Creating Digital Photorealistic Material Renders by Observing Physical Material Properties

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Abstract

When creating materials in computer graphics, the most common method is to estimate the properties based on intuition. This seems like a flawed approach, seeing as a big part of the industry has already moved to a physically based workflow. A better method would be to observe real material properties, and use that data in the application. This research delves into the art of material creation by first explaining the theory behind the properties of materials through a literature review. The review also reveals techniques that separate and visually presents these properties to artists, giving them a better understanding of how a material behaves. Through action research, an empirical study then presents a workflow for creating photorealistic renders using data collected with these techniques. While the techniques still require subjective decisions when recreating the materials, they do help artists create more accurate renderings with less guesswork.

Keywords: computer graphics, physically based workflow, material properties, photorealistic rendering.
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1 Introduction

1.1 Background

When creating digital renders in computer graphics, the most common goal is photorealism. Today, most 3d computer graphics software have built-in, highly advanced raytrace renderers, capable of producing very realistic images. These renderers simulate how the real world behaves in terms of reflections, refraction, light bounces and diffuse shadows.

Achieving this kind of realism has not always been possible though. In the early days of computer graphics, most of the research went into actually figuring out how to produce the computer generated images. At the time, computers were still in its infancy, and the lack of computing power forced computer scientists to simplify the shading algorithms. This created limitations, since the algorithms for example assumed that both the light source and the camera were infinitely small, only located at single points. Phong’s paper on his shading algorithm acknowledges these limitations [1]. These early algorithms were not energy conserving either, meaning that objects could emit more light than the scene actually produced. They also separated specularity and reflection, where specularity referred to the bright specular spot produced by a light, and reflection was usually reserved for highly reflective materials such as metals and glass to reflect an environment [2]. Today, most advanced renderers have combined these material properties to a single “reflection” component, producing more correct results [3, 4]. Nonetheless, these early shading algorithms have since then become the industry standard, especially in real-time graphics, thanks to their low computational cost and appealing results. However, they are in no way physically correct [2].

The solution to this “faulty” approach is called physically based rendering (alternatively physically based shading). It aims to more accurately simulate how the real world behaves, mostly in terms of lighting and material properties. This also means accurate values, scales and measurements can be used in the application for highly predictive and photorealistic results. As computing power has increased over the latest years, the move to this kind of physically based workflow seems inevitable. For pre-rendered applications such as film and images, this step has already been taken with the raytrace renderers. Real-time graphics has not taken this step yet, but at the time of writing, many game engines are making the move to a physically based approach [5-7].

Even though physically based rendering aims to use objective data from the real world, the most common method of creating materials is to estimate the properties based on intuition instead of using real measurements or observations. This is highlighted by Lensch et al. who states that “the limiting factor in performing photorealistic or predictive rendering is nowadays (...) the material properties” [8]. Instead, a more correct approach would be to use methods that isolate and present the values of specific material properties to the artist.

1.2 Research focus

The previous method of estimating the material properties based on intuition leaves a big margin for error in the appearance of the material. In a physically based workflow, this method seems outdated. To get correct outputs, the inputs need to be physically correct as well. This means not only that the scale is correct, and that real light units are used, but also that materials have the correct reflection, glossiness, diffuse color, and so on. This is something most artists seem to forget, especially those new to
physically based rendering. To combat this guesswork in computer graphics, this study will focus on how artists can observe real material properties.

But before being able to fully comprehend how to observe these physical properties of materials, one must have knowledge of how light and matter interact. This is why the next chapter of this paper will focus on explaining the philosophy behind the most important material properties.

Following this, methods of measuring and observing material properties will be presented. In a perfect world, artists could objectively measure all material properties and feed them directly into the computer graphics software. However, Matusik et al. mentions that while it is possible to objectively measure material properties, the methods are very difficult to apply in practice [9]. Instead, more subjective observational methods can be used, but with lower accuracy. Available techniques of both measuring and observing material properties will therefore have to be evaluated as to how viable the methods are in a professional artist’s workflow.

When the methods have been evaluated, any appropriate methods will be selected for the empirical study. These methods will be used as part of a workflow, to test how they can help when creating physically based materials. The empirical research will in other words consist of recreating a selected set of materials by collecting data from real materials using the found methods. The analysis of materials and recreation in computer graphics may imply that total realism is the goal of the research. While this is partly true, it needs to be pointed out that this research is of an artistic nature. This means subjective decisions will have to be made, since no workflow in computer graphics uses a perfectly simulated world. There will always be minor differences in lighting calculations, shading algorithms and such. However, the focus of the research is to get the most realistic materials possible. This means some artistic freedom will be taken to get the renders as close to the photorealism as possible, without worrying that the actual pixel values correspond to photographs of the materials.

The study will also reveal how the observation methods hold up against different types of materials. Each recreated material will be compared to photos of the real material to determine if the methods are sufficiently accurate. A description of the entire workflow will be presented in the empirical research chapter. After examining and recreating the materials, suggestions of how to best use the methods will be proposed.

1.3 Research objectives

The overall aim of this research is to demonstrate how to create photorealistic material renders in computer graphics by observing physical material properties. The goal is to produce awareness of how materials behave, and how to simulate them accurately. This research will show how artists can use methods of observing real materials to help recreate them in computer graphics. These methods will give artists a good starting point, from which they can alter the materials to fit a specific scene if necessary. Hopefully, since the materials will be physically based, they will be not scene specific, but instead generalized to work in most scenes.

Summed up, the objectives of this research are to:

1. Gather information about how light and matter interacts in the real world.
2. Explore methods for studying the properties of physical materials.
3. Examine a selected set of materials by using the found methods of observing material properties.
4. Render photorealistic images and compare them with photos of the physical material.
1.4 Value of this research

By using methods of observing materials, artists can get a better feel for how a material interacts with light. There is also a possibility that these observations reveal otherwise overlooked or misunderstood material behaviors to artists, due to the previous incorrect non-physically based workflow that has been used for decades. The artist will still have some freedom in deciding the final look of the material, since the data the methods present should simply be used as a reference of how a material behaves. The material could then be altered to fit a specific scene if needed.

If the recreated materials would follow the properties of their real life counterpart, it would allow for renderings to be more realistic. They would more correctly respond to the lighting condition of the scene. Another benefit of this approach is that the same material could be used in many different scenes, and it would still produce correct results, provided that the scene follows relatively physically correct settings. This also means that artists could collect a generalized material library with materials based on physical properties. This in turn would allow artists to save time that they would otherwise would had spent on recreating materials they already created numerous times before.

2 Theoretical background

To provide a background on the theory behind material properties, previous literature were read. The literature review will be presented here as a theoretical background, and consists of two parts. The first part investigates the interaction between light and matter, and aims to explain the theory behind the most important material properties. It also reveals what has been written about material creation in the past. The second part of the review describes previous methods of observing materials, both measurements and subjective observations. Later, some of these methods would be used in the empirical study to help in the recreation of the materials.

To find this information, thorough searches of online databases were made, and previous studies on material properties were collected. The Discovery search service from the University of Gävle was extensively used to collect search results from several databases. Keywords that were used consisted of for example: “physically based”, “materials”, “material properties”, “realistic”, “rendering”, “measuring” and “observing”, as well as more specific ones such as: “reflection”, “specular”, “anisotropic”, “refraction”, “diffuse”, and “subsurface scattering”. The primary source of literature came from the ACM digital library, where many conference proceedings were found from previous SIGGRAPH events. Along with these, another 20 something sources; journal articles, books, video conferences, and theses were found and evaluated. Some sources were also found by looking at what had been previously referenced. The books that were found covered a broad spectrum of topics, thus only the ones related to material creation and rendering were read. Furthermore, many journal articles found were only somewhat related to the research subject, so these were more loosely read.

2.1 Explanation of material properties

To understand how materials can be measured or observed, one must know what happens when light interacts with an object. This section will try to explain some of the physics of light, and how its properties relate to computer graphics.

In the real world, when light hits a surface it interacts with it in two possible ways: scattering and absorption. Absorption happens when the particles in a material absorbs energy from the light, changing the light’s intensity. Depending on the
material, the absorption also happens on specific wavelengths. This is what gives objects their color [10-12].

Scattering on the other hand describes how light changes direction, but not intensity. The easiest and most recognizable form of scattering is called reflection. It basically describes a mirror image, where the incoming and outgoing light angle is the same. Very few objects are reflecting perfect mirror images though. Instead, small bumps, or micro facets, in the material are causing the reflections to appear blurred. At a microscopic scale, the actual light reflected in each bump is still a mirror reflection. However, at a macroscopic level, the resulting reflection is an average of all the light reflected in the different bumps. This means the material’s microscopic roughness determines the glossiness of its reflection [8, 10-12]. There may also be bigger bumps and imperfections in materials. These are also affecting the reflection glossiness, but should instead be simulated using bump mapping or displacement, or even modeled.

An interesting behavior of reflections is called Fresnel reflectance. It describes how the amount of reflection increase rapidly as the angle of incidence, that is the angle between the surface normal and the viewing direction, increases. Basically this means that a material may have almost no reflection when looking straight at it, but when the object is at an angle the reflections are highly visible. The effect is most noticeable in non-metals (also known as insulators or dielectrics), where the reflection at 0 degrees (relative to the surface normal) is quite low. Metals (also known as conductors) do have this Fresnel reflectance as well, but their 0 degree-reflection is usually high, so it is not as visible. If one were to plot out a reflection amount vs. angle of incidence graph, the Fresnel effect for most materials would create a curve that was more or less constant at the angles 0 to 45. After this, and up to about 75 degrees, the reflections would start to increase. From 75 and up to 90 degrees, the reflections would increase sharply, hitting 100 percent reflectivity at the end [10-14]. These types of reflectivity vs. angle of incidence curves can be found for many materials on refractiveindex.info, a website dedicated to measurements of materials. By looking at the reflection calculator’s non-polarized curve on the site, artists can see how the real material behaves, as shown on figure 1 [15].

Dielectrics and metals behave a bit differently when it comes to Fresnel though. In dielectrics, the curve follows the previous description, where the reflectance is rather constant before increasing when reaching around 45 degrees. Metals on the other hand usually dip down slightly before reaching 75 degrees, after which they start to increase sharply (see figure 1). To simulate this in computer graphics, Håkan “Zap” Andersson suggests increasing the Fresnel IOR (index of refraction, the value governing the reflections at different angles of incidence) to values around 25 or 50 [16]. He demonstrates this using Mental Ray’s mia_material, which in 3ds max’s material editor shows a small reflectivity vs. angle of incidence graph. Using this graph, artists can match the IOR to the graphs found on refractiveindex.info. The empirical research would later show that Andersson’s IOR values of 25 and up were too high for most materials, and that values around 3-10 more correctly matched the graphs.
Figure 1: Shows the reflectivity vs. angle of incidence graph from refractiveindex.info. Left: the dielectric polystyrene. Right: the metal chromium. Note the dip on the right before the curve sharply increases.

In contrast to reflection, the other form of scattering is called refraction. It refers to the behavior where light penetrates into the object. In the case of transparent materials, most of the light is able to travel into, and escape through the other side of the object. Some of the light’s intensity is lost through absorption however when interacting with particles inside the material. In opaque, dielectric objects, this refraction also occurs, but most of the light is never able to travel through the entire object. Instead, the light hits particles inside the material and is again scattered onto a new trajectory. This light may in turn hit another particle, and continues to do so until either it has escaped back out of the object or has been fully absorbed. In the former scenario, the light that escapes back out from approximately the same point as the entry point is in computer graphics called the diffuse term (see Figure 2). As previously stated, the absorption during this scattering determines the material’s color. For example, a green object has absorbed most red and blue wavelengths before re-emitting the light. In the case of metals, some of the light still penetrates the object, but it immediately gets absorbed. This is the reason why metals have no apparent diffuse color. Instead, the light reflected by metals can have its wavelength altered. In metals such as gold or copper, this is what gives them their characteristic colors. In computer graphics, this should be simulated using a black diffuse color with a colored reflection. Non-metals should be treated the opposite way, since they re-emit colored diffuse, but have monochrome reflections [10-12, 17].

The light re-emitted by this refractive scattering never happens exactly at the entry point for the initial light; instead it happens over an area, as shown in Figure 2. If the light hits near the edge of an object, or if the object is thin enough, the light may bleed out from other sides. This is the reason why special subsurface scattering shaders were developed. However, these are normally only used for special materials such as skin, milk and marble. In the real world though, all dielectric materials exhibit some form of subsurface scattering. Here, scale is important. At a microscopic level, this scattering is visible in many materials. When zoomed out however, this subsurface scattering is negligible, since the light travels over an area smaller than a pixel [10-12, 17]. Hoffman therefore suggests such materials should be represented with a simple diffuse color [11, 12].
2.2 Methods for measuring and observing material properties

There are several methods of measuring real-world materials. Many professional studios today have some form of pipeline for acquiring material data [11]. One group of devices for capturing entire BRDFs (bidirectional reflectance distribution functions) is called gonioreflectometers. These devices use cameras and lights to measure how materials behave at different angles. This type of research however is often only used to improve shader algorithms [2, 9, 18, 19], and the data never reaches the artists who are recreating the materials. Most of these methods are also highly advanced and expensive, so artists cannot simply use the devices themselves. Lensch et al. claims that accuracy plays a key role when doing these types of measurements. This means a highly controlled environment is needed, as well as high quality CCD cameras and lenses since disturbances such as camera noise is unwanted [8]. There has also been some research on capturing the texture of objects. The techniques Dana et al. used in their research were also using this kind of controlled environment. They too used high-end cameras and lenses together with robotics to capture images of materials [20].

A method for measuring the reflection amount and diffuse color is shown by Nayar et al. The method takes advantage of light’s ability to act as a wave, allowing it to be polarized in a certain direction. The method they present uses only a camera, a light source and two sheets of linear polarizing film. If a sheet of linearly polarized film is held in front of a light source, the emitted light can be forced to be polarized in a certain direction. If the sheet makes the light, for example, horizontally polarized, another sheet of film can be held in front of a camera, and rotated so it is vertically polarized. This will only let through vertically polarized light, and block all other polarizations. This means one could selectively block the emitted light from the horizontally polarized light source. The key here is that specularly reflected light preserves the polarization of the light source, while diffuse light does not. The light that has been scattered inside an object will have had its polarization randomized before being reemitted. Their method too used special cameras and lenses, since they needed the accuracy for their measurements [21].
If very accurate measurements are not needed, it is possible to use the same polarization technique, but instead use a consumer digital camera to capture the data. With the help of a similar setup as Nayar et al., Hable shows a cheap and easy method for separating the diffuse and specular (reflection) component from photographs. A sheet of polarizing film is held in front of a light source, shining polarized light on an object. A camera is set to capture images of the object, and it too has a sheet of polarizing film in front of it. To separate the specular from the diffuse, two images need to be taken: one where the two sheets are aligned in the same direction, allowing the reflected light to hit the camera, and one where one of the sheets is blocking the polarized specular light, only leaving the diffuse to hit the camera. These images will then have to be composited together to form the final specular and diffuse images. For the diffuse image, the photo where the specular light was blocked only needs to be multiplied by two. The specular image needs to subtract the photo of the blocked light from the one with specularly reflected light. The result is two images, one with almost only specular reflections from the light, and one with almost only the diffuse color of the object [22].

This method has some flaws, in that the precision is not as high. For example, some left over specular and diffuse light can be seen in the images where there in theory should be none. But this technique can give artists a good general overview of how a material behaves. It is also very accessible for artists, since it is cheap and easy to perform. The resulting images cannot be used to get values directly from though, so they should instead be used as reference images for material behavior [22].

This method allows artists to determine not only the diffuse color and reflectivity of a material, but also the glossiness of the reflection. Bigger bumps are also seen in the specular image, so artists can with some training make out the structure of the material. Also, by taking multiple photos at different angles, the Fresnel effect can be visualized and be used as reference.

3 Research methods

For the research objectives to be achieved, a number of methods had to be used. The first two objectives (Gather information about how light and matter interacts in the real world, explore techniques for studying the behaviors of physical materials) were accomplished with the literature review, and were presented in the previous chapter. The last two objectives, objective 3 and 4, consisted of finding and measuring materials, and finally to recreate them in the computer graphics application. This was done as an empirical study, a sort of action research approach where the previously found observational methods were used to form a workflow. Using these methods, a number of materials were recreated and rendered. At the end of the research, both the resulting materials and the workflow itself were analyzed. The final rendered images were compared with photographs of the real materials, as this acted as support and gave proof for the conclusions that were made.

The previous chapter, the theoretical background, presented the results of the literature review. Part of it revealed methods of measuring and observing physical materials. For the empirical study, one of these methods was used. This chapter will not explain how this method was used in the workflow however, as that will be presented in the empirical research chapter along with the rest of the workflow. Instead, it describes how the different methods were evaluated, and how it was chosen which method was going to be used in the empirical study. Finally, the methods chapter will cover which materials were chosen to recreate, as well as the computer graphics software used in the research.
3.1 Data collection and methods

After reviewing the sources, one thing stood clear. Most of the previous literature spoke of highly advanced methods of measuring material properties. These methods were almost solely dedicated for the scientific use of refining shading algorithms [2, 9, 18, 19]. The focus of this project however is artistic, and these methods would not fit well into an artist’s workflow. Since the project is based on an action research approach, only methods that could be used in a real workflow were selected. This meant they had to be easily accessible, and not too costly in terms of either time or money. In contrast to the complicated methods of measuring actual properties of materials, Hable’s [22] more subjective method followed these requirements, and was found to be appropriate for this research. Instead of getting raw data, it produced images that would help the artist observe different material properties. The method would in other words produce data that would serve as a reference of how materials behave. This method seemed promising, and was therefore chosen to serve as the main technique used in the empirical research. A detailed description of this method, as well as how it was used in the workflow, is found in the next chapter – empirical research.

The empirical research was performed as an action research. This meant the “method” of the research was simply trial and error. Before beginning the empirical research, a rough summary of what needed to be done was made. This included for example what problems it needed to solve, what material properties had to be observed and what the end result would be. The actual workflow was shaped around these objectives, refining the methods as it went along.

For the empirical research, a number of materials to analyze and recreate were chosen. When compiling the list of distinctive materials, the website cgtextures.com was used as a source of material classification. Their categorization of the different types of wood, rock, metal, plastic and so on seemed to cover all the important material types [23]. Not all categories were selected though. The materials that were of interest were only a single type of material. This meant, for example, that rocks covered in dirt or moss did not represent how rock materials behave. In this way, only the “base” materials were selected. Not all materials from the list were recreated either due to the limited timeframe of the project. In the end, this did not affect the outcome of the project, since the workflow had already been demonstrated.

The materials that were selected also had to be recreated in a computer graphics application. The software that was used was Autodesk 3ds Max 2014, rendering with Chaos Group V-Ray 2.4. Since V-Ray is a physically based raytrace renderer, it allows for highly realistic and correct renders. The renders were made from a physically based standpoint, meaning that real-world units and scale were used in the application. The camera settings also corresponded to that of the real world. This thesis however, tries not to focus on the parameters of the specific program. Since most renderers and computer graphics applications have a similar set of tools and parameters, the results of this research will be applicable in most other computer graphics programs.

3.2 Data analysis

Since the study researched a workflow, it was natural for the process to be self-correcting. If a problem came up, the workflow was altered to solve it. For example, if the renders constantly came out too bright, the cause was searched for and corrected. In the end, this produced a final workflow that had undergone a kind of evolution, constantly improving and adapting to produce better results.

To verify the validity and correctness of the renders, they were compared to real photographs of the material. To do this, the environment in the rendered images had to be the same as in the photos. This meant a HDR (high dynamic range) image had to be taken and used as environment in the renders. This revealed any differences between
the images. For small changes, the material properties were often tweaked to produce more realistic results. But, as stated above, if patterns arose of the images constantly being for example too dark or too bright, the scene settings were slightly changed.

While the aim was to create the most realistic materials possible, current software cannot produce perfectly recreated renders. This has to do with algorithms being simplified for efficiency, or possibly being outright incorrect, which is something that is out of the artists’ control. The scene setup and lighting condition, even though they were as closely recreated as possible, still produced slightly different results from the real world. For this reason, some margin for error was taken into consideration. This allowed the renders to get the overall material appearance correct, but not the actual pixel values when comparing with the photos. In the end, it would still produce photorealistic results. When the materials were seen as finished, they were saved into a material library for future use.

4 Empirical research

As a summary of the previous chapters, the literature review had revealed a suitable method for observing physical material properties. To test the usefulness and validity of the method, a workflow revolving around it was constructed. A number of real materials were collected and observed using the method. This produced data that would serve as a reference of how the materials behaved. The materials were then recreated as closely as possible using the previously collected data. The information that will be presented for the empirical research chapter will therefore be the final workflow that was used. The different steps of the workflow will be presented in depth in different sections, explaining what was done and why. Finally, the next chapter – the results chapter – will show some rendered images of the recreated materials. The results will also show photographs of the real material to compare with the renders.

The overall structure of this chapter will present the workflow in the order it was performed. In this way, the reader may follow the entire process, from start to finish. This chapter has also been structured to separate the two parts of the empirical research – analyzing materials and recreating them – into different subsections. Also, in this chapter, only the final workflow is presented. It aims to present the constructed workflow of this research without analyzing it. The analytical portion of this paper takes place in the discussion chapter. Instead, this chapter clearly describes how the empirical study; the workflow created through the action research, was performed.

4.1 Observing material properties

The goal of the empirical research was to recreate materials as closely as possible. To do this, Hable’s method of separating specular from diffuse was used as the main source of material data. A collection of objects made out of different materials was collected. To test the generality of the method, a wide range of materials were chosen. Different categories such as paper, wood, metal, and plastic consisted of several types of materials: glossy, matte, rough, smooth, worn and new. The list grew to around 60 materials at the time of writing, but could be expanded for future research. About 20 of these materials in varying categories were not analyzed since appropriate material samples could not be found.

For the polarization method to work, there were a few requirements, or guidelines, that the material samples had to meet. The first was that the samples preferably should be flat. This would allow the specular reflection of the light source to show up as a spot, instead of curving around an uneven surface. If no flat object could be found, spherical or cylindrical objects were the next best thing. These proved a bit more difficult to estimate the properties, since the reflections of the light were
distorted and squeezed onto a small area. The flat, spherical or cylindrical objects allowed the research to focus on the material properties, instead of having to model an accurate surface to get correct reflections. The objects also had to be large enough to fit the entire specular spot onto. Since glossy materials have narrower specular spots than matte materials, it meant the sample objects could be smaller. Matte objects on the other hand often filled the entire field of view of the camera.

The amount of composite materials, that is materials made out of several different materials, was also minimized. Some were still collected, such as asphalt and concrete. These proved to be very hard to estimate the reflections of, since they consisted of many small pieces that reflected light differently. They also went against another guideline, one that said to minimize rugged surfaces. Large bumps in a material would in effect conflict with the first guideline, saying that the objects should be flat. The smaller the bumps were, the less of a problem this was. The asphalt and concrete both went against this, making them even more difficult to recreate. The final guideline was to use “base materials”, meaning that objects, for example a rock covered in mud, could not be categorized as a rock, but instead should be placed in the appropriate category for dirt or mud.

Once the samples had been collected, the analysis and recreation of them in the computer graphics application could begin. The first step in the workflow was to use the polarization setup to acquire diffuse and specular of the different materials. A controlled environment was needed where only a single light source could be used. Otherwise, the sample objects would get specular reflections from multiple lights. For this reason, a small room was sealed off from all outside light. In addition to this, a black cloth was put over the surface the material samples were to stand on. This would minimize light bounces that would otherwise illuminate the objects. In this room, a setup using a single directional lamp, a camera, and polarizer film was built. The camera that was used was a Canon EOS 600D, coupled with a Nikon 28mm f/2.8 AI-S lens. To minimize lens flares, the aperture was set to f/22, and ISO was kept at 100 to reduce noise. The exposure was adjusted with the shutter speed, which was set to 1,3s for the final shots. The light used was a common 25W tungsten light bulb with a directional lamp shade, and so the camera’s white balance was set to tungsten mode. The camera was placed on a tripod, and the light was clamped onto a steady surface to get consistent results. To avoid alignment problems later when compositing the photos, a remote shutter was also used.

In total four photos of each material had to be taken: two at a low angle of incidence, and two at a high angle of incidence, as shown in figure 3. This would reveal the specularity of the materials at different angles, showing Fresnel reflections in effect. Due to the inverse square law of light, the distance between the light and the object had to remain constant, even when the position of them changed. Otherwise, the intensity of the reflections would change between the two angles. This would in turn provide unreliable results, which could not have been used to estimate the Fresnel effect. The distance between the object and the light source was therefore carefully measured to get the most accurate results. The Fresnel effect for the two angles is shown in figure 4.

One sheet of polarizer film was positioned securely in front of the camera. This sheet would remain constant, not changing the rotation of the polarization. Another polarizer sheet was held in front of the light source, as close as possible to avoid letting out unpolarized light. This sheet was not constant, as the method required two photos of opposite polarizations. This sheet was positioned and rotated manually by hand. This meant perfect polarizer alignments were not possible. To minimize the amount of unblocked light reaching the camera, the built-in histogram on the camera would show when most of the light was blocked. This still let some light through, but it was an inconsiderable amount, so it was easy to ignore. This topic is examined closer in the discussion chapter.
Each material sample was placed on the flat surface in front of the camera. For relatively thin materials this worked well. However, some objects were too large to reflect the light. For example, the flat surface on the underside of a large pot would be too high up to fit the camera’s field of view. In this case, the surface on which the samples stood on was lowered. This allowed the camera and light to remain unchanged, while still being able to analyze both small and large objects.

Before taking the photos, the camera was pointed directly at the specular spot produced by the light. Here it helped to use a highly reflective material since it was easy to see the reflections. The lamp was also rotated towards the same point, producing the highest specular reflection possible.

When the calibrations had been finished, the real photos could be taken. First a material was placed in front of the camera. A sheet of polarizing film was held in front of the lamp, aligned to let the light hit the camera. Using the remote shutter control, a picture was taken in this configuration. The polarizer was then rotated 90 degrees to block the reflected light to hit the camera, and another photo was taken. Several materials were photographed in a row this way before changing the position of the light and the camera, to photograph them at the other angle of incidence. The same procedure was done once again in the other configuration.

The images then had to be composited together. To do this, following Hable’s advice, the calculations should be done in linear color space. This can be done in many applications, but for this project The Foundry’s Nuke 6.3 was used. The two images of each angle were taken into the application. For the diffuse images, the photos where the specular reflection was blocked were used. They were simply composited on top of themselves with the “plus” blending mode. For the specular images, both the photos of the blocked and unblocked light were used. The photo with the blocked light was composited over the unblocked one with the “minus” blending mode. The resulting diffuse images were usable right away, but the specular images needed some tweaking. Using a perfect method to separate reflections would in theory produce completely monochrome results when analyzing dielectric materials. This was not the case though with the method used in this research. The specular images still had some diffuse color left from the object, as seen in figure 5. This made it hard to estimate the reflectivity of the material, so the specular images were made monochrome. While this was a simple workaround, it proved to suffice when
analyzing objects without colored reflections. The only material that this became a problem for was bronze. This topic will be discussed further in the discussion chapter. How the materials were recreated is revealed in the next section.

Figure 4: Shows the specular results of the polarization technique for two analyzed materials – rubber and Styrofoam. Note the Fresnel reflections on both materials.

Figure 5: Shows the diffuse and specular results for painted metal. Note the reflection of the lamp in the diffuse image and the non-monochrome uncorrected specular image.
4.2 Recreating the materials

After analyzing the materials, they could be recreated in the computer graphics application, in this case Autodesk 3ds Max 2014. A test scene was built in the application using the same measurements that were used in the real polarization room. A virtual camera and light were then placed in the correct positions. In the scene, the camera was set to use the same exposure settings as the real camera, and the light was set to 25W with approximately the same color temperature as the real light. However, the exposure was still not correct, since in the real photographs the polarizer films blocked some of the light. The amount of blockage was unknown, so the virtual exposure had to be adjusted manually until it looked correct. This was adjusted even more after analyzing some materials to get a better exposure. To get correct reflections of the materials, a rough replica of the sample object was modeled and placed in the correct position. This would allow the reflections to curve around the object in a similar way that the real one did. The actual geometry of the models did not have bumps, as that was solved using bump mapping. Keeping in mind that these materials could be reused, these smaller bumps were ones that would appear on all similar materials. Bigger dents that were distinctive for only this object could have been modeled, but mostly they were not, in order to save time.

With the test scene complete, the material’s properties could now be altered. The first step was to decide what type of material to use. The literature review revealed that all dielectrics exhibit some amount of subsurface scattering (shortened SSS). However, since the effect is seen only at a microscopic level in most materials, a normal material (in this case a VRayMtl) was used for the majority of the dielectric materials. To see if an object needed a special SSS material though, a diode light was held against the objects. If it revealed that the light did indeed shine through the object, a SSS material would have to be used. Materials such as marble, porcelain, paper and some plastics showed off this SSS effect, so these materials were made using VRay’s VRayFastSSS2 material. This type of material had the same properties as the normal material, only with the ability for light to scatter inside objects. This allowed the workflow to remain the same for all types of materials. The only difference in the workflow when creating a SSS material was to estimate the scattering properties at the end when all the other properties had been set correctly. Measuring these scattering properties objectively would be preferred, but in this project they were simply estimated by looking at them.

The first thing to be recreated was the reflectivity of the materials. Here the images produced by the polarization technique were used as reference. The specular images had most of its diffuse color removed, causing it to turn almost black except for the specular spot. To match the image, the material was therefore first set to have around 3-5/255 in diffuse color. After this, Fresnel reflections were enabled, and the IOR was simply set to an arbitrary value that could still be plausible for the type of material that was being created. For dielectrics, this value was usually left at the default 1.6, but for metals this was set to around 5 to 20. These values were only used get the Fresnel effect somewhat right, and were changed later.

When trying to match the reflectivity and glossiness, the high angle of incidence photo was used first. The reflection and glossiness are heavily linked to each other, since matting a reflection spreads it out, making it less intense. After testing several materials, the workflow revealed the best method was to add some reflectivity, around 128/255, just to get some reflections, and match the glossiness before the reflection amount. To do this, the glossiness value was set to something that looked right. The image was rendered and saved out, and together with the reference image, was opened in an image editing program. The rendered image was put on top of the photo, and was toggled on and off. This easily showed any differences in the glossiness of the images. Back in the application, the glossiness was tweaked, and the same process was repeated until there were only minimal differences. Next, the same was done for the
reflectivity. The value was adjusted to something that looked correct. A rendered image was then compared to the actual photo of the material, and any differences were corrected.

Next the Fresnel had to be changed. The camera and light were placed in the low angle of incidence position. Here the IOR was simply increased or decreased until the reflectivity matched with the reference photo. The same comparison technique was used here to get the correct value. When recreating metals, the IOR was altered to match the reflectivity vs. angle of incidence graph with the one found on refractiveindex.info.

Also at the low angle of incidence camera angle, any irregularities such as scratches and bumps were seen in the photos. These were simulated using bump mapping. In some materials, there were irregularities in the amount of glossiness or reflection. This meant a texture had to be used in the correct slot. In 3ds Max, there is a built-in map type called composite, which supports texture layering with blending modes. This was used extensively for bump, reflection and glossiness maps. For the latter two, a base color was put in the undermost layer that had a luminance value that corresponded to the values that had been found when comparing the renders to the photos. On top of this, textures could be added with various blending modes, building up the final texture while still keeping the material modular. After matching the bump, glossiness and reflection of the material, the diffuse color was changed. The diffuse image from the polarization technique was used as reference here. However, the actual color in the image was not usable directly in the application since the image was slightly underexposed and tinted by the white balance settings. It was used more as a reference of the structure and texture of the material. The color of the diffuse was set to a rough estimate of the real color. To finalize the material, the diffuse, reflection and glossiness had to be compared to photos of the real material in real environments.

To see how the materials behaved in a real environment, a HDR probe had to be captured. This would allow the virtual scene to be lit by real-world lighting. Using a highly reflective sphere, 7 exposures from 4 different angles 90 degrees apart were shot. Reference photos of the materials in the same position as the reflective ball were also taken using the same settings. This would allow the photos and the rendered images to have similar lighting and reflections. The multiple exposures of the reflective ball were merged together in Adobe Photoshop CS6 to form 4 HDR images. Those images were then taken into HDR Shop 1.0, where they were unwrapped into a Latitude/Longitude map, effectively stretching the sphere into a quadrate. The 4 stretched images were then taken back into Photoshop where they were stitched together to form a single tiling environment texture, ready to be used in the application.

Back in 3ds Max, the HDR image was set as the light source. The half-finished material was placed in this environment, and the camera was positioned as it had been when taking the reference photos. By rendering an image here, the differences between the photos and the recreated materials became apparent. While the general look of the materials were close to the photos, most materials required some additional tweaking, such as increasing the reflections, setting the correct diffuse, and lowering the glossiness. After these minor changes were made, the materials could be seen as finished. As a final confirmation of the behavior of the materials, the real material samples were examined. They were looked at from different angles, seeing how they reflected light. The same was done to the virtual materials, rendering them in different angles. Generally, this did not reveal any new data, so these renders were simply done as a confirmation that the materials behaved correctly in different conditions. When the renders produced satisfying results, the material was done and put into a material library.
5 Results

In this chapter, some of the final rendered images are presented in the figures 6 through 11. Each figure consists of four images showing a single type of material, and follows the same basic structure. In the top left corner of the images, a reference photo of the real material is shown. The top right corner shows a render of the recreated material in the same camera angle as the reference photo. The bottom left corner of the figures shows the rendered materials in a different angle. In the bottom right corner, another render of the material is shown, but in a different environment.

The rendered images are shown here without any post processing effects; these are the raw renders of the materials.

Figure 6: Shows a photo and renders of painted metal.

Figure 7: Shows a photo and renders of brushed metal.
Figure 8: Shows a photo and renders of bronze.

Figure 9: Shows a photo and renders of glossy porcelain.
Figure 10: Shows a photo and renders of matte porcelain.

Figure 11: Shows a photo and renders of PVC plastic.
6 Discussion

In this chapter, the results of the empirical research will be discussed. It will start off by examining the workflow that was found. The methods used will be argued for or against, and alternate solutions may be proposed. General recommendations relating to the workflow will also be proposed here. It will also discuss how the methods used held up when analyzing different types of materials.

Following this, the outcome of the workflow will be discussed. Did the workflow produce usable results, and were they photorealistic? Here the rendered images will be compared to the photographs. Possible connections, patterns, and differences will be looked for and presented at the end of this chapter.

6.1 Workflow

When researching the workflow, several topics of discussion came up. These were both big and small points, from things that could change the outcome of the project, to things that simply need clarification. This section will cover these topics in chronological order, starting with the polarization technique. Since this method was the main source of input data, it highly influenced the final result. While the precision of this method was not perfect, it still produced results that were very useful in the workflow.

The effects of these imprecisions were noticeable in the resulting diffuse and specular images. In highly reflective and glossy materials, the specular reflection of the light was still seen in the diffuse image, as seen previously in figure 5. This is likely due to a combination of different factors. Firstly, since the polarization films were not perfectly aligned, some light still made it through even though they should be blocked. However, even though if they would be perfectly aligned, some of the light would likely still have made it through. This would be because the sheets of polarizing films are not perfectly manufactured, along with the light changing its polarization somewhere along its path. But the leftover specular reflections in the diffuse images were only seen in glossy materials, meaning the reflections were only covering a small area of the image. This meant the diffuse color and texture was still easily discerned, making the images still usable. Another issue with the diffuse image was that black materials such as leather, rubber and black plastic usually showed light dispersion from the polarization films, creating faint shades of red and green over the image. This too was easy to ignore, since it only showed up on materials with black diffuse colors. This dispersion should logically have showed up on the other materials as well, but maybe since light is additive, it did not show on brighter materials.

The specular images were not perfect either. To get a specular image, it had to be composited by subtracting the blocked light image from the unblocked light image. Theoretically, this is the correct approach. But because of the camera optics, there is also bloom, glow and lens flares produced when the unblocked reflected light is allowed to hit the sensor. The blooming was also emphasized by the sheet of film in front of the lens, adding yet another element that diffuses the incoming light. This was one of the few big issues with the technique. Because of the blooming, the actual intensity and glossiness of the specular image was hard to estimate. Since the blooming effect could not be simulated correctly in the computer graphics application, the rendered images never produced the glowing effect the photos had, making them hard to match. After analyzing several materials, some patterns were detected that would help treat this issue. Since matte reflections spread out the reflection spot making it dimmer, it means that the issue of blooming due to overly bright pixels only became apparent on glossy materials. It also showed that the blooming generally only occurred on very reflective materials such as metals, some paints, and some plastics. This narrowed down the problem to only a few materials, and for the materials where it did become a problem; the reflectivity and glossiness was known to be high, making
it a bit easier to estimate. An alternate method of dealing with this problem would be to shoot multiple exposures of the materials. One exposure would overexpose the specular spot, but get good exposure on the diffuse image. Another set of images would underexpose the diffuse, and instead get good exposure on the specular image. This would reduce the issue with the blooming, but instead it would add another step when recreating the materials, since the virtual camera would have to change settings between matching the diffuse color and the reflectivity.

As shown in the results chapter (figure 5), these specular images had residues from the diffuse color. Theoretically, dielectric materials should only show monochrome specular images. However, this was not the case with the images produced by this technique. The blooming was probably the reason why the composited specular image still had some diffuse color, since the calculations became incorrect because of the extra brightness from the bloom. Because the diffuse color made it hard to estimate the reflections of materials, the specular images were desaturated. This workaround proved to be acceptable for most materials. But for materials with colored reflections such as bronze, another solution was needed. No other technique was used, and so the same workflow was used for the bronze material. As an added step after matching the other parameters however, was to add some saturation to the reflection. This would lower the luminance of the reflection color, so it simultaneously had to be slightly brightened. Renders were then made to compare with the reference photo, and any differences were corrected. An alternative to this method could be to photograph the material in a completely white environment. This would presumably show any colored tinting of the reflection, as well as the added benefit of showing Fresnel reflections in effect if the object was curved.

In this project, a reflective sphere was used for capturing a HDR environment. An alternate technique would be to capture multiple angles using a wide angle lens and panning the camera around. Whatever the method used, the result should be an environment image capable of being used for lighting virtual scenes. Both of these techniques have its pros and cons. One issue with the one used in this project is the need for an almost perfectly reflective sphere. Any dents and scratches will affect the unwrapped result, and will make the environment appear warped. While the sphere used was not entirely perfect, it was good enough to be used as an environment. The main goal was after all to get correct lighting information from the image, and as a secondary goal to get perfect reflections. For these reasons, the HDR capture technique sufficed. Also, by using this technique to capture a HDR probe, the reflection of the camera was seen on the sphere. Generally when capturing HDR’s for use in computer graphics this is unwanted. However, when shooting the reference images of the materials, the reflection of the camera would appear on the objects as well, making this HDR capture technique have a minor advantage over the other one using the wide angle lens.

When capturing these images, the decision was made to shoot them in a controllable environment. This meant the HDR could not be taken outside where the lighting conditions change. Even on a cloudless day, the sun’s position in the sky would change while shooting the reflective ball and all the material samples. There also wouldn’t be any chance of replicating the exact conditions if more materials were to be analyzed at another time. Instead, the HDR probe was shot inside and at night, only illuminating the scene with controllable artificial lights. This solved all the issues relating to changing lighting conditions.
6.2 Outcome

The result of this research is a workflow capable of producing realistic materials. While the materials do not build on actual measurements, they are made with references that help artists estimate the properties closely. But by comparing the rendered images with photographs of the materials, there are still minor differences that can reveal which one is the real image. One thing that all renders showed was a lack of contrast in the reflections from the environment. The lighting was also slightly different, even though the HDR was captured in the same environment. This suggests that somewhere the calculations differ from the real world. That may lie in the camera’s color calculations when saving out the images, the calculations when merging the different exposures, or it may lie in the computer graphics program’s technique of reading the HDR file when converting it to lighting information. It may also be the fact that the reflective sphere was not perfect and that the Fresnel effect darkened the image. Whatever the cause, it produced similar but not identical results as the reference photo.

Another telltale sign of almost all computer graphics renders, not only the ones produced for this project, is the lack of imperfections and minor details. Very few objects in the real world are perfectly clean or uniformly colored. While this project aimed to add details that were characteristic for the material that was being recreated, one of the things that separate the renders from the photos is the lack of dirt and wear on the objects. For example, the bronze material showed quite distinct dirtiness and oxidation on the photographs, none of which the renders had. For increased realism in renders, these sorts of details should be added. The renders resulting from this project are still realistic, but adding custom details would certainly improve the renders even more.

One of the main goals of this research was for the workflow to produce correct looking renders. While doing this, the workflow also had to be time and cost efficient for it to be usable in a professional pipeline. After setting up the polarization equipment, the actual gathering of material data took under a minute per material. Also, the cost of a set of polarization films is really low, and a consumer grade digital camera is also relatively cheap. To get higher quality images, a CCD camera might be used, but is not necessary to get usable reference photos.

But while the actual collection of material data did not take long, that time was instead spent on recreating the materials. Each of the material properties were compared to the photographs, and this took quite a bit of time. In total, the entire process of recreating a single material took a few hours. However, this included texture creation and render times, both of which were the most time consuming parts of the workflow. And even though the material creation took some time, one of the goals was to be able to reuse the materials in other projects. This allowed some time to be spent on getting the materials as correct as possible. By then putting the finished material in a library, a big part of the material creation process is already done for future projects.
7 Conclusion

This chapter will quite clearly describe why the results of this research matter for artists wanting to recreate materials. As a reminder, the overall aim of this research was to demonstrate how to create photorealistic material renders by using observations of physical material properties. To complete this goal, a number of objectives were set:

1. Gather information about how light and matter interacts in the real world.
2. Explore methods for studying the properties of physical materials.
3. Examine a selected set of materials by using the found methods of observing material properties.
4. Render photorealistic images and compare them with photos of the physical material.

By looking at these objectives, it is clear that the study has successfully accomplished them all. But what does this mean for material creation as a subject? That is what this chapter will try to answer.

7.1 Research objectives: findings and conclusions

For artists to be able to recreate materials in computer graphics, a basic understanding of how the real world behaves is necessary. To simulate the real world accurately, knowledge about why materials behave as they do is needed. This knowledge may in turn be used by experienced material artists to create materials without measurements, since they already know how they would behave. But information about physically based material creation however, is somewhat hard to find. Physically based shading is a relatively new subject, and not a whole lot of documentation on this type of material creation is available for artists. This can lead to them learning the wrong methods, such as putting all lighting and shadow information into the diffuse texture, which was a common method before physically based shading was introduced. However, with the knowledge of how materials actually behave, this inaccurate approach can be a thing of the past.

The technique used in this research of separating and revealing material properties has shown to be highly useful in a workflow. With the knowledge of how materials behave, the images the technique produced could easily be used to identify the structure of the materials. Using only two images, several material properties were revealed (diffuse, reflectivity, glossiness, Fresnel IOR, bump). The method was also easy to use once it was set up, and required little resources. This makes the method very cost effective, since it produces a lot of information for very little money. The drawback is of course that it does not produce perfectly accurate results. For example, the specular images had residues from the diffuse color of the materials. Materials with colored reflections are also a troublesome area; one needing more advanced methods to truly reveal the properties. Another drawback is that the technique requires subjective interpretation. The images themselves do not reveal data usable directly in the computer graphics application. Artists still have to estimate the properties, but they can do it with less guesswork by using the images as references. This aids in creating more realistic renderings, more than simple intuition would have allowed.

7.2 Future of material creation

This research has shown a functional material creation workflow using methods of observing physical material properties. While the process is not yet automated and instead uses estimations, it still produces realistic renderings. The main advantage of other methods is its ease of use and cost effectiveness. Since the setup is not a big investment moneywise, it would seem appropriate for professionals to consider trying this technique, especially if they have no other method of getting material data. For
future research, the process may be improved by eliminating the need for subjective interpretation. Also, since today’s algorithms still do not perfectly simulate the real world, a generalized set of material properties may be needed in all computer graphics applications. These properties would adhere to the actual physical properties of real materials. This could pave the way for methods of analyzing materials and objectively measuring their properties. A public material library could then be created, where artists can download the materials they need, just like today’s texture libraries. This would remove the need for guesswork completely, since the properties are already set. To retain the artistic side of material creation, any textures could be applied by the artists. Until then, artists can use methods such as the one presented in this research to make the best out of the situation and assemble their own material library.

References


