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UNIVERSITY OF LEEDS

Final Report

Physically Based Shading Models in Real-time Rendering

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Submitted in accordance with the requirements for the degree of Computer Science (Digital & Technology Solutions) BSc

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COMP3932 Synoptic Project

The candidate confirms that the following have been submitted.

Items	Format	Recipient(s) and Date
Final Report	PDF file	Uploaded to Minerva (DD/MM/YY)
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Summary

<Concise statement of the problem you intended to solve and main achievements (no more than one A4 page)>

Acknowledgements

<The page should contain any acknowledgements to those who have assisted with your work. Where you have worked as part of a team, you should, where appropriate, reference to any contribution made by other to the project.>

Note that it is not acceptable to solicit assistance on ‘proof reading’ which is defined as the “the systematic checking and identification of errors in spelling, punctuation, grammar and sentence construction, formatting and layout in the test”; see
`https://www.leeds.ac.uk/secretariat/documents/proof_reading_policy.pdf`

Contents

Chapter 1

Introduction and Background Research

1.1 Introduction

Rendering is the process of generating images, or *frames*, of a virtual world. Real-time rendering requires that the generation of these frames is done at a fast enough rate so that the viewer feels they are taking part in an immersive, dynamic experience. Typically, this rate needs to be at least 30 FPS (Frames Per Second), with 60 FPS and beyond being desirable [1]. This imposes a maximum time budget of 33 to 16 milliseconds in which each frame must be generated, the *frame time*. Real-time rendering presents a compelling problem: how can the visual fidelity of a rendered scene be maximised, whilst adhering to this strict computational budget.

Rendering can be performed using one of two techniques, ray tracing or rasterization. Ray tracing is based on a model that is analogous to how humans perceive light and colour in the real-world. In the real-world, rays of light are produced from many sources, bounce from one object to the next, and eventually reach the viewers eyes. Ray tracing models this same process, but in reverse, with the rays originating from the views eyes, and being traced back to their sources. Provided enough rays are sampled, this approach produces very realistic images. Although ray tracing is the standard in the realm of movie production, its expensive computational requirements lead to frame times in the region of minutes instead of milliseconds [2]. Aside from so notable exceptions[1], this prohibits its use in real-time applications. As a result, real-time rendering employs another technique, rasterization.

With rasterization, each object in the world is composed of an arrangement of primitive shapes, most commonly, triangles, and their material is described through a number of parameters. When rendering, the world is transformed and projected onto a 2D plane. Within this plane, a fixed region maps to the space of the output image; all triangles that lie outside this region are clipped. The remaining triangles are then split into granular pieces, called *fragments*. A colour is calculated for each fragment by evaluating the amount of light that shines on that fragment in the world, and then how that light interacts with the material of the object that fragment belongs to. Performing this calculation is called *shading*, and how it is done is defined by a *shading model*. After resolving which fragments lie on top of which others, the final image is presented to the user. This whole rasterization process is referred to as the graphics rendering pipeline, and dedicated hardware has been developed to carry it out, the *Graphics Processing Unit* (GPU).

The appearance of the final rendered frames is largely determined by the shading model, and therefore the choice of such a model is crucial. For a long time, the standard shading model used for photo-realistic real-time rendering was Blinn-Phong; it was utilised in popular game engines, and was the default model used in OpenGL's fixed function pipeline [5] [6] [7]. Blinn-Phong is an empirical model: it is based on human observations of how light interacts with materials, rather

[1] With the introduction of hardware accelerated ray tracing on consumer GPUs [3], the use of ray tracing to render specific visual phenomena, such as reflections, has seen use in some modern games [4].

than the underlying real-world physical rules that govern those interactions [8]. Blinn-Phong can produce reasonably realistic images, and is computationally inexpensive - a very desirable trait for real-time rendering. However, due to its non-physically based nature, Blinn-Phong has many issues. Paramount amongst which is its inability to render certain physical phenomena, which limits the realism of rendered frames. Furthermore, the parameters of Blinn-Phong that are used to specify material properties, bear little relation to the characteristics of physical materials. This problem manifests itself in a tight coupling between material parameters and lighting conditions. In order to accurately depict the same physical material under different lighting conditions, it may be necessary to specify differing values for these parameters. This reduces the reusability of assets, making artist workflow more difficult.

In an effort to alleviate these issues, the replacement of Blinn-Phong in favour of physically based shading models has seen widespread adoption. Such models work by evaluating equations that simulate the real world physical interaction of light and objects. Using these models for shading is known as *Physically Based Shading* (PBS), and their use in the wider rendering pipeline is called *Physically Based Rendering* (PBR). PBS represented a seismic shift in the real-time rendering industry, with major game engines migrating to a PBR pipeline [9] [10].

The aim of this project is to investigate the use of physically based shading models in real time rendering. Specifically, I will seek to highlight the benefits of PBS when compared to the technology is superseded, Blinn-Phong shading.

The advantages of using PBS over Blinn-Phong shading can be broadly categorised into two groups: the improvements to artist workflow; and the improved photorealism. As mentioned previously, because of how materials are defined in Blinn-Phong shading they are often not portable between different lighting environments. In contrast, the parameters that determine materials in PBS are based on physical properties. This permits the reuse of materials and assets over different lighting configurations [10] [11]. Burley outlines how this reduction in the need for "material 're-do's" yields an extremely significant improvement to artist workflow [12]. Although these benefits are an important motivating factor for using PBS, the practical issues that arise from trying to investigate and quantify them (I don't have access to a team of artists) mean that this report will focus solely on exploring those advantages in the latter category – how does PBS render frames that are more photorealistic than Blinn-Phong?

Answering this question by simply commenting on the general perceived realism of a frame when compared to another, is a largely subjective exercise. Instead, in a concerted effort to be as objective as possible, I will examine the benefits of PBS by identifying physical phenomena that it models in its rendered frames, but that are absent when using Blinn-Phong shading. To this end, I will be developing a piece of software that can render scenes using both Blinn-Phong shading, and PBS.

1.2 Mathematical Notation

When reasoning about different mathematical expressions and models, it's of vital importance that a standard, coherent notation is used throughout.

$\mathbf{n}$	Normal vector
$\mathbf{l}$	Light direction
$\mathbf{v}$	View vector
$\mathbf{c}_x$	The RGB triplet vector representing the colour of x
$\mathbf{a} \cdot \mathbf{b}$	The dot product of vectors $\mathbf{a}$ and $\mathbf{b}$
$\lVert\mathbf{a}\rVert$	The norm of vector $\mathbf{a}$
x^+	Clamp x to 0 if $x < 0$

1.3 Literature review

The review begins with a discussion of the Blinn-Phong shading model; this provides the necessary background knowledge for the later comparison with physically based shading models to be performed. We then delve into the physics of how light interacts with matter, and how this pertains to shading. An exploration of the theory underpinning physically based shading models follows, and then we present several such models. After, we consider how lights can be represented in a physical manner. Finally, we finish by focusing on the wider PBR aspect with a discussion on how we store pixel colours, and the transformations that need to be applied before passing those colours to the display.

1.3.1 Blinn-Phong Shading

Phong Model

In 1975, Phong introduced a simple shading model for rendering realistic images [8]. The original model is parametrised as the sum of two terms, *diffuse* and *specular*, but in practice it is commonly supplemented with a third term, *ambient*. Each one describes the contribution of a different lighting component. Splitting shading into the evaluation of a diffuse and specular term is common practice, and the physical basis for doing this is explained in section 1.3.2.

An ideal diffuse surface follows Lambert's law: light incident onto a point will be diffused in all directions equally [13]. Therefore, the determining factor in the appearance of such surfaces is the intensity of the incident light, which is a function of the direction of incident light and the orientation of the shaded surface. The diffuse term encodes the lighting effects of parity between a primitive's surface orientation and the direction of the light, with surfaces facing the light being illuminated more intensely than those facing away from it. This behaviour is formulated as:

$$\mathbf{c}_{shaded_{diff}} = \mathbf{c}_{surface_{diff}} \mathbf{c}_{light_{diff}} (\mathbf{n} \cdot \mathbf{l})^+$$

$\mathbf{c}_{shaded_{diff}}$, $\mathbf{c}_{surface_{diff}}$, and $\mathbf{c}_{light_{diff}}$ are the RGB triplets that represent the diffuse colour of the shaded fragment, the diffuse colour of the surface, and the diffuse colour of the incident light respectively. This separation of the light and surface colours into separate components was not present in Phong's original model. However, many implementations have increased the flexibility of the model by exposing these additional parameters [14]. The *normal*, $\mathbf{n}$, is the unit vector pointing away from the surface at the shaded point, giving the orientation of the surface. The *light direction*, $\mathbf{v}$, is the unit vector pointing in the direction of the incident light. See Figure 1.1 for an illustration of the principle vectors used in the Phong shading model (and indeed, by most shading models). The dot product of two unit vectors is equivalent to taking the cosine of the angle between them. Therefore, $(\mathbf{n} \cdot \mathbf{l})^+$ will increase from 0 to 1 as the angle between the incident light direction and the surface normal decreases. Thus, the more aligned the surface orientation and light direction are, the greater the intensity of the diffuse term. Negative values of the dot product indicate that the light direction is underneath the surface. In these cases the light is not incident upon the surface at all, so the dot product is clamped to 0.

The specular term of the model captures the ability for surfaces to exhibit highlights due to surface reflections. When light is incident upon a surface, it will experience some reflection, and when the reflected light is aligned with the direction of the viewer, this is perceived as a region of increased illumination, a *specular highlight*. The formula for the specular term is:

$$\mathbf{c}_{shaded_{spec}} = \mathbf{c}_{surface_{spec}} \mathbf{c}_{light_{spec}} ((\mathbf{r} \cdot \mathbf{v})^+)^{surface_{shininess}}$$

Where $\mathbf{r}$ is the reflection of the incident light about the surface normal, and is defined as:

$$\mathbf{r} = 2(\mathbf{n} \cdot \mathbf{l})\mathbf{n} - \mathbf{l}$$

The RGB triplets are similar to those in the diffuse equation, except these are specific to the specular response. Phong's original model had the colour of the specular highlight be the same as the overall colour of the light (not split into separate diffuse and specular components). This gave all materials an overly plastic appearance. Introducing the $\mathbf{c}_{surface_{spec}}$ and $\mathbf{c}_{light_{spec}}$ variables allows for the colour of the specular highlight to be fully configurable, mitigating this issue [14]. The *view vector*, $\mathbf{v}$, is the unit vector pointing in the direction of the viewer. The dot product measures the alignment between the view direction, and the direction of the reflected incident light. The $surface_{shininess}$ parameter determines the concentration of the reflected light rays. The higher the value, the more focused the reflected rays are, the smaller the specular highlight becomes, and the shinier the object appears. Typical values range from 1 to 100.

Finally, we have the ambient term. In the model developed so far, if a shaded point is not directly visible from a light source, then it will be black. In reality, such points are never completely unilluminated - rays from light sources will bounce around the environment, eventually lighting these obscured areas. So far we have only considered *direct lighting*; the ambient term is used to crudely approximate the illumination that is a consequence of this *indirect lighting*:

$$\mathbf{c}_{shaded_{ambi}} = \mathbf{c}_{surface_{ambi}} x$$

$\mathbf{c}_{surface_{ambi}}$ controls the colour of the ambient shading. Typically, it is just set equal to $\mathbf{c}_{surface_{diff}}$. x is a constant value defined for the whole scene, rather than per light, and controls the amount of indirect lighting that occurs. A value of $x = 0.2$ is commonly used, with anything greater often giving unrealistic results. Illumination via indirect lighting is usually quite subtle as light loses energy every time it reflects of a surface.

These three terms are summed together to give the overall Phong shading model:

$$\mathbf{c}_{shaded} = \mathbf{c}_{shaded_{ambi}} + \mathbf{c}_{shaded_{diff}} + \mathbf{c}_{shaded_{spec}}$$

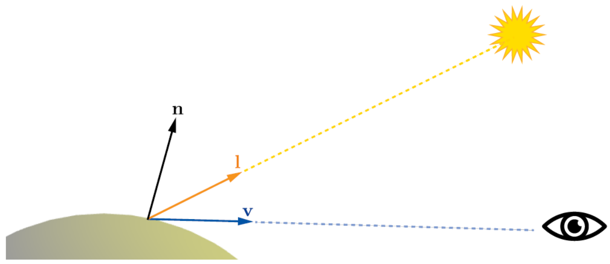


Figure 1.1: The surface normal $\mathbf{n}$, light direction $\mathbf{l}$, and view vector $\mathbf{v}$ [15]

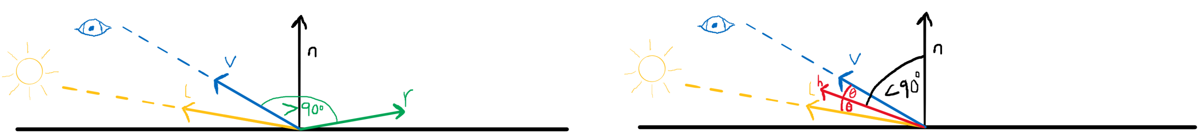
Blinn-Phong Model

One of the issues with the Phong shading model is made apparent when viewing a rough (low *shininess* value) surface from a direction close to the incident light. The corresponding reflected light vector makes an angle with the view direction that is greater than 90°. In this instance, the dot product $\mathbf{r} \cdot \mathbf{v}$ evaluates to a negative value, and is thus clamped to 0, leading to no specular contribution. However, for very rough surfaces, the specular highlight is so wide that even at these greater angles, there should still be a specular contribution. See Figure 1.2a for an illustration of the problem.

In 1977, Blinn remedied this issue by modifying the Phong shading model with a more accurate specular term [16]. He utilised the half vector, $\mathbf{h}$, dispensing with the reflected light vector, $\mathbf{r}$, and replaced the existing specular dot product with $\mathbf{h} \cdot \mathbf{n}$. $\mathbf{h}$ is a unit vector pointing in the direction that is halfway between the $\mathbf{l}$ and $\mathbf{v}$ vectors. It is calculated as:

$$\mathbf{h} = \frac{\mathbf{l}+\mathbf{v}}{||\mathbf{l}+\mathbf{v}||}$$

Blinn's specular term emulates the overall behaviour of the original Phong term. As the (now conceptual) reflection vector $\mathbf{r}$ aligns with $\mathbf{v}$, so does the half vector $\mathbf{h}$ align with the surface normal $\mathbf{n}$. Crucially though, $\mathbf{h} \cdot \mathbf{n}$ will only evaluate to a negative value, and subsequently be clamped to 0, if $\mathbf{l}$ or $\mathbf{v}$ is beneath the surface. Therefore, the scenario in which rough surfaces were being shaded incorrectly with no specular contribution, is resolved. See 1.2b for an illustration.



(a) The angle between $\mathbf{r}$ and $\mathbf{v}$ can exceed 90° whilst $\mathbf{l}$ and $\mathbf{v}$ are still above the surface

(b) The angle between $\mathbf{h}$ and $\mathbf{n}$ can't exceed 90° without $\mathbf{l}$ or $\mathbf{v}$ being below the surface

Figure 1.2

Blinn's modification to the Phong model is known as the Blinn-Phong shading model, and it produces more realistic images than the original. The model is formulated as:

$$\mathbf{c}_{shaded} = p_{ambi} + p_{diff}(\mathbf{n} \cdot \mathbf{l})^{+} + p_{spec}((\mathbf{h} \cdot \mathbf{n})^{+})^{surface_{shininess}}$$

where

$$p_{ambi} = \mathbf{c}_{surface_{ambi}} x$$

$$p_{diff} = \mathbf{c}_{surface_{diff}}\mathbf{c}_{light_{diff}}$$
$$p_{spec} = \mathbf{c}_{surface_{spec}}\mathbf{c}_{light_{spec}}$$

Expressing the model in this way draws attention to the relative proportions of each component that contributes to the overall shading. These proportions, p, are modulated via lighting parameters: $light$ variables and x; and material parameters: $surface$ variables.

In scenes with multiple lights, we perform the shading equation for each one and then sum up the intermediate values to get the overall colour of the fragment.

1.3.2 Physics of Light-Matter Interaction

Visible Light

The Electromagnetic spectrum is a distribution of wavelengths, of which a small section is spanned by visible light. More specifically, visible light are those electromagnetic (EM) waves with a wavelength between 400nm, violet, and 700nm, red. Typically, visible light will contain a combination of wavelengths within this range. We can express light waves as a relation between each wavelength and its associated energy, in what are known as Spectral Power Distributions (SPD). Although renderers exist that store light as SPDs, the negative performance implications that accompany this approach mean that in practice, an abstraction is often used [17]. This abstraction exploits the relative imprecision of the human visual perception system. Using a linear combination of three wavelengths, R, G and B, we can accurately represent any visible light wave and colour [18]. Renderers store this combination as an RGB triplet, with each value giving the weight of its associated wavelength.

The area of study concerned with quantifying EM waves is called *Radiometry* [19]. Several *radiometric* measurements exist, with the most commonly used one in rendering being *radiance*, L. Radiance measures the power of a single EM ray. It's defined as energy over time (power), with respect to area and direction: W/m^2sr. Power is expressed in Watts, area in metres squared, and direction in *Steradians*. Steradians are to solid angles, what radians are to normal angles. A solid angle is the 3D version of a normal 2D angle. Evaluating a shading model is equivalent to computing the radiance of a single light ray that goes from the shaded fragment to the viewer. See section 1.3.3 for more details.

Light Interaction with Matter

The way in which light interacts with matter is characterised by the matter's *index of refraction* (IOR). The IOR defines the speed that light travels through the matter, given in relative terms to the speed of light in a vacuum. The IOR can also be extended to describe the absorption qualities of the matter, in what is known as the *complex index of refraction*. Some matter absorbs light waves by converting part of their energy to heat, causing an attenuation of the lights amplitude and intensity. Both forms of refractive index can vary by wavelength.

Light interacts with matter in three ways. When light is travelling through a volume of matter with a uniform IOR, a *homogenous medium*, it will not deviate in its direction. However, the absorption value of the IOR may cause the light to undergo changes in intensity, and if this varies by wavelength, changes in colour also. Water is an example of a homogenous medium that absorbs light, but mostly around the red wavelengths - this gives its distinctive blue and green colour.

Light behaves differently in a *heterogeneous medium*, where the IOR is not uniform. If light encounters a change in IOR that takes place over a distance smaller that a light wavelength, it will *scatter* into multiple directions. The frequency of scattered light will be the same as the original light. In the likely case that the original light is comprised of a distribution of different wavelengths and frequencies, each one will interact independently. The scattered light will move in all directions, but at different intensities.

Finally, light can interact with matter in a manner that is opposite to that of absorption. *Emission* can take place within matter, where other forms of energy are converted to light energy, and light is emitted. Light sources work in this way.

In general, the appearance of most media is as a consequence of both scattering and absorption.

Light Incident to Surfaces

When shading, we are interested in simulating what happens when light is incident upon the surface of an object. When this interaction occurs, two properties effect the outcome: the geometry of the surface, and the nature of the substances either side of the surface.

We first consider the substance factor and assume that the surface's geometry is a perfectly flat plane. An object's surface can then be described as a flat two-dimensional boundary separating two volumes with differing IORs. In rendering it is typical that the outer volume is comprised of air, which has an IOR of 1. The inner volume has an IOR defined by the material of the object. Any light wave that impinges on the boundary will encounter an abrupt change in the IOR, which - as explained above - will result in scattering. Because the boundary is a flat plane, the nature of this scattering is well defined: some of the scattered waves will continue moving into the surface, the *transmitted wave*, and the others will be reflected at the surface and move away, the *reflected wave*. The reflected wave propagates in a direction that is the reflection of the incident wave about the surface normal. The transmitted wave will undergo *refraction* and move at an angle of θ_t, which is defined by the relative IOR of the two volumes and the angle of the incident light, θ_i [20]. See Figure 1.3 for an illustration of this scattering behaviour. The proportion of reflected versus transmitted light follows the Fresnel equations, which are explained in section [TODO: REFERENCE FRESNEL SECTION]. The transmitted wave will interact with the interior of the object in the same way as light interacts with any medium - it will experience some degree of scattering and absorption.

Now we focus on the effect that the geometry plays when light is incident on a surface. The case we have just seen of a perfectly flat surface is of course not possible; all surfaces have some variation in their geometry. Any irregularities in the geometry that are smaller than a single light wavelength do not have any impact. Irregularities larger than 100 wavelengths constitute their own local plane of flatness, with their own orientation. Irregularities that have a size within this range cause the surface-light interaction to behave differently. However, when shading we typically stay within the realm of *geometrical optics*, which means we ignore the effects of these irregularities[2] [22]. Geometrical optics strictly deals with light as rays, not waves, and these rays

[2]Although not widely used in real-time rendering, some shading models do exist for simulating the phenomena

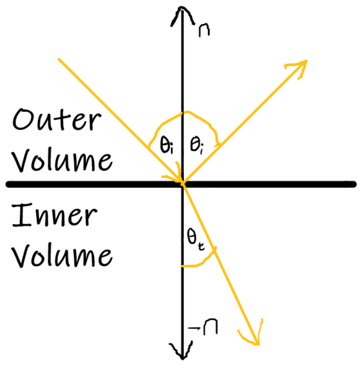


Figure 1.3: The scattering that occurs when light is incident upon a perfectly flat boundary

always intersect locally flat planes in the manner described above and illustrated in Figure 1.3. When shading, a single pixel or fragment will span much more than 100 wavelengths, so we need to account for the local planes of flatness that exist in this region. Irregularities at this scale are referred to as *microgeometry*. Each individual plane of microgeometry will reflect light in one direction, and diffract it in another. Therefore, when determining the effect of microgeometry over a whole pixel, we can consider the light to be reflected and diffracted in many directions. These directions are defined by the individual orientations of the microgeometry, and quantified by regarding them as a distribution of normals. The tighter the distribution, the tighter the spread of reflected and diffracted directions. The roughness of the material directly controls the variance of this distribution. Section [TODO: REFERENCE NDF SECTION] discusses this in detail.

Transmitted Light Interaction

As explained previously, the light that is transmitted into the interior of an object will experience a mixture of scattering and absorption. In some materials, the light will be scattered enough that it is re-emitted at the surface of the object in a process called *subsurface scattering*. See Figure 1.4a for an illustration. The distance between the subsurface scattered light and the original incident light is determined by the nature of the material, and is very important when shading. If the subsurface scattering distances are smaller than the span of one pixel, we call it *local subsurface scattering*. In such cases, the subsurface scattered light is combined with the light reflected from the object surface to form a local shading model, where the outgoing light at one point is wholly determined by the incoming light at that same point. Due to the protracted interactions that subsurface scattered light encounters before being re-emitted, it will have a distinctly different colour to the surface reflected light. For this reason, shading is split into two different terms: the *specular term* captures the light reflected at the object surface, whilst the *diffuse term* models the local subsurface scattering. See Figure 1.4b for an illustration of these two shading components.

Shading is more complex when the subsurface scattering distances are larger than a single pixel. *Global subsurface scattering* is often encountered when rendering skin or wax, and although special models have been developed to shade these materials, it is beyond the scope of this report [23].

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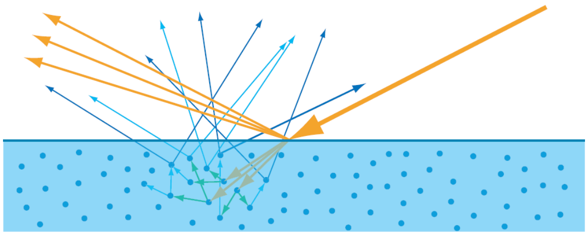
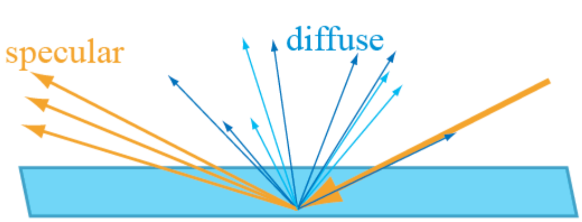
that occur when light interacts with geometrical irregularities of this size [21]



(a) Light is re-emitted at the surface of an object by means of subsurface scattering



(b) When shading a point we consider the specular and diffuse terms

Figure 1.4: Taken from [15]

Metals and Dielectrics

The proportion of scattering and absorption that transmitted light induces varies by material. There are two main categories of materials that we encounter day-to-day: metals and *dielectrics*. Metals immediately absorb any transmitted light, meaning their appearance is solely provided by the specular term. Most other materials are non-conductive, called dielectrics. These materials do allow for subsurface scattering, so both the specular and diffuse terms characterise their appearance.

1.3.3 The Reflectance Equation

WHERE?: [In contrast, pure air is an example of a homogenous medium that absorbs very little light. Therefore, light travelling though pure air is both unchanged in its direction, and amplitude. This proves to be very convenient for rendering as we often model light rays propagating through pure air; in these instances we can ignore the effect air may have as it will be insignificant.]

- Reflectance equation
- BRDFs
  - What makes a good BRDF (energy conservation and the reihtsz... reciprocity)
  - Fresnel Reflectance (https://link.springer.com/content/pdf/10.1007/s10891-011-0452-5.pdf)
  - Microfacet theory
  - Surface reflection
  - Subsurface reflection
- Lights
- HDR, tonemapping and gamma correction (display encoding)

Chapter 2

Methods

<Everything that comes under the 'Methods' criterion in the mark scheme should be described in one, or possibly more than one, chapter(s).>

2.1 A section

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Chapter 3

Results

<Results, evaluation (including user evaluation) *etc.* should be described in one or more chapters. See the 'Results and Discussion' criterion in the mark scheme for the sorts of material that may be included here.>

Fresnel effect shown; energy conservation shown; more artist options shown; show the specular lobe is more accurate using PBR approaches (page 338 of the real-time rendering book)? Take pictures from papers - reconstruct scene and show how PBR is close to the paper image and Blinn-Phong isn't.

3.1 A section

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3.1.1 A sub-section

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3.2 Another section

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Chapter 4

Discussion

<Everything that comes under the ‘Results and Discussion’ criterion in the mark scheme that has not been addressed in an earlier chapter should be included in this final chapter. The following section headings are suggestions only.>

4.1 Conclusions

Aliquam lectus. Vivamus leo. Quisque ornare tellus ullamcorper nulla. Mauris porttitor pharetra tortor. Sed fringilla justo sed mauris. Mauris tellus. Sed non leo. Nullam elementum, magna in cursus sodales, augue est scelerisque sapien, venenatis congue nulla arcu et pede. Ut suscipit enim vel sapien. Donec congue. Maecenas urna mi, suscipit in, placerat ut, vestibulum ut, massa. Fusce ultrices nulla et nisl.

4.2 Ideas for future work

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Appendix A

Self-appraisal

<This appendix should contain everything covered by the 'self-appraisal' criterion in the mark scheme. Although there is no length limit for this section, 2—4 pages will normally be sufficient. The format of this section is not prescribed, but you may like to organise your discussion into the following sections and subsections.>

A.1 Critical self-evaluation

A.2 Personal reflection and lessons learned

A.3 Legal, social, ethical and professional issues

<Refer to each of these issues in turn. If one or more is not relevant to your project, you should still explain *why* you think it was not relevant.>

A.3.1 Legal issues

A.3.2 Social issues

A.3.3 Ethical issues

A.3.4 Professional issues

Appendix B

External Material

<This appendix should provide a brief record of materials used in the solution that are not the student's own work. Such materials might be pieces of codes made available from a research group/company or from the internet, datasets prepared by external users or any preliminary materials/drafts/notes provided by a supervisor. It should be clear what was used as ready-made components and what was developed as part of the project. This appendix should be included even if no external materials were used, in which case a statement to that effect is all that is required.>