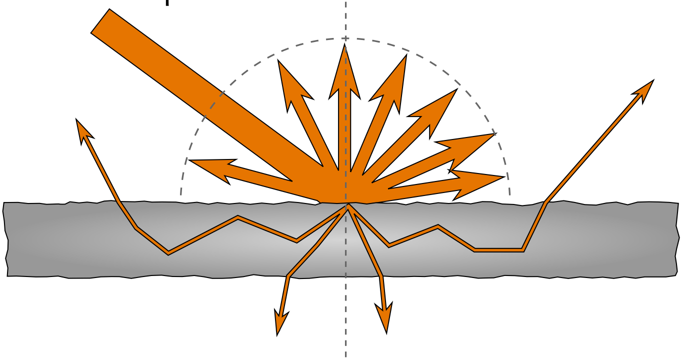
M.Sc. in Digital Media Engineering
T.I.M.E. Double Degree Program

Supervisor: Jeppe Revall Frisvad

22nd August 2014

Introduction

- Subsurface scattering (SS) is a physical phenomenon that occurs in a wide range of materials (marble, skin, fruit)
- Light repeatedly bounces inside the material and then comes out into another point



- We want to model faithfully SS in a synthetic image

Introduction



Problem statement

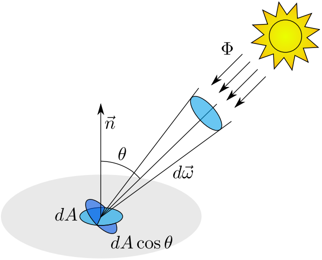
Our goal is to faithfully represent SS phenomena in a synthetically generated image:

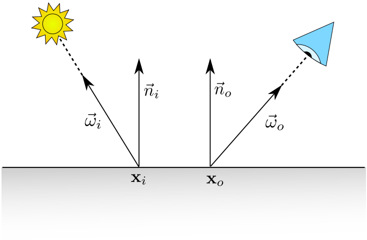
- Using a analytical BSSRDF model [Frisvad et al., 2014]
- Visually close as possible to a offline-rendered solution
- With low memory requirements
- In real-time or at least at interactive frame rates (<100ms per frame) using a GPU-based solution

Light transport

- We define a quantity to describe light carried by a ray, the radiance:

$$\mathsf{L}(\vec{\omega}) = \frac{\mathrm{d}^2\Phi}{\mathrm{d}\omega \mathrm{d}A\cos\theta}$$





- Given two points on a surface, we define the BSSRDF as:

$$\mathsf{S}(\mathbf{x}_\mathrm{i}, \vec{\omega}_\mathrm{i}, \mathbf{x}_\mathrm{o}, \vec{\omega}_\mathrm{o}) = \frac{\mathrm{d}\mathsf{L}_\mathrm{o}(\mathbf{x}_\mathrm{o}, \vec{\omega}_\mathrm{o})}{\mathsf{L}_\mathrm{i}(\mathbf{x}_\mathrm{i}, \vec{\omega}_\mathrm{i})\cos\theta_\mathrm{i}\mathrm{d}\vec{\omega}_\mathrm{i}\mathrm{d}A_\mathrm{i}}$$

That relates the entering flux with the exiting radiance.

The rendering equation

- From the definition of BSSRDF we obtain the area formulation of the rendering equation [Jensen et al., 2001]:

$$L_o(\mathbf{x}_o, \vec{\omega}_o) = L_e(\mathbf{x}_o, \vec{\omega}_o) + \int_A \int_{2\pi} S(\mathbf{x}_i, \vec{\omega}_i, \mathbf{x}_o, \vec{\omega}_o) L_i(\mathbf{x}_i, \vec{\omega}_i)(\vec{n} \cdot \vec{\omega}_i) d\vec{\omega}_i dA_i$$

- Many BSSRDF functions have been proposed in literature [Jensen et al., 2001; D'Eon and Irving, 2011; Frisvad et al., 2014]

Standard dipole

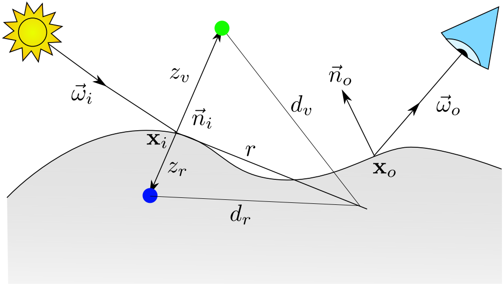
- The standard dipole [Jensen et al., 2001] was one of the first BSSRDF functions proposed
- It uses the diffusion approximation [Ishimaru, 1997] of the radiative transport equation (RTE)
- The approximation describes how light propagates from a point source in an infinite scattering medium:

$$\phi(\mathbf{x}) = \frac{\Phi}{4\pi D} \frac{e^{\sigma_{tr} r}}{r}$$

Where

$$\phi(\mathbf{x}) = \int_{4\pi} L(\mathbf{x}, \vec{\omega}) d\vec{\omega}$$

- For a BSSRDF, we need to put a boundary condition: fluence decreases linearly until a distance $z = 2AD$ from the surface
- We model the interaction as two small light point sources, a virtual and a real source



$$S_d(x_i, \vec{\omega}_i, x_i, \vec{\omega}_o) = \frac{\alpha'}{4\pi^2}\left[\frac{z_r(1+\sigma_{tr}d_r)\, e^{-\sigma_{tr}d_r}}{d_r^3} + \frac{z_v(1+\sigma_{tr}d_v)\, e^{-\sigma_{tr}d_v}}{d_v^3}\right]$$

Directional dipole

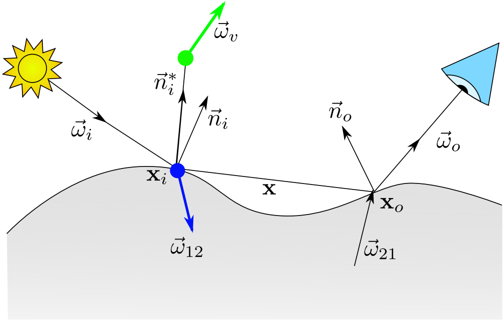
- [Frisvad et al., 2014] defined a new BSSRDF function that keeps the directionality of the incoming light into account
- The models uses a more precise diffusion approximation, that yields the following fluence formula:

$$\phi(\mathbf{x}, \theta) = \frac{\Phi}{4\pi \mathsf{D}} \frac{\mathsf{e}^{\sigma_{\mathrm{tr}} \mathsf{r}}}{\mathsf{r}} \left(1 + 3\mathsf{D} \frac{1 + \sigma_{\mathrm{tr}} \mathsf{r}}{\mathsf{r}} \cos\theta\right)$$

  Where we have an extra term that accounts for directionality
- As in the previous model, a dipole is used, but with ray sources

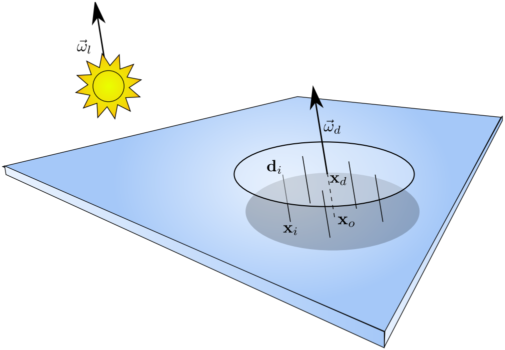
Directional dipole

- Some extra corrections are needed in order to get a good boundary condition
  (modified tangent plane, distance to the real source)



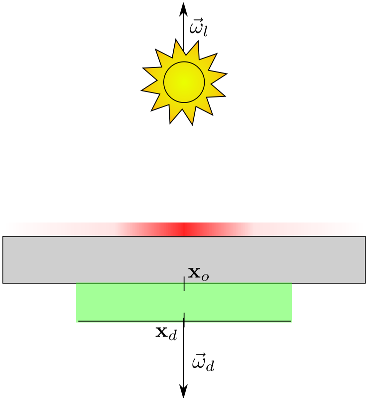
$$S_d(x_i, \vec{\omega}_i, x_o) = S'_d(x_o - x_i, \vec{\omega}_{12}, d_r) - S'_d(x_o - x_v, \vec{\omega}_v, d_v)$$

- Scattering effects have a limited range, that depends on the scattering properties of the material (especially on $1/\sigma_{\mathrm{tr}}$)
- We can then consider contributions from a disk on the surface
- The disk has a center point $\mathbf{x}_{\mathrm{d}}$ and a direction $\vec{\omega}_{\mathrm{d}}$

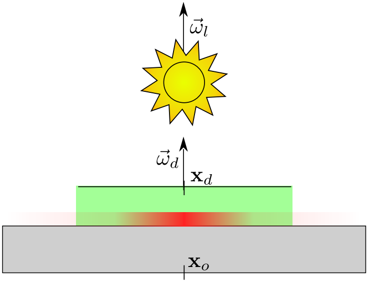


Method

- We place the disk oriented towards the light ($\vec{\omega}_{\mathrm{d}} = \vec{\omega}_{\mathrm{l}}$) and close enough to the light in order to cover the surface



Naïve disk placement

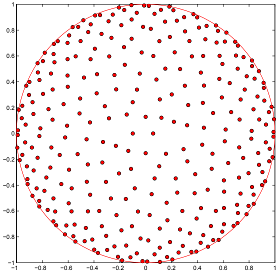


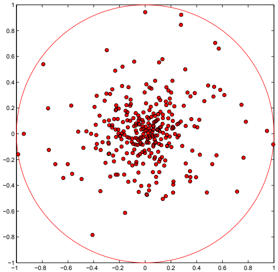
Our disk placement

Method

- Given these assumptions on the disk, we discretize the rendering equation
- We distribute the samples on the disk exponentially with distribution $\text{pdf}(x) = \sigma_{tr}\, e^{-\sigma_{tr} x}$

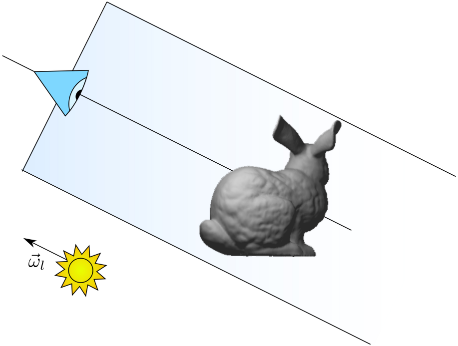
$$L_o(\mathbf{x}_o, \vec{\omega}_o) = L_d \frac{A_c}{N} \sum_{i=1}^{N} S(\mathbf{x}_i, \vec{\omega}_l, \mathbf{x}_o, \vec{\omega}_o) e^{\sigma_{tr} r_i}$$





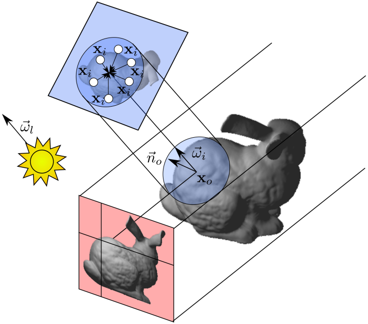
Implementation (step 1)

- We render the scene from the light point of view (as in shadow mapping)
- We store positions and normals in a texture, the light map
- We get the closest points to light



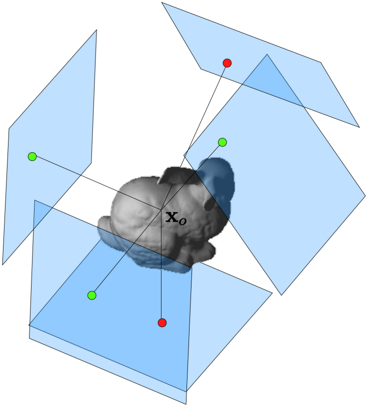
Implementation (step 2)

- We render the object from a certain number of directions in the radiance map
- The directions can be chosen randomly or placed by the artist
- For each pixel we sample the points from the light map and sum up the BSSRDF contribution



Implementation (step 3)

- We finally sample the radiance map to get the single contribution for a point on the surface
- The result is averaged over the directions from which the surface point is visible



Implementation

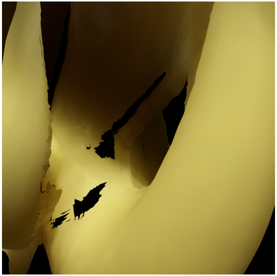
Figure: Stanford Bunny, potato material. Note the self shadowing automatically generated by the algorithm.

Advantages

- Accounts for self shadowing and self occlusion
- Accounts for occlusion between different objects
- Directly coupled with an existing shadow mapping pipeline
- Low memory requirements compared to a full voxelization
- The final step can be adapted to forward and deferred shading pipelines

Disadvantages

- Noisy result, that need to be either accumulated or blurred in order to achieve a smooth result
- Cameras that cover the surface need to be placed manually (to avoid tearing)
- Inherited problems from shadow mapping (constant shadow bias)



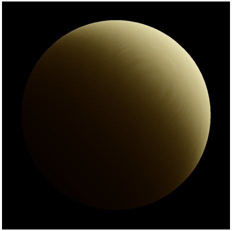
Extensions

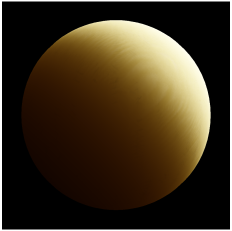
- `Multiple lights`
  We sum the contribution of multiple lights in the shader
- `Point lights`
  We scale the incoming intensity by a inverse square distance term

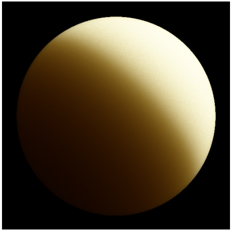
Environment lighting

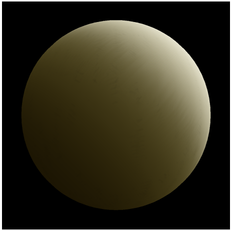
- We simulate it using 16 directional lights
- We choose "random" points on a light map
- The distribution chosen accounts to make the points fall in areas with high radiance

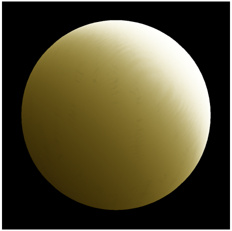
Results (quality)


(a) $N = 100$


(b) $N = 1000$


(c) Reference


(d) $N = 100$


(e) $N = 1000$

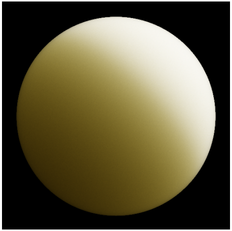

(f) Reference

Figure: Comparison on spheres of potato and white grapefruit juice.

Results (quality)

(a) $N = 50$ (ca. 90 milliseconds)

(b) Reference (6 hours, 16 millions samples)

Figure: Result comparison for the Stanford Dragon model. Parameters for ketchup.

Results (quality)

(a) $N = 100$

(b) Reference (30 minutes, 10^6 samples)

Figure: Result comparison for the Happy Buddha model. Parameters for potato.

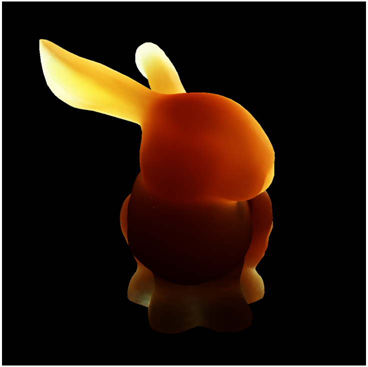
Results (quality)

(a) $N = 90$

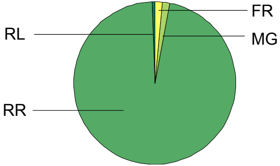
(b) Reference [Frisvad et al., 2014]

Figure: Result comparison for the Happy Buddha model (environment lighting, Uffizi map). Parameters for potato.

Results (performance)



(a)Beer Bunny, 67.7ms. Point light. $N = 180$, $M = 210$, $q = 2$



RL	RR	MG	FR	Tot
0.20	66.18	0.8	0.44	67.72

(b)Detailed timings.

Figure: Graph that illustrates how the timings are split into the different phases of the algorithm. All tests use $W_l = W_s = 512$.

Results (performance)

Model	#Δ	Number of samples (N)			
		1	10	50	100
Bunny	10^4	2.1	5.3	19.8	38.2
Dragon	10^5	12.5	35.2	140.6	275.3
Buddha	10^6	96.7	97.7	128.0	216.0

Table: Timings in milliseconds of our method for different models and number of samples N (potato material properties). One directional light, 16 directions for rendering and reconstructing.

Results (performance)

Model	#Δ	Size of the radiance map (W_s)		
		256	512	1024
Bunny	10^4	11.4	20.0	39.0
Dragon	10^5	75.4	142.1	299.4
Buddha	10^6	98.2	127.0	258.2

Table: Timings in milliseconds of our method for different models and size of the radiance map W_s (ketchup material properties). The other parameters were $N = 50$, $L = 1$, $W_l = 512$, $M = 1000$, $K = 16$.

Results (performance)

Model	#Δ	Number of directions (K)			
		4	8	16	32
Bunny	10^4	6.6	10.0	20.1	42.1
Dragon	10^5	36.7	70.1	143.0	306.2
Buddha	10^6	32.5	55.8	128.3	363.5

Table: Timings in milliseconds of our method for different models and different number of directions K (ketchup material properties). The other parameters were $N = 50$, $L = 1$, $W_s = W_l = 512$, $M = 1000$.

Conclusions

- We implemented a solution for fast rendering of translucent materials using a state of the art directional BSSRDF
- We obtained results comparable to offline rendered solutions
- We obtained an improvement of five orders of magnitude over offline rendered solutions
- We obtained a flexible method that is applicable to current real-time graphics engines

Thank you!

References

Eugene D'Eon and Geoffrey Irving. A quantized-diffusion model for rendering translucent materials. In ACM SIGGRAPH 2011 Papers, SIGGRAPH '11, pages 56:1--56:14, New York, NY, USA, 2011. ACM.

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