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A translucency classification for computer graphics

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Abstract

Translucency is a visual property attributed to objects that light may cross without transmitting a clear image of the scene which is behind. In absence of a more precise definition, this perceptual attribute is often considered as an intermediate between transparency, which is the property of objects that light may cross by transmitting a clear image of the scene behind, and opacity, which is the property of blocking the transmission of light and therefore masking completely the scene behind. If it is rather clear that translucency is closely related to light scattering, it is difficult to classify the translucent appearance according to one scale only, due to the different types of scattering, which can occur as well as the role of absorbance and thickness of the material. Through synthetic images rendered by optical models, we show that surface scattering, volume (or subsurface) scattering, possibly mixed with selective absorption, produce different types of translucency effects and different intermediates between transparency and opacity. We thus propose to represent translucency according to three axes related to these three optical phenomena: surface scattering, volume scattering, and absorption.

Introduction

While it is used to denote the appearance of a wide range of materials such as milk, jade, ceramic, or skin, translucency is a perceptual and physical concept, which is still not well defined. Many models have been developed in computer graphics to render various light effects but translucency has not been fully explored yet.

Translucency is often viewed as the intermediate between transparency and opacity. Among the rare studies dedicated to this concept, the one by Fleming *et al*. [1] addresses the opposition between translucency and opacity through image synthesis. For example, the authors show that translucency of smooth objects is more noticeable when the object is illuminated from behind than when illuminated on the front side. Moreover, when illuminated by a directional source, an opaque object appears more contrasted than a translucent one. The last point the authors explored is the addition of a blur in the images but this operation is not sufficient to explain the perception of translucency because other phenomena such as depth of field or penumbra effects can be at the origin of similar blurring effect. Another study from Gkioulekas *et al.* [2] shows the importance of single scattering within the material to explain differences in translucency. Finally, Ref. [3] stipulates that opacity, translucency and transparency can be described on the same scale to carry out a perceptual experiment.

However, the elements provided in the literature mentioned above are not precise enough to render the different kinds of translucency we can find with objects according to the material in which they are made and their thickness. It is noticeable that the oppositions transparency/translucency and translucency/opacity do not rely on similar perceptual criteria nor similar physical phenomena.

We may agree on the fact that a object is considered as translucent when light can go through it while being scattered. As a result, the scene that is transmitted through the object appears blurred. Two diffusion phenomena may occur: light may be scattered either at the object's surface, which is called surface scattering, or within the object itself, which is known as subsurface scattering, or volume scattering.

Decomposing translucency among absorption, surface and volume scattering would lead to a more complete, physically-based, intuitive and artist-friendly representation, which may be useful for computer graphics or manufacturing.

In this paper, we define a three-dimensional representation system adapted to a wide range of translucency effects in Section 1. The implementation details are given in Section 2, and some specific points in this representation space are illustrated through generated synthetic images in Section 3. These results are discussed in Section 4, and Section 5 draws the conclusions.

1. Three-dimensional representation space

In 1225, an English theologian Robert Grosseteste wrote a short text in latin entitled "De Colore" which has been interpreted by Ref. [4] as the first intent of a color classification system composed of three axes. The authors have defined these axes based on three oppositions stated in Grosseteste's text: *obscura/clara* (dark/light), *pauca/multa* (little/much), *impurum/purum* (pure/impure); and proposed a representation of Grosseteste's system as a cube, similar to the RGB cube for representing colors in a digital image. This idea of assessing a main visual attribute with independent criteria inspired our approach for assessing translucency.

We have identified three main optical phenomena giving to the objects their transparency, translucency or opacity. To build our representation system, each of these phenomena has been described independently from one another by using a physical law or a model. Some assumptions have been made so that only one parameter is enough to describe the appearance variation over one axis:

– absorption, parameterized by the density of absorbers in the material, the absorbers being characterized by an absorption coefficient.
– surface scattering (i.e., the scattering of light at the air-material interface), parameterized by a surface roughness parameter,
– volume scattering, i.e., the scattering of light within the material itself, parameterized by a scatterer density.

The three-dimensional representation is featured in Figure 1, and the optical models used to render the three optical phenomena are presented below.

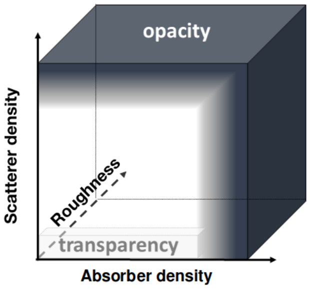

***Figure 1**. Three-dimensional space representing translucent materials. Each axis corresponds to one of the physical phenomena among absorption, surface scattering and volume scattering. The absorption axis is described by the absorber density, the surface scattering axis is controlled by the roughness parameter, and the sub-surface scattering axis is described by the scatterer density.*

Absorption

The absorbance of an object is described by Beer-Lambert-Bouguer's law [5]. Let's denote A the absorbance of the material and T its transmittance. The Beer-Lambert-Bouguer's law is defined as in Equation (1), where σ is the attenuation cross section, n the absorber density and d the thickness that is crossed by the light through the object.

$$T = 10^{-A} = e^{-\sigma n d} \quad (1)$$

The transmittance decreases with the thickness of the object. Along this axis, we consider that the absorptivity of the material is fixed, and so we defined the absorber density n as the variable parameter, which controls the absorption of the material.

We assume in our approach that absorption is the only phenomenon responsible for coloration of the material. At the origin of this "absorption" axis, the material is transparent and achromatic (i.e. clear). As the material is more absorbing, its color becomes darker and more saturated. Finally, for an infinite absorbance, the material becomes completely dark and opaque. Along this axis (the other two parameters being zero) are represented the purely absorbing media with a flat surface, which are either transparent or opaque, but not translucent. The appearance along this axis can be seen in Figure 3.

Surface scattering

We use the micro-facet model proposed by Walter [6] to compute surface scattering in both reflection and transmission. The model uses Smith's masking-shadowing function [7], and the isotropic GGX micro-facet normal distribution, which provides a close match to the measured data. It allows controlling the surface scattering through a surface roughness parameter, which corresponds to the standard deviation of the slope distribution. At the origin of this axis, the roughness parameter is zero, which corresponds to a smooth and perfectly transparent material. By increasing this parameter, the material becomes rougher and the object less translucent. In Walter's model, inter-reflections between the micro-facets are not taken into account. This results in an energy loss, sensible when the roughness is too high. The correct amount of energy leaving a rough surface can be derived by using the approach that Heitz [8] has developed in order to take into account these inter-reflections as the common micro-facet models does not. Along this "surface scattering" axis are represented the clear materials with rough surface, which are translucent but cannot be opaque (Figure 4).

Sub-surface scattering

For the scattering of light within the material itself, we compute it according to the dipole model proposed by Jensen [9], by assuming inclusions in the medium, which scatter the light in an isotropic way. This is the density of this scatterer, which allows us to control the appearance of the material along this axis. At the origin of the "volume scattering" axis, the density of the diffusing inclusions is zero: the material appears as achromatic and transparent. As the inclusion density increases, the lateral diffusion within the material becomes more important. Beyond a certain limit, the density is so high that the free mean path of the light within the material is very short and the material looks totally opaque. This particular case corresponds to the interfaced Lambertian model proposed in Ref. [10]. Along this axis are represented the scattering and non-absorbing materials, whose appearance can vary from transparent to white opaque through various degrees of translucency (Figure 5).

2. Implementation

In computer graphics, the way materials scatter light is characterized by their BSDF (Bidirectional Scattering Distribution Function). These models are valid if the incident light is only scattered locally at the surface of the object (surface scattering). It is mostly the case for transparent, opaque or thin translucent objects. This function can be decomposed into two light contributions: the light that is reflected by the surface of the object, described by the BRDF (Bidirectional Reflection Distribution Function) and the light that is transmitted through the object described by the BTDF (Bidirectional Transmission Distribution Function). In the case of a completely opaque material, no light is transmitted through the object and only the BRDF is used. As most objects considered in this paper can be crossed by light, we will use the more general term BSDF.

For a thicker translucent material, the scattered light may emerge at a certain distance from where the light has entered into this material. Rendering this effect needs to take into account light scattering within the material with a Bidirectional Surface Scattering Reflection Distribution Function (BSSRDF). The BSSRDF can be modeled by solving the radiative transfer equation [11], generally using the diffusion approximation [12]. Taking into account the sub-surface scattering has revolutionized the rendering of translucent materials in animation or video games, particularly thanks to the contribution of Jensen *and al.* [9].

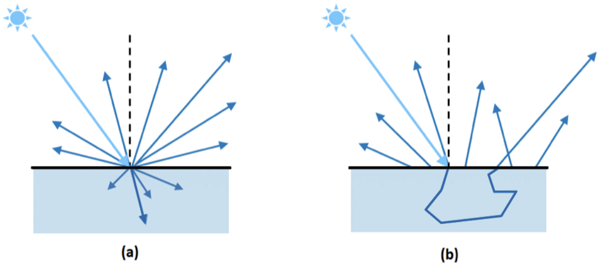
(a)
(b)

***Figure 2**. Difference between BSDF and BSSRDF. (a) The light is only scattered at the incident point, which can be modeled with a BRDF. (b) The light can emerge at a certain distance from the incident point, which is modeled with a BSSRDF.*

Finally, the BSDF can be viewed as a simplification of the BSSRDF by considering that the incoming point of the light in the object is the same as its exiting point.

The BSSRDF model that we use to generate objects with different translucencies in our representation system combines the different models presented above for absorption, surface scattering and volume scattering.

The translucency effect can be visually appreciated through the synthetic images of a spherical object placed in front of a surrounding by an environment map representing a landscape. The images are generated with the open source renderer Mitsuba [12]. The first two axes are rendered with existing BSDFs models that are already implemented in Mitsuba: the "absorption" axis can be design by using a model that accounts for the absorption occurring in a dielectric material ("dielectric" plug-in). The "surface scattering axis" is modeled by a micro-facet model that uses the GGX normal distribution ("roughdielectric" plug-in. In order to account for the multiple reflections between the micro-facets, an improvement of this model has been proposed by Heitz [8], which is available as a new Mitsuba plug-in ("roughdielectricGGX" plug-in). However, in order to design the sub-surface scattering axis, we need a BSSRDF model handling both perfect transparency and complete opacity. Unfortunately, as far as we know, such a model does not exist. We therefore designed our own model.

To describe the volume scattering in the material, we use the "dipole" plug-in that is available in Mitsuba, which applies the BSSRDF according to Jensen's model [9]. This plug-in only accounts for the scattering that is happening inside the material. We need to add the effects that are occurring at the air-material interface and which are described by a BSDF.

In the renderer, one BSDF is usable for transparent dielectric materials $BSDF_1$ ("dielectric" plug-in), and a different one is usable for perfectly opaque materials $BSDF_2$ ("plastic" plug-in). To obtain materials from transparent to opaque with a translucent look both in reflection and in transmission, we chose to linearly combine these two BSDFs such as:

$$BSDF=\alpha_1 BSDF_1+\alpha_2 BSDF_2 \qquad (2)$$

where $\alpha_1+\alpha_2=1$ in order to guarantee the conservation of energy. The final model is then composed of the BSDF defined by the Equation (2), and the BSSRDF obtained with the "dipole" plug-in. The scatterer density which is the parameter describing the "sub-surface scattering axis". On the one hand, in the BSSRDF, it can be modified by a scale parameter. On the other hand, the scatterer density varies with the coefficient α_2: when α_2 is really small, there is almost no inclusion. The material appears to be transparent as the "dielectric" plug-in does ($(\alpha_2=0)$. An increase of α_2 corresponds to an increase of the scatterer density until the material becomes opaque as described by the "plastic" plug-in $(\alpha_2=1)$.

3. Illustration through objects in glass

By way of illustration, we propose to consider spherical objects made in glass, whose refractive index *n* = 1.5 is assumed to be constant over the visible spectrum of light.

All the rendered images are generated by using 1024 samples per pixel. Our representation system has been designed so as the three axes are independent to each another. First, we vary one physical parameter, the other two ones being zero, and observe the influence of this parameter alone on the translucency of the glass bowl.

***Figure 3**. Absorption axis. The absorber density increases from the left-most object (non-absorbing) to the right-most object (opaque black).*

As absorption depends on wavelength, it is responsible for the color of the object. We remind that in our study we assume that there is no other cause to the coloration of the object. In the example shown in Figure 3, we selected a spectral absorption coefficient having a reddish hue. By increasing the density of absorbers, the bowl becomes darker, until opacity (black). In any case, the object remains transparent. The ball behaves like a lens and inverts the image of the background landscape. Apart from the reflection of the sun, the image reflected by the front side of the ball is relatively insignificant. It is only revealed by contrast when the object is opaque.

***Figure 4**. Surface scattering axis. The roughness increases from the left-most object to the right-most one. The absorbance is zero along this axis.*

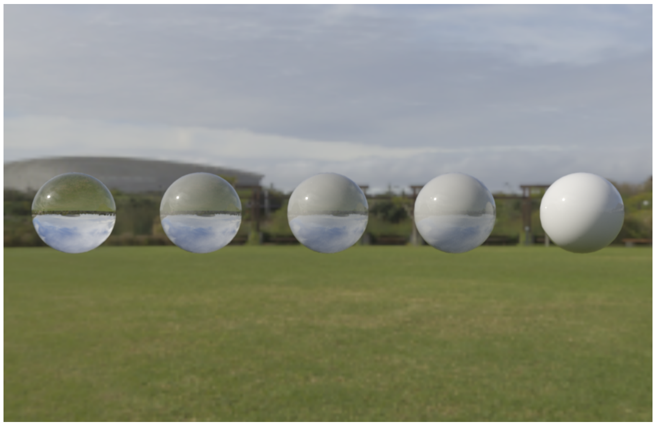

Figure 5*. Sub-surface scattering axis. The scatterer density increases from the left-most object to the right-most one. The absorbance is being zero along this axis, a milky appearance is observed.*

The rendering of balls where only surface scattering occurs is displayed in Figure 4. We accounted for the multiple reflections as proposed by Heitz [8]. Consequently, the ball does not become darker as the roughness increases, in opposition with the results rendered by common surface scattering models. The left-most ball is perfectly smooth, the roughness parameter being set to 0.0. From left to right the four other balls are rendered with a respective roughness of 0.05, 0.1, 0.25, 0.5. We can notice that the rough appearance of the object does not varies linearly with the roughness parameter. Visually, the images in transmission and in reflection (less visible here than for transparent materials) are becoming more and more blurred, up to a certain roughness value from which the appearance of the object becomes almost homogeneous. Although it is possible to get this impression, opacity is never reached: there is always some light transmitted by the object. From a perceptual point of view, perceived translucency depends on the blurred nature of the transmitted image, and therefore on the distance between the translucent object and the observed scene. For example, a tracing paper sheet allows to replicate an image that is placed underneath and in contact with it, but does not allow to distinguish clearly an image that is placed a few millimeters away.

Regarding to the sub-surface scattering axis, illustrated in Figure 5, the obtained result is coherent with our expectations. The sphere is going from totally transparent to milky or white marbleish aspect, until total opacity.

By comparing Figures 4 and 5, the difference between surface scattering and sub-surface scattering is well noticeable. In practice, with real objects, this distinction is not always obvious, especially in case of low scattering. When looking at a white film, it is often difficult to know whether the whiteness is due to volume or surface scattering, and one of the only way to know it is by applying a thin layer of liquid with refractive index close to the one of the object. In case of surface scattering, the oil layer makes a smooth interface and the object becomes transparent. In the case of sub-surface scattering, the oil has no effect on the visual appearance of the translucent object.

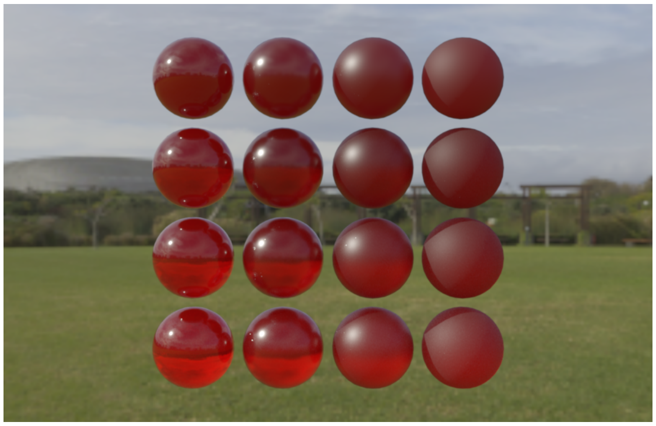

Figure 6*. Variation of surface and sub-surface scattering while the absorption is constant. From left to right: increase of the surface scattering. From bottom to top: increase of the subsurface scattering.*

Figure 7*. Evolution in the absorption/sub-surface scattering plane. There is no surface scattering, so the air-material interface is perfectly smooth. In this case, the scatterers are also the absorbers. From left to right the density of these particles is increasing.*

4. Discussion

The three-dimensional space that we have defined for representing translucency enables placing objects with different absorber density, surface roughness and scatterer density in a cube, as shown earlier in Figure 1. Transparency is achieved in absence of scattering and corresponds to the absorption axis (See examples in the picture of Figure 3) except the highly absorbing materials, which make the object opaque. The opaque objects are located near the planes of maximum absorption and maximum volume scattering. All the other states inside the cube correspond to translucent materials. It is even possible to navigate in this three-dimensional space in order to choose/design the appearance of an object. This cubic representation is obviously richer than the traditional one-dimensional scale (transparency / translucency / opacity), and has also the advantage of being based on optical properties of the material.

For example, Figure 6 shows different glass bowls whose are located in a plane within the representation system, corresponding to a constant absorber density. Surface scattering increases from left to right, and volume scattering increases from bottom to top. Although the appearances of the different objects evolve in a sensitive way, it is difficult to interpret the materials as transparent or opaque, and diffusing in surface or volume. This confusion is explained by the simultaneous perception of more or less blurred images in transmission and in reflection. If reflection prevails in terms of luminance, the object seems opaque. This impression of opacity increases as surface scattering increases because the image of the landscape in the background is not visible anymore. Hence, some objects look opaque while they still transmit light from the background.

The main argument in favor of this representation system is its simplicity, which lies on the fact that we have selected only three optical phenomena non-correlated to each other. This simple approach implies various assumptions:

- The color of an object is assumed to be only due to its properties of absorption. These assumptions is acceptable for many materials but excludes some other phenomena such as dispersion or chromatic scattering, Rayleigh scattering for example.
- The scattering particles are assumed to be randomly distributed and the effect of light scattering on the surface and/or in volume are assumed to be isotropic. However, textured and anisotropic effects, visible for example on certain openwork textiles, would favor some scattering directions that would significantly modify the perceived translucency.
- Absorption and volume scattering are assumed to be uncorrelated, an assumption, which is rarely satisfied. Moreover, the diffusing particles can also be absorbing. Thus, the representation of the volume diffusion axis (Figure 5) is a very special case where scattering-only particles are in a non-absorbing binder. If the density of scattering particles increases, absorption should also increase in a proportional way. For example, in the case of pigments the absorbers and the scatterers correspond to the same inclusions in the material. As a consequence, when the absorber density increases then the scatterer density increases in the same way. Figure 7 illustrates this effect: tthe object gradually becomes opaque and its color becomes more and more saturated. The color of the opaque object is neither white (no absorption) nor black (no sub-surface scattering).

The proposed representation system can be adapted to the above situations without losing the general idea. On the other hand, taking into account some other optical phenomena such as interference, diffraction, or photo-luminescence would probably require increasing the dimensionality of the representation space. These phenomena can, in some cases, provide information in contradiction with the information related with usual light scattering mechanisms and thus disturb the interpretation of the translucency attribute.

5. Conclusion

The translucency of an object is often interpreted through the thickness variation of that object, and therefore the variation of the light it transmits. Nevertheless, even an opaque object can be considered as translucent when the penetration of light in the material is perceived. This property is intrinsic of the material and opposed to transparency: On the one hand, the non-scattering and therefore transparent materials possibly colored due to the absorption of light; On the other hand, the wide variety of scattering materials whose translucent appearances depends on whether the light is scattered on the surface or in the volume.

As far as we know, this study is the first intent to classify translucency effects by considering the dimensionality of this visual attribute, based on some physical phenomena that produce it. The representation system for translucency representation suggested is suitable for artists and designers for an intuitive control of the material appearance in computer graphics. Each axis accounts for a different BSDF function that we assumed to be independent from one another, and it may easily be extended to suit any purpose.

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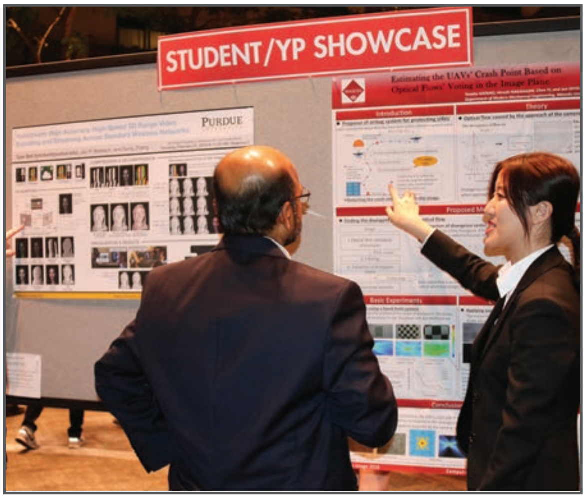

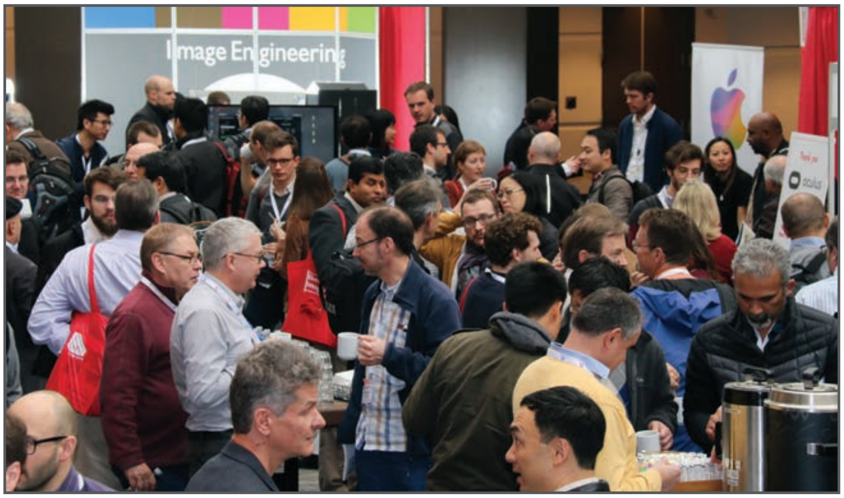

AR is a fundamental and transformative interface and platform.

20+ years from my initial working demo to today's AR displays

Optimistic that it won't take another 20 to reach ubiquitous consumer AR!