Overview of Appearance Models

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1 Introduction

Figure 1: Rust.

In the physical world, there are many varieties of surfaces, each with unique reflection and transmission characteristics, which when exposed to illumination make them identifiable by their appearance. The appearance of surfaces can seem simple, such as plastic or mirror, or it can be extremely complicated, such as rusty metal (fig. 1). There are many different ways in which *Computer Graphics* tries to capture all this richness. It can be done by explicit geometry modeling of every surface detail. This can be very expensive, and sometimes it's not possible. On the other end of the spectrum is texturing, and BRDFs, which capture the positional and directional dependencies of reflection. The emphasis of this class is on reflection models. We will not talk much about color, since it is very well studied. Our discussion of reflection models will include also transmission and participating media, since understanding volumetric effects is very important for modeling of appearance of marble, water, skin, and other transparent and translucent materials.

The subject of appearance is interdisciplinary since it is of interest in many different fields. Appearance is studied (of course from very different points of view) in such areas as physics, material science, perception in psychology, and art. Other applications of appearance generation include ceramics, pigments/dyes, building materials, cleaning and polishing, textiles, metals, and cosmetics. Using the computer, people can perform simulations that could not be done previously.

Since in computer graphics rendering we are trying to simulate appearance of things, we need good models for this purpose. However, in many cases we are far from this goal. Scenes of artificial environments have been synthesized quite well; just consider the images you have seen of rooms, factories, and buildings. Sometimes, it's very hard to distinguish such images from a photograph. But in rendered images of natural objects, the lack of good models is apparent. There are very few acceptable rendered images of animals, plants, or minerals.

This class will cover following topics:

- Modeling of how light interacts with matter
- Measurement
- Vision — inverse problem (extraction of parameters from images and fitting models to measured results)
- Perception

The last two topics will be discussed in the second part of the course next quarter.

There are three ways of looking at appearance:

- Basic physical processes.
- Structure Models (description of structure of materials vs. texture map, for example).
- Phenomenological Models (equations that capture the way things look).

We will look at each one in turn.

2 Physical Processes

One of the attempts to understand process of interaction of light with the surface of materials led to Fresnel's equations. Figure 2 shows reflectance curves for copper and glass calculated using these equations. If you look at the glass from different angles to it's surface, the amount of reflected light will be different. At the grazing angle, almost total reflection occurs, and glass will act as a mirror, but at the normal view, very little

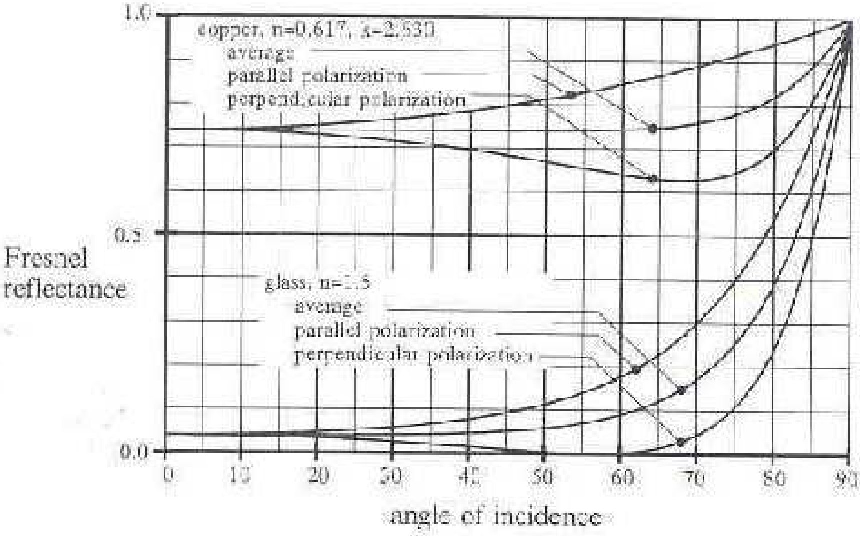

Figure 2: Fresnel Reflectance. Top curves — copper, bottom — glass.

light is reflected, and you will mostly see what is behind the glass. Also, there is no color shift, and the reflection of the light source will have the same color as the light source itself.

Reflection from metals is considerably different, since the percentage of reflected light changes with wavelength. Classic examples are described in papers by Pete Shirly [16] and Rob Cook [3]. Figure 3 shows the dependence of copper mirror reflectance on viewing angle and wavelength, and color shift.

Another phenomenon is reflection below a surface, when light interacts with the material. Water is a good example, since it's transparent for light, and water appearance changes depending on what we actually see: light reflected off its surface, light that penetrated the water and reflected from the bottom, or light that was scattered off water molecules and escaped. It is also very interesting to consider what can be seen by a diver looking up from below the water's surface. He can see the whole sky compressed to part of hemisphere around the zenith. There is almost no light coming from horizontal directions. This is called the optical Manhole effect (fig. 5). The explanation of this effect lies in the fact that water has higher a index of refraction than atmosphere, and therefore at certain viewing angles total internal reflection occurs. ¿From horizontal directions, the diver will see only light scattered in the water, which unlike refracted light lacks any coherent information.

The roughness of surfaces is responsible for many interesting effects. A classic example is a CDROM, which displays beautiful diffraction patterns (fig. 7). Zooming into the disc's surface reveals the pit details pictured in figure 6.

Another example of what surface features can do is the reflection of the sun in the

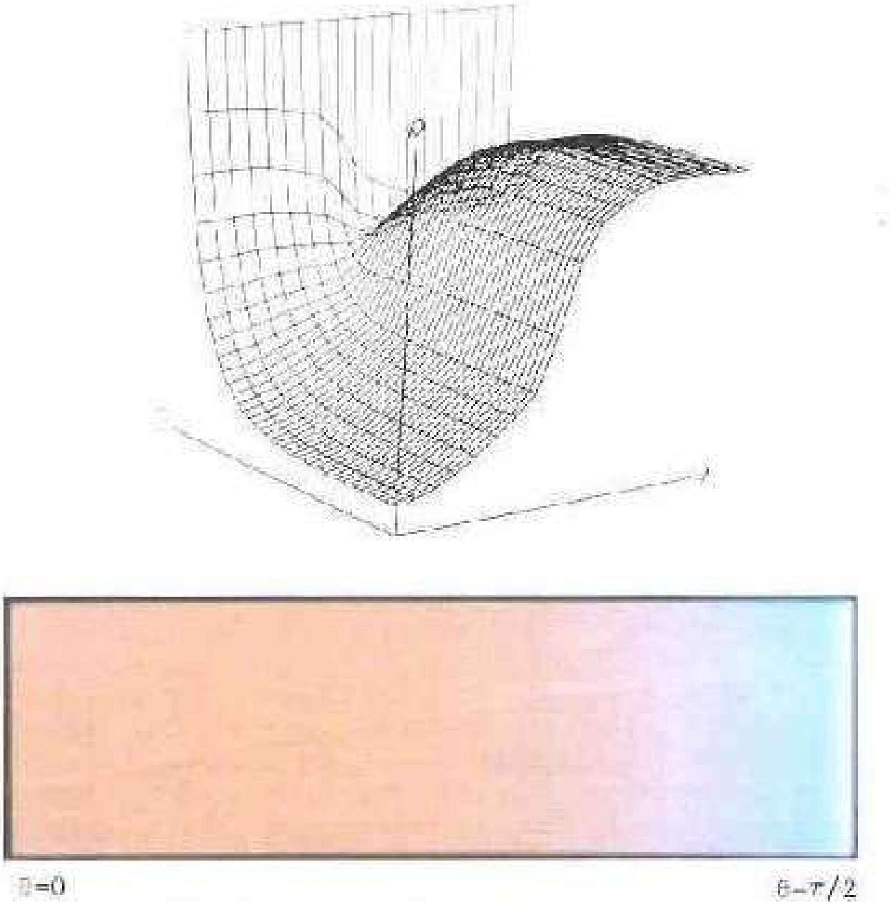

Figure 3: Reflectance and Color of copper mirror.

sea. If the surface of the sea were perfectly flat, then reflection would just be of the sun's disc. However, waves change everything. At different distances from the viewer, different parts of waves reflect the sun. As the result, the reflection stretches out into a very long oval (fig. 8).

A very important role in appearance is played by the selfshadowing of surface features. This can be seen very well in images of the Moon [13], with it's highlights and shadows (fig. 9). Some surfaces reveal a similar surface structure with bumps and pits if looked at very closely. As a result of selfshadowing, the appearance of a surface changes with a change in the point of view and the position of the light source. For example, when a light source is at grazing angles to the surface, much more shadowing of surface featurs occur, and it looks quite dark. Accounting for these effects is an important part of appearance modeling.

To validate an appearance model, understand physical processes of light-matter in-

Figure 4: Copper colored (left) and copper (right) vases. Rendered using Cook-Torrance reflection model.

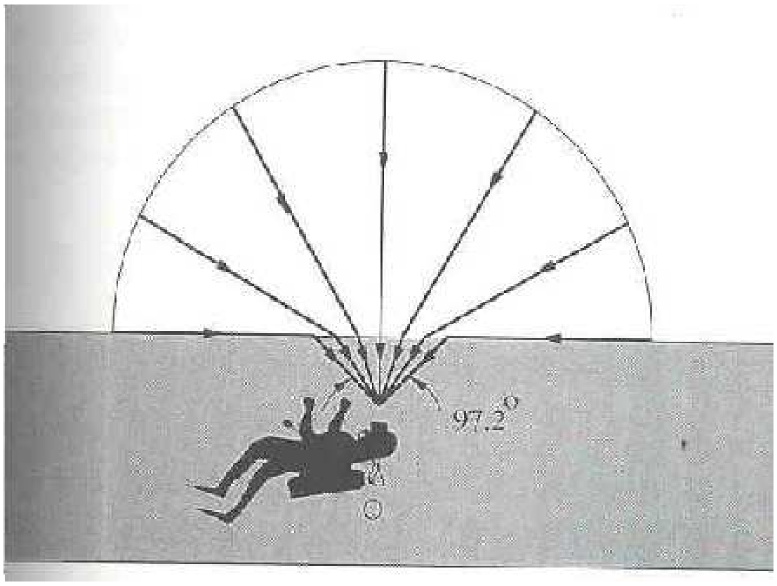

Figure 5: Manhole effect.

teraction, or to apply real tabular values for reflection in image synthesis, the ability to measure reflection of real materials is very important. Such measurements are performed in the following way. The material is made into a thin surface and illuminated by the light from a single direction. Then, reflected light is measured at all angles. Of course, the process is much more complex than it sounds. One of the complications arises when features of surface are locally concave, and then light goes through multiple interreflections. Another complication is reflection at the sample's edge, which is especially difficult to avoid at grazing angles.

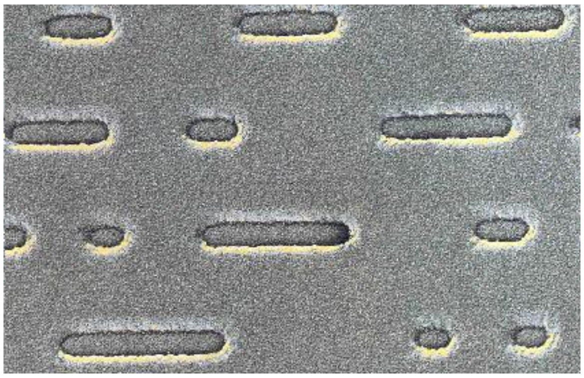

Figure 6: Closeup of CDROM surface.

Figure 7: Rendered CDROM from Jos Stam paper [17].

One more physical phenomena which we will look at is volumetric effects. The appearance of transparent materials and participating media depend on scattering and absorption of light within those materials. For example, very exotic colors can be seen in the water of the Yellowstone ponds (fig. 12). These colors are due to minerals and sediments dissolved in the water. Suspended water particles scatter and absorb light. These processes are wavelength dependent. The important quantity here is albedo, which is the ratio of the scattering coefficient to the total extinction coefficient. If the absorption of a material is high, the material looks more pigmented; if the scattering coefficient of the material is raised, the material looks more white.

The demonstration of this fact is described in [11]. Fairly large pieces of green glass are put in a bottle. The glass looks quite green. Then the glass is progressively crushed into smaller pieces, and it looks more and more whitish. As the number of particles increases and their size decreases, the probability that a ray of light will be scattered

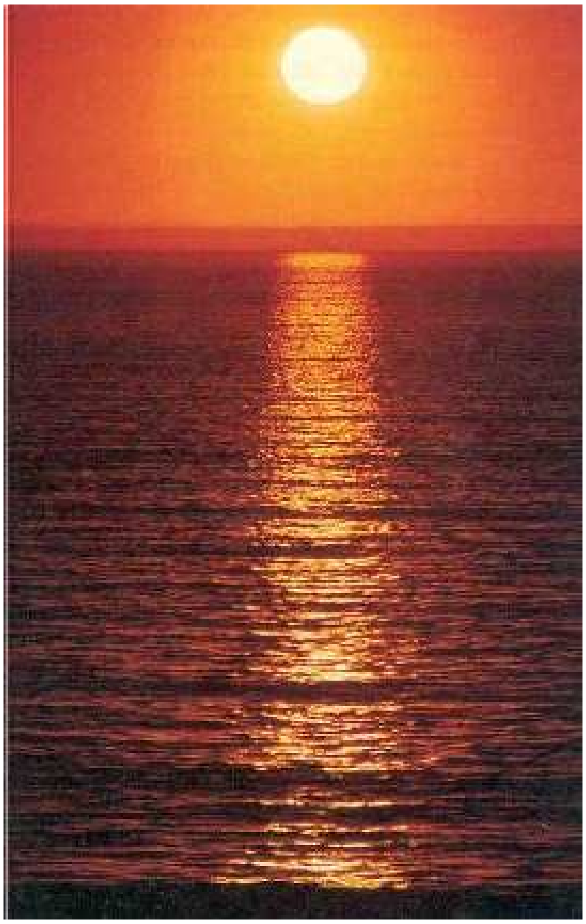

Figure 8: Sunset.

inside the mass of glass particles increases compared to probability of that a ray will be attenuated by absorption. Therefore, the glass looks whiter as it approaches a powder (fig. 13).

Clouds provide another great example of how scattering works inside a participating medium. Inside a cloud, the absorption is low, but scattering is very high, and so almost all the light that goes into the cloud, eventually gets out. As a result, the color of a cloud is very bright white. However, you sometimes see black clouds in front of the Sun. This means that little light goes through the cloud, because it is outscattered from it's path from the Sun to viewer's eyes. But the light is scattered in different directions, rather than being absorbed.

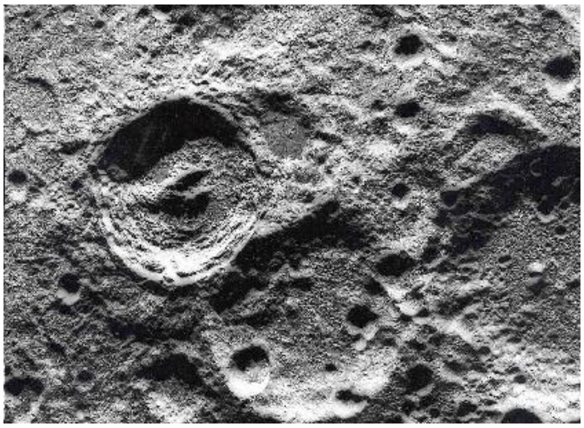

Figure 9: Moon surface.

Figure 10: Painted stucco from “Surfaces” [12].

3 Structure Models

The second approach to the construction of appearance models is understanding the structure of a material. It’s very hard to model the appearance of things in nature without knowing their microstructure. Just consider such complex materials as rust, butterfly wings, insect eyes, and fabric. (figs. 15, 16).

Examples of such structured materials are patinas (fig. 17). Such coverings on bare metal can completely change the way the metal looks. The appropriate model is layered, and Pat Hanrahan and Wofgang Krueger developed such a layered material model and applied it to rendering skin and leaves [9]. Julie Dorsey and Pat Hanrahan developed a physically-based model of metallic patinas [4], and even animated the tarnishing of a bronze sculpture over time.

This leads into another type of appearance modeling, which simulates the history of global effects, rather than just trying to simulate static appearance. This gives important

Figure 11: Marble Taiwan Green Dark, [12].

Figure 12: Yellowstone's Opalescent pool [15].

insight and generality. The example is joint work of Pat Hanrahan and Julie Dorsy from MIT university [5] on modeling weathering effects on the surfaces of buildings and statues. The appearance was modeled by simulating the flow of water. The authors looked into the chemical and physical interaction of water with stone surfaces, and simulated absorption of water by the surface and staining of the surface. The results are impressive, and would be very hard to achieve with other traditional methods, such as texturing.

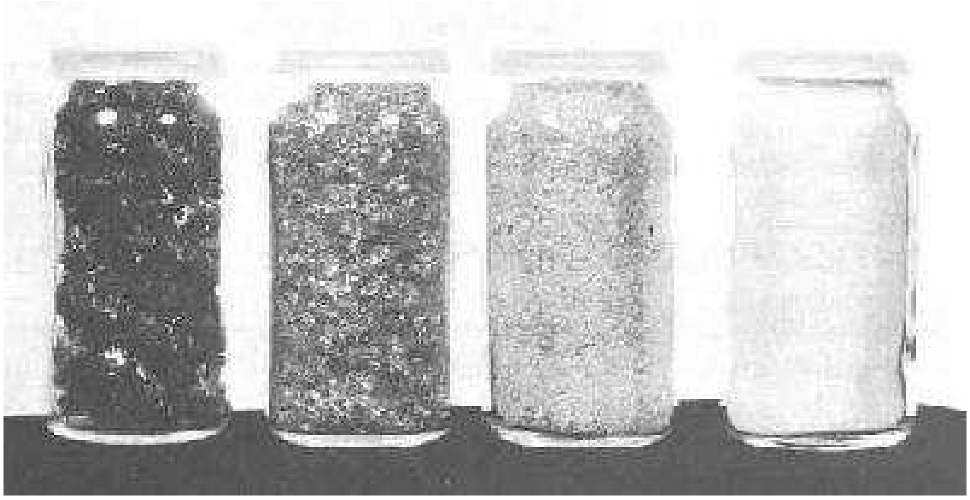

Figure 13: Crashed glass.

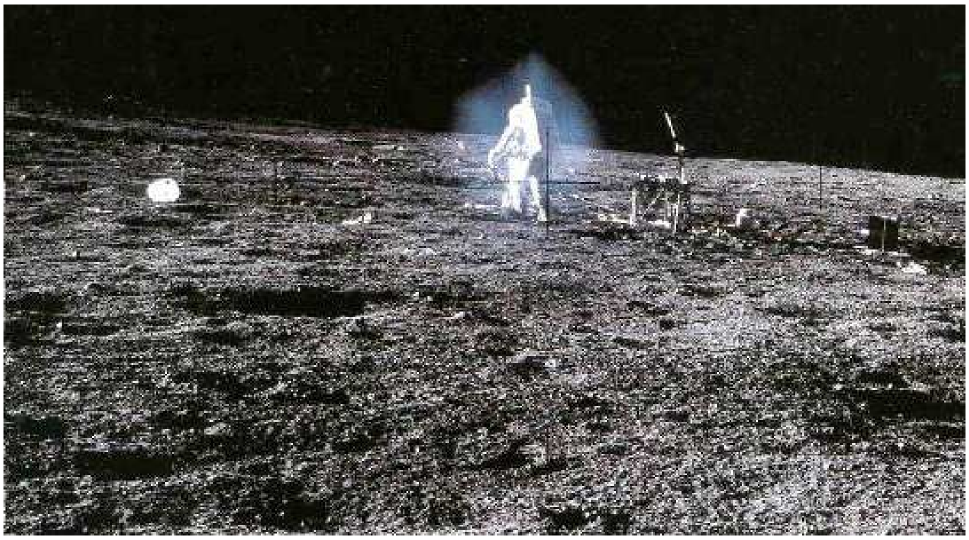

Figure 14: Glow around an astronaut.

4 Phenomenological Models

The third approach to simulating appearance we will discuss is the use of phenomenological models, which attempt to capture the appearance of objects through mathematical abstraction and simplification. The first example we discuss is the Phong reflection model. This model has no physical basis; it simply attempts to capture the appearance of highlights on surfaces from point lights without the complexities of physics. Such point light do not exist, but it's also one of the abstractions widely used in computer graphics.

Figure 15: Butterfly wing.

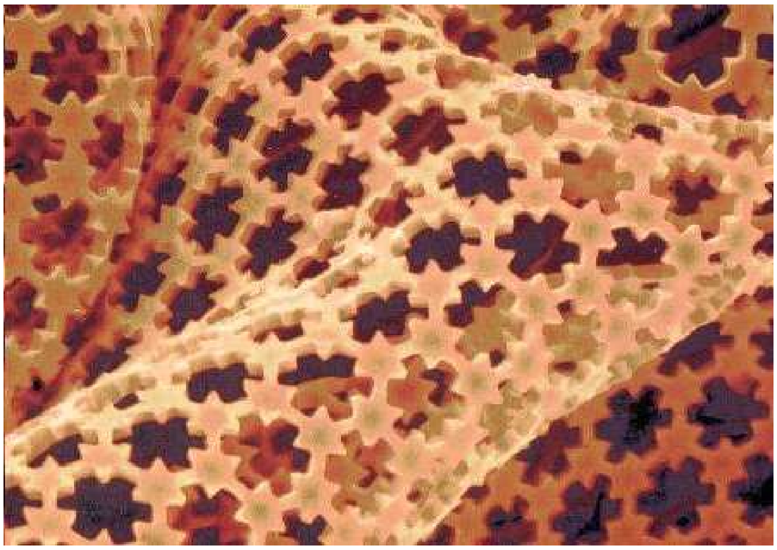

Figure 16: Plastic microfabric.

According to the Phong model, the value for the highlight spread at a particular point is:

$$L = (R_L * V)^s = (R_V * L)^s$$

By good fortune, it turns out that this highlight is equivalent to the one that results if the light source is of finite size as well. Phong's model works in certain situations,

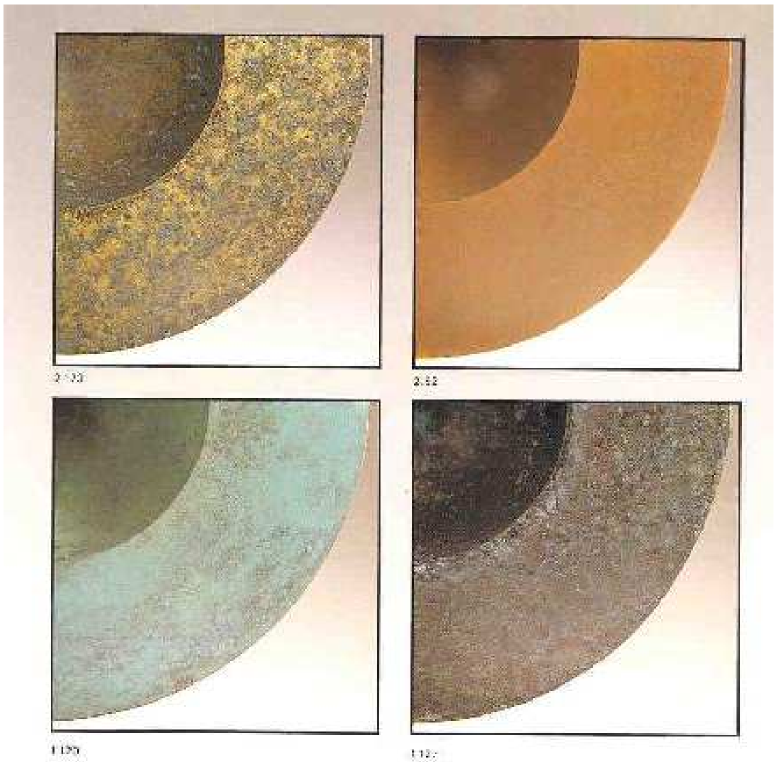

Figure 17: Examples of patinas from [10].

but it is wrong: for example, it does not predict reflection from rough surfaces. Another phenomenological model widely used in CG is diffuse reflection:

$$L = p * E_i * \cos(\theta_i)$$

There are no materials in nature that have completely diffuse reflection. However, reflection from surfaces of many materials can be reasonably approximated by this formula, without going into the details of any actual physical processes. In reality, when reflection from the surface is nearly isotropic, it is a result of multiple subsurface scattering. The third model of this kind is the BRDF – bidirectional reflection distribution function. This is a nice mathematical and physical abstraction that hides the complexity of the interaction of light with matter.

Sometimes, a well-chosen simplification can lead to a useful model works as an approximation in a wider variety of conditions. Consider the Torrence-Sparrow model, which assumes that surface microfeatures are V-grooves, and tries to predict reflection from such a surface. Of course, no surface actually fits this model, but analyzing the reflection from such a surface makes it possible to get at the heart of what is really happening, and results can be be quite good at predicting reflection from actual rough surfaces. Other mathematical abstractions are Gaussian rough surfaces, Zernicke polynomials/splines/wavelets, and Schlick's Fresnel approximations.

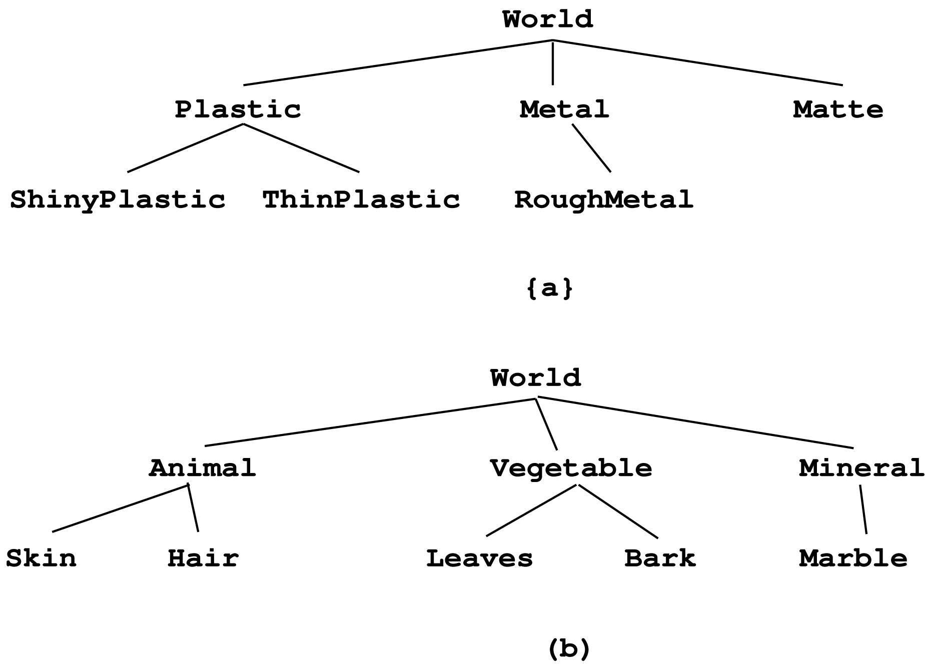

Figure 18: Taxonomy of materials. (a) in RenderMan, (b) natural.

Even though it might be desirable, it's very unlikely that a complete, comprehensive, unified appearance model for every material will ever be created. However, it is quite feasible to build a taxonomy of models, and this has been done by a number of people. Part of Pixar's RenderMan taxonomy [1] is drawn in figure 18(a). Plastic, Metal, and Matte materials applied to a vase can be seen in figure 19. A different, somewhat more natural taxonomy of materials is shown in figure 18(b).

Figure 19: Examples of RenderMan materials applied to a vase.

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