The Perception of Simulated Materials

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ABSTRACT

Numerically modeling the interaction of light with materials is an essential step in generating realistic synthetic images. While there have been many studies of how people perceive physical materials, very little work has been done that facilitates efficient numerical modeling. Perceptual experiments and guidelines are needed for material measurement, specification and rendering. For measurement, many devices and methods have been developed for capturing spectral, directional and spatial variations of light/material interactions, but no guidelines exist for the accuracy required. For specification, only very preliminary work has been done to find meaningful parameters for users to search for and to select materials in software systems. For rendering, insight is needed on the perceptual impact of material models when combined with global illumination methods.

Keywords: Computer Graphics, Realistic Image Synthesis, Materials, Reflectance, Textures

1. INTRODUCTION

Generating realistic images is one of the goals of computer graphics image synthesis. Plausibly realistic images may be needed for applications such as feature films or games, or predictive realistic images may be needed in product design or training simulations. For either class of application, definitions of the materials that objects are made of are needed. Numerous models for materials have been developed, and databases of measured data for various materials have been compiled. Despite decades of research, the basic issues of what is required of a model to make a simulated material look plausible, or the accuracy required of a model for a simulation to faithfully reproduce appearance are poorly understood. The purpose of this paper is to better define these issues in computer graphics with the goal of inspiring new lines of research in perception of materials.

While the perception of shape has received much more attention,[1] there is a growing body of research in human and computer vision on the perception of materials. Vision research starts at the opposite end of the imaging problem from where computer graphics starts. Broadly speaking vision starts with the person or sensor, and considers what makes one material look different from another. Examples of vision research that inform material simulation in computer graphics include Hartung and Kersten's work on distinguishing shiny from matte objects,[2] Fleming et al.'s work on illumination and material perception[3] , and Fleming and Bülthoff's study of translucent materials.[4] The work on matte versus specular explains the effectiveness of reflection maps in displaying specular objects, even when the reflected scene is not accurate. The work on illumination on material perception has led to the development of improved material selection interfaces such as BRDF-shop.[5] The work on translucent materials resulted in a list of reliable heuristics that can be used to enhance the impression of translucency in a rendering. This further informed the work by Khan et al. that allows the substitution of materials in images and videos.[6]

However, because vision approaches start at the human/sensor end of the process, it can be difficult to trace the insights they obtain to improved methods for defining materials. Vision approaches often end with the analysis of images. The analysis of image statistics can be useful in constructing models for how humans classify materials, and in developing machine vision methods for the same task. In material models for graphics though we seek definitions that will apply to the generation of an infinite number of different images.

There have been many successful applications of insights from perception to topics related to image synthesis such as global illumination calculations and geometric simplification. In global illumination, successful work exploits the fact that illumination approximations can be computed progressively and the results monitored in image space where it is possible to apply perceptual metrics.[7,8] In geometric simplification metrics such as

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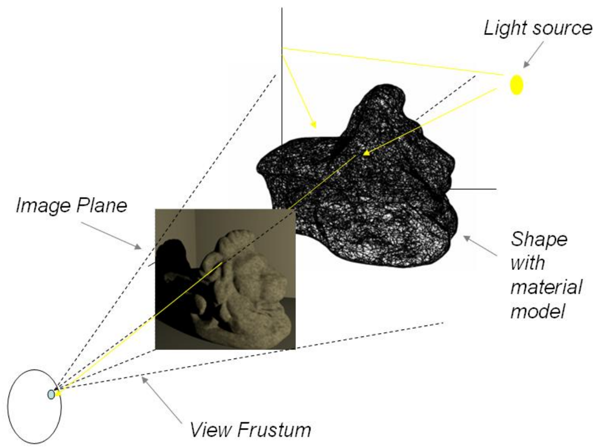

Figure 1. A synthetic image of an object is formed by computing the visible light reaching the eye as a result of the illumination environment, and the shape and material of the object.

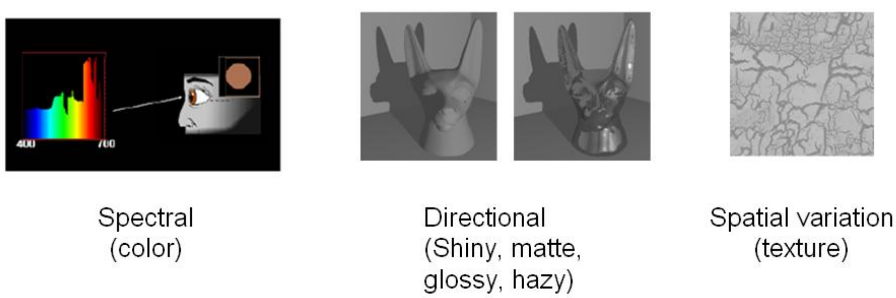

Figure 2. A material definition describes how light is redirected as a function of wavelength, direction and position.

salience[9,10] can exploit the existence of high resolution model to compare its visual quality to a lower resolution model. More work is needed to apply similar approaches to modeling materials.

There are three main areas where we need a characterization of the perception of materials for computer graphics: measurement, specification and rendering. There have been recently been promising efforts in tackling each of these areas with either perceptual experiments or principles by computer graphics researchers. We will examine each area in turn, describe existing work and the open problems. We begin by describing the physical principles and models that are used in defining computer graphics materials.

2. UNDERLYING PHYSICS AND FIRST PRINCIPLES MODELS

An image is formed, as illustrated in Figure 1, by computing the visible light reaching the eye through the image plane. This light depends on the shape of an object, the illumination environment, and the object material. A material description needs to define how light incident on the object is redirected – either scattered or absorbed.

The redirection of light has three different aspects as shown in Figure 2 – spectral, directional, and spatial. These types of variations correspond to different ways we describe our perception of materials – wavelength variations resulting in color, directional variations resulting in matte, glossy and/or translucent appearance, and spatial variations resulting in texture. The spatial variations may be point to point variations in wavelength and directionality, or may be small scale geometric variations such as pores, bumps or wrinkles.

Modeling of light and material could be done at the scale of photons and atoms. However, in practice geometric optics is almost always assumed in graphics (except for objects that clearly display diffraction and interference

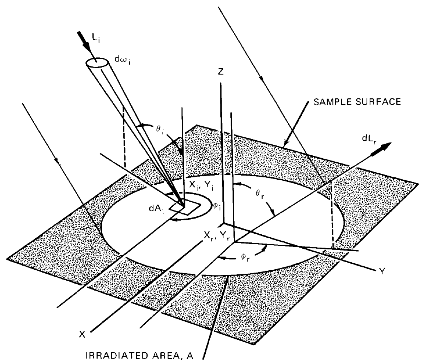

Figure 3. The BSSRDF expresses how light at a particular wavelength is redirected as a function of the incident and exitant positions and directions (Figure reproduced from NBS 160.[13])

Figure 4. The definition of what is a material and what is a collection of objects depends on scale. From far away (a) the beach appears to be covered by some material, on closer view in (b) and (c) it appears to be covered by small pebbles.

effects such as compact discs[11] or butterfly wings.[12]) A general function for characterizing a material's interaction with light is the the bidirectional scattering-surface reflectance distribution function (BSSRDF) S:

$$S(\lambda, (\mathbf{x_i}, \Theta_i) \rightarrow (\mathbf{x_r}, \Theta_r)) = dL_r(\lambda, \mathbf{x_r} \rightarrow \Theta_r)/L_i(\lambda, \mathbf{x_i} \leftarrow \Theta_i) cos\theta_i d\omega_i, \quad (1)$$

The distribution function describes how light at a wavelength λ entering the material at a point x_i from a direction $\Theta_i = (\theta_i, \phi_i)$ is scattered and re-emerges at a point x_r in a direction Θ_r. The positions and directions are shown in Figure 3, which is reproduced from the National Bureau of Standards publication where the BSSRDF distribution was first defined in this manner.[13]

Whether something qualifies as a material specified by a BSSRDF, or a material with BSSRDF and fine geometric structure, or a collection of objects each composed of a material defined by a different BSSRDF is a function of scale. In Figure 4a) people are standing on a beach covered by some material that appears to have primarily wavelength variation with position, at closer range in b) there are small geometric variations in the material, and even closer still in c), rather than appearing to be a material this looks like a pile of individual pebbles each composed of a somewhat different material.

Even with the geometric optics assumption the complicated form of the BSSRDF is not completely general – it doesn't include behavior where the wavelength of light leaving the surface is different from the incident (fluorescence), there is a time lag between the incident and leaving light (phosphorescence), or where there are polarization effects. All of these effects have been studied in computer graphics,[14,15] but are generally regarded as special cases that are only important for specific materials such as gems.[16]

For materials that do not have significant subsurface scattering, for example metals, the bidirectional reflectance distribution function (BRDF) f_r is used, which is just the BSSRDF with $x_i = x_r$:

$$f_r(\lambda, \mathbf{x}, \Theta_i \rightarrow \Theta_r) = dL_r(\lambda, \mathbf{x} \rightarrow \Theta_r)/L_i(\lambda, \mathbf{x} \leftarrow \Theta_i) cos\theta_i d\omega_i, \quad (2)$$

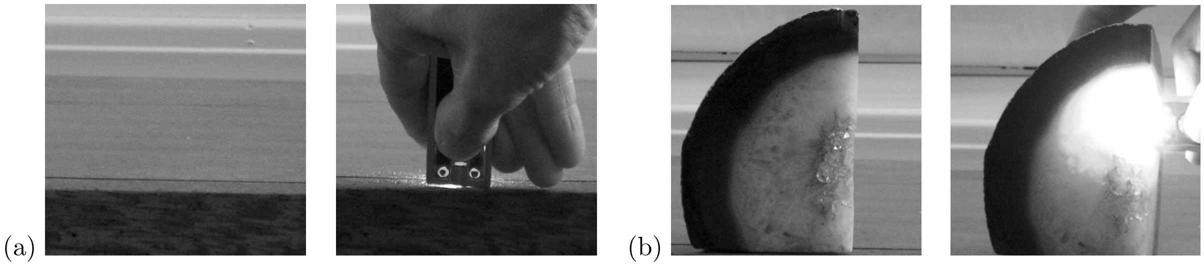

Figure 5. Holding a light next to a material can be used for a quick assessment of the effect of subsurface scattering. The wood on the left (a) doesn't appear to have subsurface scattering, while the rock on the right (b) does.

The full BSSRDF has received a lot of attention recently because of its importance in realistically rendering human skin, an important material in feature film and games. A full BSSRDF is not needed for all materials. However there is no specific definition of when it is adequate to use a BRDF rather than BSSRDF. Examples of when it does and does not appear to be necessary are shown in Figure 5. The image of rock on the right of Figure 5 illustrates that not only may it be necessary, but it the BSSRF can depend on complicated macroscopic volumetric structure of the material.

There are general physical constraints on the values that BSSRDF and BRDF. The fraction of light scattered can not be greater than one, so the integral of the reflectance function over all possible leaving positions and angles is bounded. Light obeys reciprocity, so the value of the function is the same when the incident and reflected directions (and positions in the case of BSSRDF) are reversed.

There are also physical characteristics of the reflectance/scattering functions for different material types derived from electromagnetic theory. Metals conduct electricity, and so light is absorbed within metals within molecular length scales, causing metals to appear opaque. Solving Maxwell's equations for smooth surfaces results in the mirror reflection law, Snell's law, and the Fresnel reflectance that increases with incident angle.

Working from these first principles, a lot of work in graphics has gone into creating analytical physical BRDF (and to some extent BSSRDF) models based on detailed descriptions of surface microstructure. Examples include surface models such as the Cook-Torrance,[17] He-Torrance[18] and Oren-Nayar[19] models, and models including substructure such as pigment particles and flakes as in Ershov et al.'s paint model.[20] First principle models in general are verified by comparison to physical measurements, but the most successful demonstrate perceptual effects.

In the case of Cook and Torrance's work,[17] they analyzed the Fresnel reflectance for specific material types. They note that most plastics consistent of a pigment particles in a clear binder material. The top smooth surface is composed of the binder which reflects all wavelengths to approximately the degree. The wavelength reflection from the smooth surface of metals however depends on the wavelength variation of the index of refraction of the metals. As a result they reasoned that a "copper colored" or "gold colored" plastic object looks like plastic because it has white highlights, while copper or gold metal look like metal because of their colored highlights.

In another example Oren and Nayar's work explained the absence of very dark edges on some matte objects. They demonstrated that the orientation of small scale facets on the material results in back scatter, so that when viewed from near the light source direction materials can look relatively bright at edges where matte objects are dark.

The appearance of metals versus dielectric objects (how do we tell a an object is silver?) and importance of backscatter (how noticeable is this under realistic illumination?) remain issues to explore further.

There has also been work recently to model the effect of bundles or groups of macroscopic geometry on features of material appearance. An example is Marschner et al.'s work on the bundles of fibers that form hair[21] that predicts a hair reflectance with secondary highlights. Another example is Irawan and Marschner's work on woven fabric that predicts unique highlight shapes depending on the fiber type and weave of the fabric.[22,23]

3. MEASUREMENT

Measurement is needed to reproduce the appearance of existing physical materials. Reasons for modeling existing physical materials include using an existing material in a new design and documenting an existing object for studies in history or archaeology.

Traditional BRDF measurement for applications in physics and engineering have been developed with high precision, measuring the light reflected in a very narrow direction from a precisely directed incident beam. An example of such a precision device is the NIST STARR apparatus.[24]

Recognizing that the same precision is not economically feasible, and probably not required, relatively inexpensive image based reflectance measurement systems have been developed for graphics applications. For example Marschner described an approach that coats a sphere with the material to be measured and captures an image with the reflected light for many exitant directions at once.[25] Lensch et al. developed an image based method for estimating the spatially varying reflectance functions for materials on an existing object.[26] Dana et al. invented the concept of a "bidirectional texture function", which is captured by imaging large areas of a material for multiple incident light directions and view directions.[27]

While image based measurements have been successful, there are still only very small databases of such measurements available for use in graphics since they are tedious to make. Furthermore, unlike traditional engineering measurements they rarely include specific estimates of error. Such errors may be high in absolute terms, but perhaps acceptable in terms of the appearance of the images the models are used in.

The required accuracy for BRDF measurements in graphics has not been studied with any rigor. While the accuracy necessary obviously depends on the application, guidelines for a maximum accuracy required are needed for measurements that are done for applications such as widely used material databases and for documentation of museum artifacts. It is unclear how the accuracy should be stated – a certain percentage regardless of the raw value? What is the minimum sampling required? Are different standards needed for different classes of materials? Are different angular sampling rates needed for different spatial variations? Simply recommending that you should measure as much as you can afford doesn't adequately constrain the problem. What trade-offs should be made between wavelength, spatial and angular samples?

An alternative to the exhaustive NIST style high precision measurements, are practical measurements made for industrial appearance applications. Hunter and Harold[28] define numerous visual properties and describe devices designed to evaluate them by measuring scattering at limited numbers of incident and exitant angles. Westlund and Meyer[29] explored deriving computer graphics reflectance models from these industrial appearance measurement devices. Additional work is needed to find how well this approach works over a range of materials, and if the existing devices could be modified or augmented to give acceptable material data for computer graphics applications.

For textures, a simple method of measurement is to take an evenly lit image of a spatially varying surface. Perceptually informed methods have been developed to characterized these measured data to produce unlimited expanses of the same texture. For example, Heeger and Bergen[30] use the observation that textures appear the same when image statistics are matched.

Two dimensional samples of three dimensional textures have also been used to estimate the three dimensional texture using a physical model from stereology by Jagnow et al.[31] In their work, materials composed of embedded large particles are considered, and the statistical distribution of size and density of particles is estimated. In this case, perceptual experiments weren't performed, but a physical comparison to simulation was presented for the user to make their own judgment. It was assumed that viewing Figure 6 would lead to the conclusion that the new method produced better visual results for the class of materials studied.

The stereology method proposed by Jagnow et al. requires estimating the shape of the three dimensional particles suspended in the materials. Choosing between different methods for estimating shape from a two dimensional slices is not as clear cut a problem as determining whether a method that explicitly models particles produces superior results for materials consisting of particles. In subsequent work by Jagnow et al.[32] methods for estimating particle shape were evaluated using psychophysical experiments comparing textures from a "ground truth" synthetic volume, and textures generated using different particle estimate techniques. Since textures

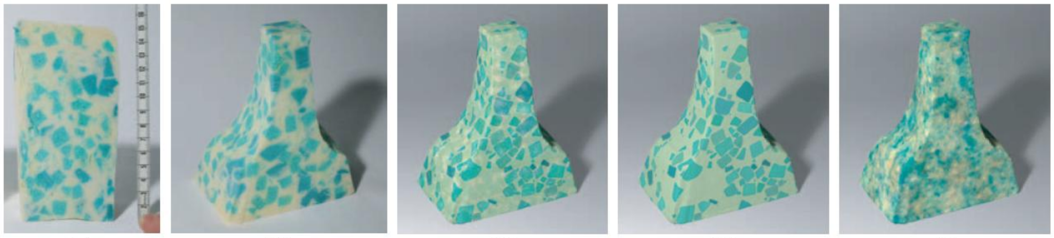
(a) (b) (c) (d) (e)

Figure 6. An example showing perceptual differences, where it was assumed that extensive experiments weren't needed to show the advantage of one method over the other for a particular class of solid textures, from.[31] Image (a) shows a sample 2D slice of material, and (b) an object made from the material. Images (c) and (d) show simulations using the method from stereology, and (e) a simulation using a previous method.

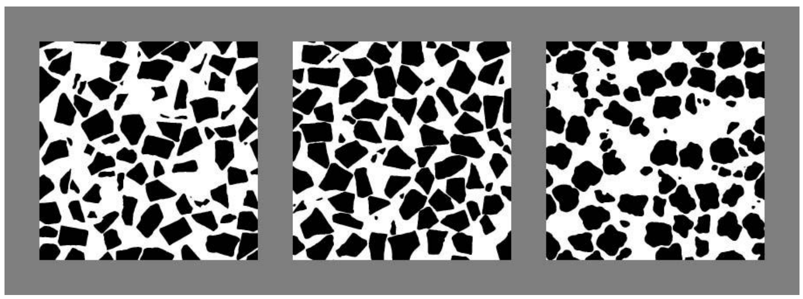

Figure 7. An example screen shot from a study described by Jagnow et al.[32] to compare techniques for estimating embedded particle shape. The center image is a slice from a "ground truth" synthetic material. The observer is asked to select whether the left or right image came from the same material. One of the images was generated from the ground truth material, one from a texture generated with one of the particle estimation techniques being studied.

aren't expected to look the same pixel by pixel, the experiment asked observers to select which of two textures looked like it had come from the same material as the center texture, as shown in Figure 7

Recently researchers have attempted to measure both the spatial and temporal variations in material appearance due to weathering.[33,34] Since these variations depend on object geometry and environment, making use of the measured data is challenging. What measurements besides BSSRDF need to be made to completely document the weathered appearance? Figure 8 shows a comparison of an object that was physically weathered, and a synthetic image of the same object with weathering effects transferred from a measured object using reflectance data augmented with geometric data. Such comparison cases are difficult and time consuming to prepare. While there are similarities in the images, it isn't clear whether the observer gets the same impression of the weathered material – what visual variations would there be if the same physical process were repeated many times? What sort of judgments is the observer meant to make from the image? Better definition of the weathering problem and design of perceptual experiments are needed to gain more insight to move this area of measurement forward.

4. SPECIFICATION

In graphics systems the user needs to specify the materials to attach to digital shapes. This may mean selecting from a large number of existing materials, or editing an existing material.

4.1 Current Interfaces

Current interfaces used to specify materials from some popular graphics systems are shown in Figure 9. Each interface is complicated and brings up multiple sub-menus, and not all are shown here. No standards are followed. However, all of the interfaces are built around the computer graphics data structures used to define components of material appearance rather than perceptual features. Spectral characteristics are specified with RGB color,

Figure 8. An example comparison of the same object physically (right) and synthetically (left) weathered from Lu et al.[33] Perceptual tests would be useful to evaluate the synthetic results, but would be difficult to conduct.

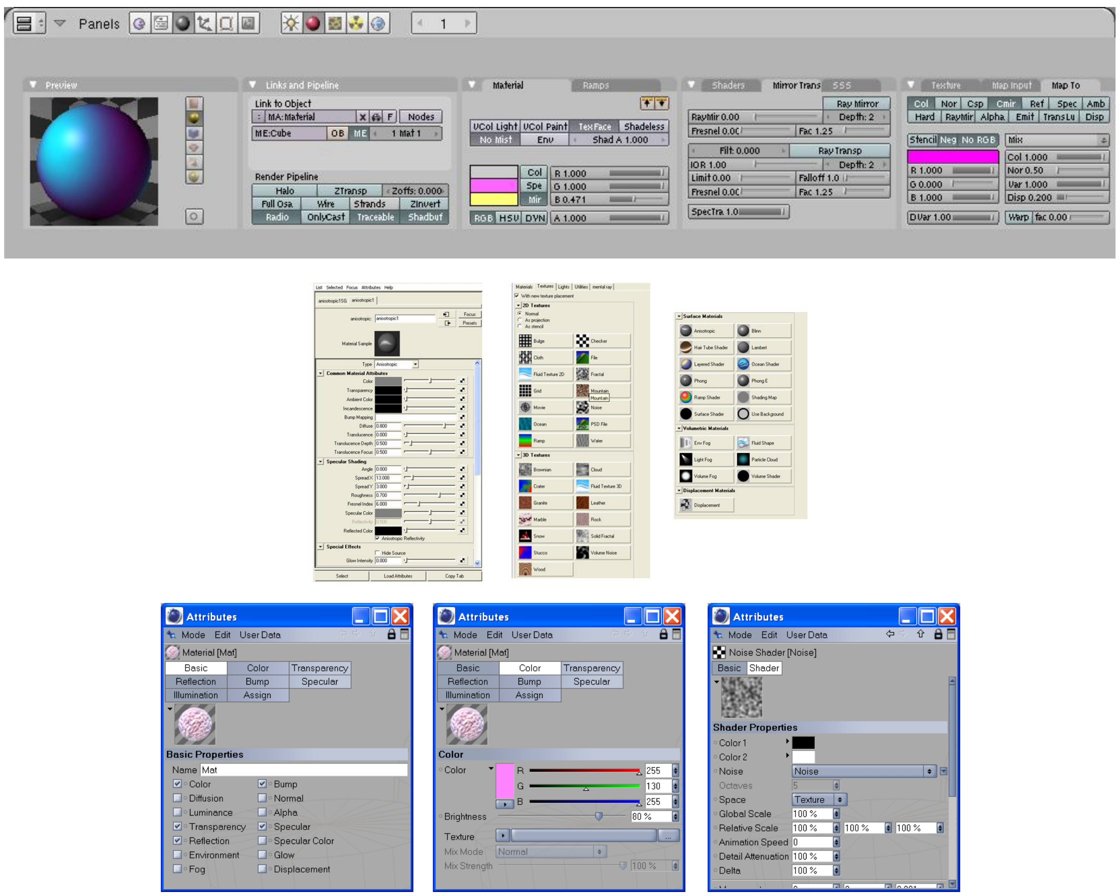

Figure 9. Interfaces for material specification from Blender (top), Maya(middle) and Cinema4D (bottom).

directionality is specified with common graphics reflectance models and their parameters (e.g. Oren-Nayar or Cook-Torrance), and spatial variations are given by texture maps or procedural functions. Procedural functions that define spatial variations in terms of basis functions spanning subsets of all variations possible are Perlin noise[35] and Worley cellular textures.[36]

Systems such as Blender `http://www.blender.org/`, Maya `http://www.autodesk.com/`, and Cinema4D `http://www.maxon.com` provide the capability to define a wide range of materials. In a "proof by marketplace" these interfaces are effective in the sense that users invest a lot of time and/or money in using them to define materials that are used to generate compelling realistic images. However, the learning curve for each system is high, and being an expert in one system does not transfer into learning another quickly

In the domain of geometry creation in computer aided design (CAD), there is evidence that techniques based on fundamental design principles allow users to learn new packages quickly. Weibe[37] measured the ability of engineering students to learn and use a new commercial CAD modeling software package after learning a first package. While this was a limited and early study, an insight gained was that students were apparently better able to transfer skills between packages that better incorporated basic design principles - in this case the use of constraint-based modeling. By rethinking the material specification process in terms of material appearance rather than computer graphics data structures and models, it may be possible to vastly improve the interfaces over those shown in Figure 9 and make them easier to learn.

How natural can a material interface be? How much should a person need to learn to specify materials? One approach is to learn to observe materials to decompose them into spectral, directional and spatial effects, without reference to specific computer graphics models. Examples of this type of approach have been given by Dorsey et al.[38,39] This follows the tradition of teaching observation in art, although with a different view of how appearance should be analyzed. Perhaps alternative approaches to observation and understanding the features of appearance that can be transferred into numerical specifications can be developed.

Different interfaces have been proposed that appear quite different from the sliders and radio buttons common in current systems. In BRDF-Shop the user paints the appearance desired, however the system is limited to selecting spatially uniform BRDF's. Painting avoids having to decompose the appearance, or to even think of terms to describe it. A hazard of painting, even if generalized for spatially varying descriptions, is that it is always tied to a specific illumination, shape and scale.

From a coding point of view, a complete material specification is expressed in software referred to as a "shader." Elaborate and efficient shaders can be written by programmers with knowledge of graphics hardware. Cook[40] developed the idea of a "shade tree" that describes how various textures and reflectance models are combined to form a particular material behavior. To allow artist/designers to generate efficient shader code McGuire et al.[41] developed a visual programming interface for users to specify a material as an "abstract shade tree" that can then be efficiently encoded for various graphics hardware systems. While the visual interface gives the user a different view of how the various graphics models are applied, it doesn't represent a different set of structures and parameters for the user to express the appearance of the material they want to use.

4.2 Plausibility and Feasibility

Current graphics systems and shader programming languages allow the definition of materials that could not physically exist. For some applications, being able to physically produce the material may not be important, but generally it is important that the material look plausible. A material should somehow relate to our experience of viewing materials in the real world. In most cases a large fraction of the parameter space for different types of materials in graphics systems produce materials that look unnatural.

Energy conservation and reciprocity, discussed in Section 2, are the only constraints that have been proposed for making a plausible material.[42] However, it isn't clear that these constraints are necessary or sufficient for a material to appear plausible. More study is needed to understand to what extent conservation and reciprocity are required, and whether there are other constraints on the nature of the directionality of reflection.

There is also more study needed in the area of plausible textures. Perlin noise functions are used to simulate natural irregularities in materials. Reinhard et al.[43] compared commonly recommended Perlin model parameters, and found that they varied from commonly accepted second order image statistics. Both Perlin noise and Worley cellular textures have been used for many natural materials, without a specific study of the natural appearance for various combinations of parameters.

4.3 Navigation

One problem in existing systems is that even when a material definition is found that is in some sense close to the desired material, it is difficult to find the adjustments to move closer. Several researchers have begun looking at developing perceptual dimensions for graphics controls to allow navigation in material space.

Work by Pellacini et al.[44] established perceptual dimensions for gloss to use in adjusting the parameters of a simple reflectance model. Matusik et al.[45] expanded the dimensionality of this approach by using a collection of measured BRDF's and asking a user to classify their appearance according to a predetermined set of traits such as "roughness" and "greasiness". Using these traits, they were able to organize the measured data in a manner that would let the user navigate between the data set according to these traits. Expanding this to larger numbers of traits, material types and users has not been attempted.

Determining meaningful parameters and perceptually equal sized steps in parameter space requires numerous perceptual experiments. Ngan et al.[46] propose simplifying the problem by representing the materials as images. Steps in any parameter direction can be represented by images around the current material definition, and equal sized steps can be determined using image metrics. This converts the problem from running experiments identifying perceptual traits to identifying suitable illumination, shapes and poses to use in the selection of material.

4.4 Material Classification

There are clearly different classes of materials in the world, and it isn't clear that there is a continuous space of all reasonable possibilities. From a practical point of view it isn't likely that someone trying to specify a material corresponding to iridescent bird feathers would start out with a piece of granite and adjust independent parameters until the result looked correct.

It is more likely that a person would take a catalog approach, and select a material type. This approach is used in the LightWorks rendering system `http://www.lightworks-user.com/` which offers catalogs of materials from the manufacturers of architectural products such as Sherwin-Williams paints, Westbond Carpets, and MoldTech plastics. Third party materials are authored in a proprietary LWA format through software sold by LightWorks. In this case, the material accuracy may not be verified by any psychophysical testing, but the interest of manufacturers in selling product over a long term provides motivation for the material models to be reliable.

However, how can the catalog approach be extended to materials that don't exist yet and need to be specified? After selecting a class of materials, and a typical instance, how can the user adjust it? Are there some universal knobs that are appropriate (e.g. shinier), or are they always material specific? For a very narrow range of materials in a particular editor can be composed such as the metallic car paint color editor by Shimizu et al.[47] It should be noted that this editor is primarily for experimenting with particular aspects of appearance deemed important for one design approach. A more complex editor is proposed by Ershov et al.[48] The complexity is the result of designing a material in terms of a physical recipe for actually producing the paint.

The granite and leather examples shown in Figure 10 from the Maya rendering package are examples for a more general catalog. Maya offers options for material types such as the leather and snow shown here. However the parameters are in terms of a cellular texturing procedure (for leather) and a subsurface scattering model (for snow), rather than the grain and patina terms people might use for leather appearance, or the size of crystals that might be used for snow. A basic question is whether given a type of material if named dimensions that are recognized are needed, or whether it is adequate to determine the number of dimensions and let the user experiment with varying the parameters.

4.5 Search and Retrieval

With the high level of activity in graphics around the world, rather than building geometries or textures an alternative has become to use an engine such as Google to search for the desired data. A wide variety of image search engines have been developed, and a geometry search engine is available from the Princeton Graphics Group at `http://shape.cs.princeton.edu/search.html`. There are two obstacles to the development of a materials search engine:

- A standardized format for material descriptions equivalent to the VRML, OBJ formats for geometry or JPG and TIF for images has not emerged.
- A reliable method to make signatures for materials to run queries against has not been developed.

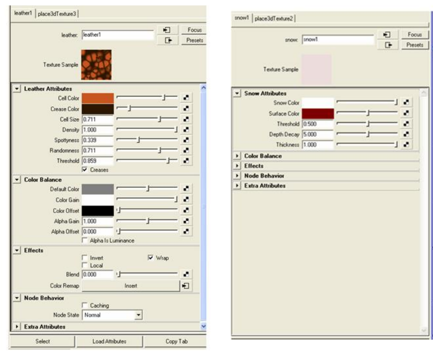

Figure 10. Interfaces for leather and snow specification in Maya.

Even if the full material model isn't expressed in a standard form, some standard representations of the material such as images on specific objects under specific illumination (as proposed by Ngan for material navigation) could be added as metadata to any material definition. Textual tags could also be added. Research is need to find the representations and tags that could reliably be used for material retrieval.

5. RENDERING

The purpose of defining materials is to use them in rendering images. Any rendering process is limited by memory or time. Regardless of the available resources, it is always advantageous to use the most compact definition of any graphics input that is adequate for the current rendering. Finding simplified material models for specific renderings is the area that has the greatest potential for immediate improvements, since it can be most easily related to image metrics.

In this area recent work by Vangorp et al.[49] studied the interaction of object shape and material reflectance in appearance. They found that an object's material can look quite different depending on the properties of the shape of the object.

Ramanarayanan et al.[50] introduced the idea of "visual equivalence" to describe objects in images that have the same appearance, even though the images have noticeable differences when examined in detail. They define a visual equivalence predictor (VEP) that they can apply to a shape, simple reflectance model, and illumination description. Using the VEP allows the calculation of an image that is visually equivalent to an exact rendering using reduced resources.

These results from both Vangorp et al. and Ramanarayanan et al. indicate the possibility of substantially adjusting the resources devoted to a material description object by object, and scene by scene.

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