Physically Correct Refractive Effects

Matthew Turnbull

Abstract

This paper focuses on physically correct refraction effects in optically dense materials. This is accomplished by taking various material properties into account.

1. Introduction

Refraction happens when light passes from one medium of a certain optical density (i.e. air) to another medium of a different optical density (i.e. glass). The change in optical density causes the light to change speed, and thus bend at the boundary.

Basic refractive effects can be achieved via an extension of ray tracing. However, the naive approach of simply tracing the primary refracted ray leaves much to be desired. In order for a more realistic refractive model to be achieved, properties such as reflectance, transmittance, and absorption.

2 Basic Refraction

Basic refraction is achieved according to *Snell's Law.* This law is simply as follows:

$$\frac{\sin\theta_i}{\sin\theta_t} = \frac{v_1}{v_2} = \frac{n_2}{n_1}$$

θ_i and θ_t are the angles of the incident and transmitted vectors (respectively) to the normal. n_1 and n_2 are the measures of the optical density of the incoming and outgoing mediums (respectively).It is simple to calculate the transmitted vector:

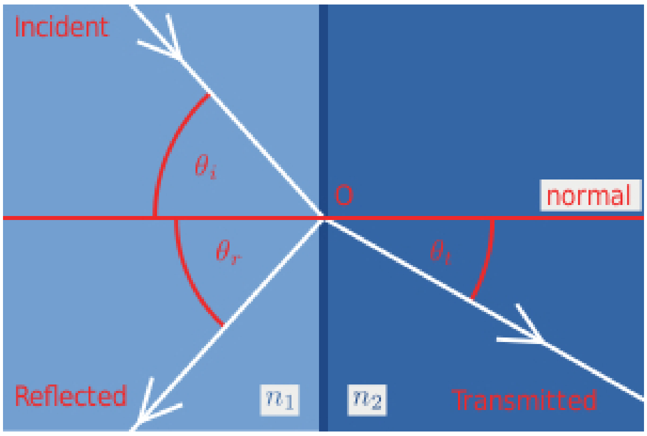
n = n_1 / n_2
cosThetaI = (incoming · normal) * -1
sinThetaI = sqrt(1 – cosThetaI^2)
sinThetaT = n * sinThetaI
cosThetaT = sqrt(1 – sinThetaT^2)
outgoing = (incoming * n) + ((n * cosThetaI – cosThetaT) * normal)
normalize outgoing

It is important to note that when moving to a medium with a lower optical density ($n_1 < n_2$), a phenomenon called Total Internal Reflection. This means that all of the light will be reflected.

If Total Internal Reflection happened, then sinThetaT will be >= 1 (which is parallel to the surface - or undefined).

3.1 Fresnel equations

The Fresnel equations describes how light travels across the barrier between the two refractive materials. Depending on the change in optical density, a portion of the light is transmitted and a portion is reflected.



3.2 Reflectance

Reflectance is the measure of how much energy is reflected from the material interface. This property is dependent on the polarization of the incident ray.

These equations describe the reflectance of s- and p- polarized light.

$$R_s = \left(\frac{n_1\cos\theta_i - n_2\cos\theta_t}{n_1\cos\theta_i + n_2\cos\theta_t}\right)^2$$

$$R_p = \left(\frac{n_1\cos\theta_t - n_2\cos\theta_i}{n_1\cos\theta_t + n_2\cos\theta_i}\right)^2$$

If the indecent light is not polarized (equal amounts of s- and -p polarizations), then the reflection coefficient is simply the average $R = (R_s + R_p)/2$.

This is an ideal place to check for Total Internal Reflection. If Total Internal Reflection happens, then reflectance is 1.

3.3 Transmittance

Just as reflectance is the measure of reflected light, transmittance is the measure of transmitted light.

Transmittance for polarized light is given by $T_s = 1 - R_s$ and $T_p = 1 - R_p$. Unpolarized light is simply $T = 1 - R$.

3.4 Absorption

When light passes through an optically dense medium, a portion of its energy is absorbed. The Beer–Lambert–Bouguer (Beer's) law relates transparency of a material to it's properties.

$$T_{abs} = 10^{-\alpha \ell}$$

T_{abs} is the transparency of the object, α is the absorbency coefficient, and ℓ is the length of ray traced through the object.

This only happens when passing through an object, so it only needs to be computed for rays refracted into an object or for internal reflections.

4 Improved Refraction

First compute the adjusted reflectance and transmittance:

reflected = R * reflected_color
transmitted = T * transmitted_color

If *reflected* > 0 then trace a reflected ray, and multiply the returned light value by *reflected*. Likewise, if *transmitted* > 0, trace a refracted ray and multiply the returned light value by *transmitted*.

If we are inside of an object, also multiply the final color value by the absorbency $T_{abs.}$

Finally, sum the final reflected light (if there is any), the final transmitted light (if there is any), and the local diffuse light.

3.5 Extensions

Originally intended for this project was photon mapping and spectral photon casting. However, due to unfortunate time constraints and implementation problems, both were left incomplete.

In the first pass of photon mapping, a quantity of 'photons' from the light sources into the scene. The intended use in this context is to simulate and capture the caustics produced by reflective and refractive objects.

In casting the photons into the scene, the same basic algorithm from the ray tracing component. However, instead of collecting and accumulating light, it is being emitted and absorbed.

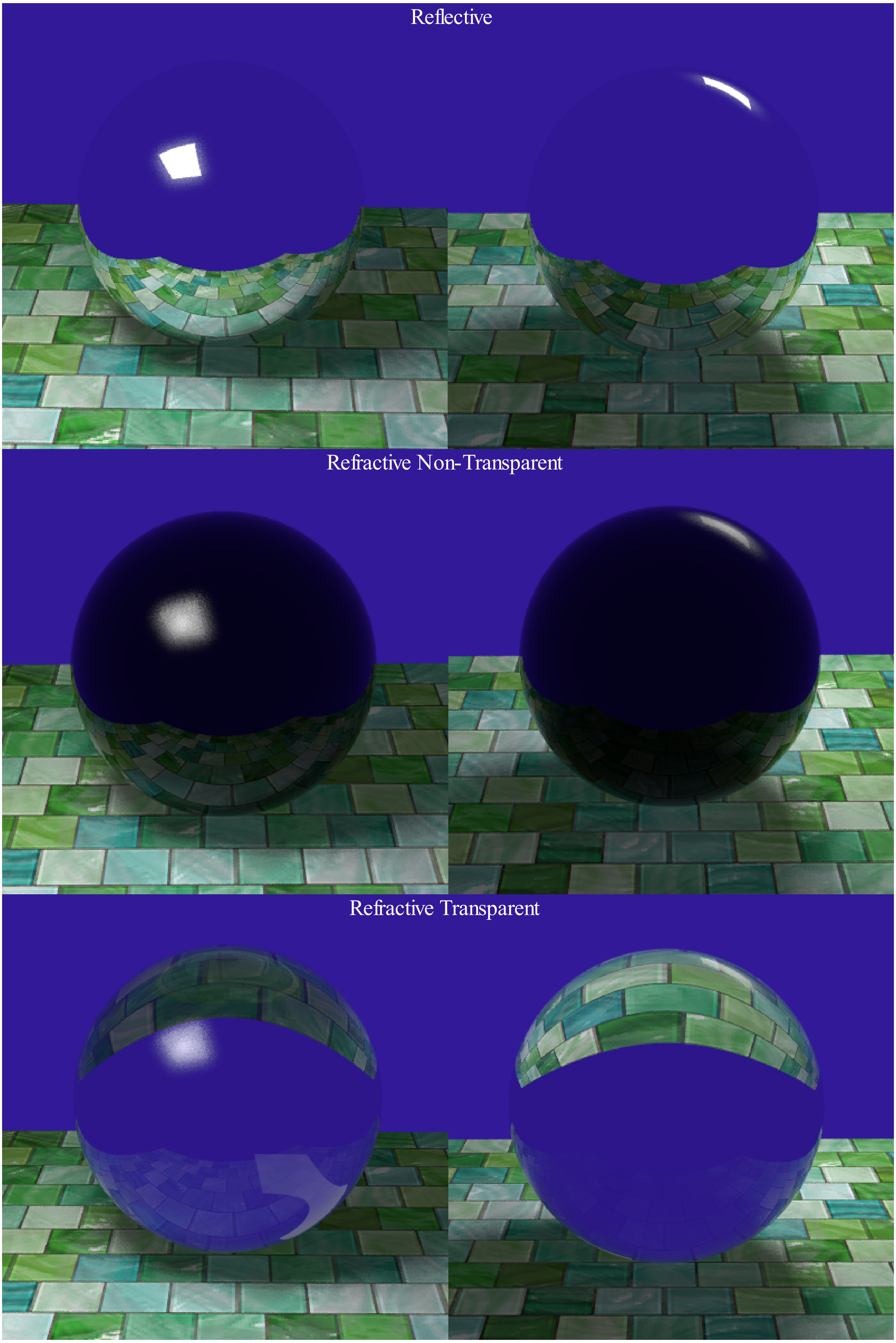
The second pass of photon mapping is a standard ray trace. However, instead of using ambient, diffuse light, the photon map is quired for the photon recorded at ray intersections/bounces/refractions.

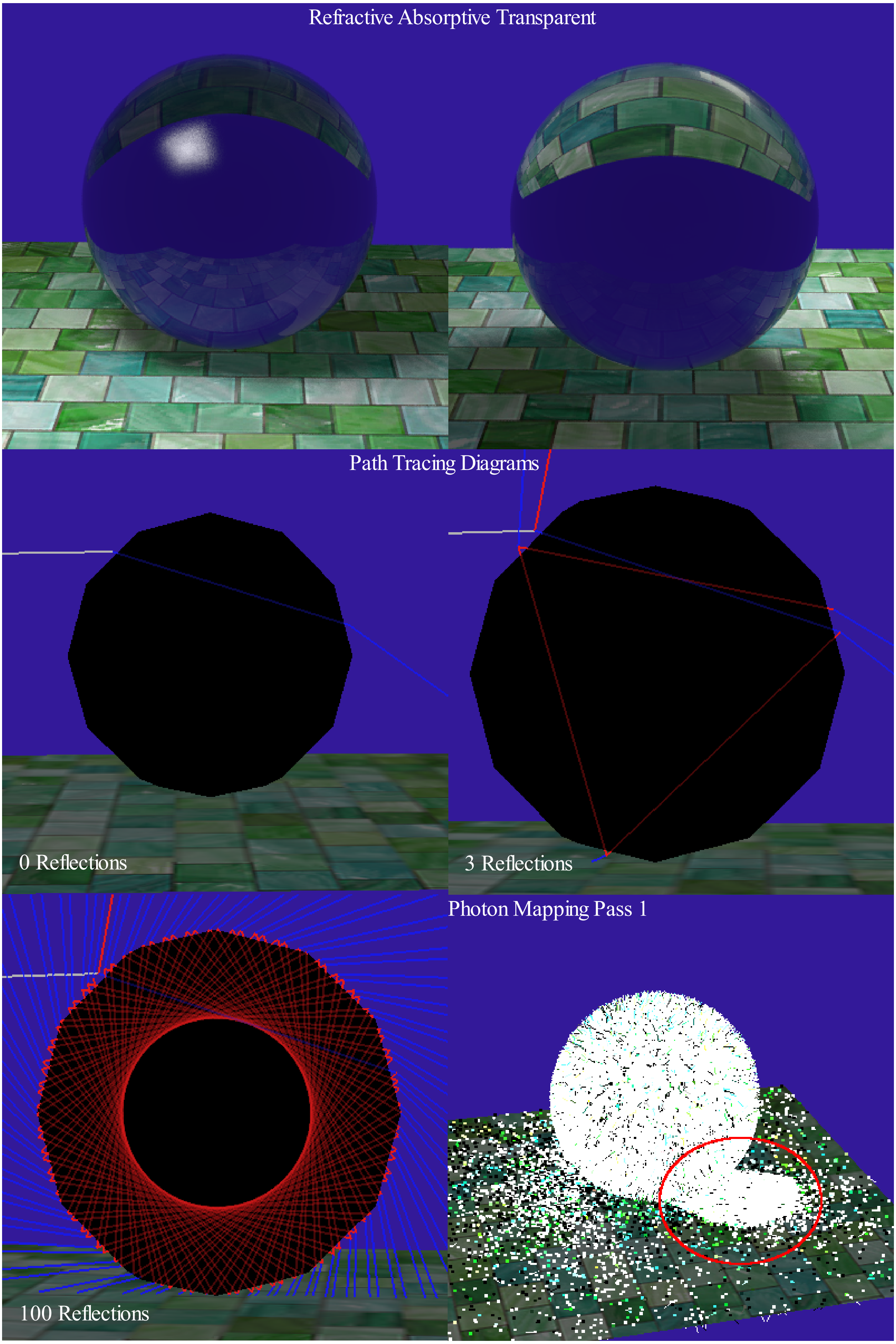
However there is still something missing, which is where spectral photon casting would have come in. White light is comprised of a large number of different wavelengths. Light if different wavelengths will bend at different angles across the same refractive boundary.

Ray tracers often do not implement this because it is expensive to compute.

5 Conclusion

Even without the more advanced photon mapping techniques, it's possible to get relatively good looking refractive effects without adding much expense to the overall computation.


Reflective
Refractive Non-Transparent
Refractive Transparent


Refractive Absorptive Transparent
Path Tracing Diagrams
0 Reflections
3 Reflections
100 Reflections
Photon Mapping Pass 1

References

[1] Massal, Grégory: Camera model and depth of field.
http://www.codermind.com/articles/Raytracer-in-C++-Depth-of-field-Fresnel-blobs.html

[2] Bikker, Jacco: Raytracing: Theory & Implementation Part 3, Refractions and Beer's Law.
http://www.devmaster.net/articles/raytracing_series/part3.php

[3] "Beer–Lambert law".
http://en.wikipedia.org/wiki/Beer's_law

[4] "Fresnel equations".
http://en.wikipedia.org/wiki/Fresnel_equations

[5] "Total internal reflection".
http://en.wikipedia.org/wiki/Total_internal_reflection

[6] Jensen, Henrik Wann: "Global Illumination using Photon Maps". In "Rendering Techniques '96". Eds. X. Pueyo and P. Schröder. Springer-Verlag, pp. 21-30, 1996

[7] Walker, John: "Colour Rendering of Spectra".
http://www.fourmilab.ch/documents/specrend/