Overview of Appearance Models

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1 Introduction

Figure 1: Rust.

The exist many kinds of surfaces in the natural world: shiny, glossy, lustrous, matte, metallic, etc. Their appearance can be very complicated, for example, rusty metal (Fig. 1). To be able to capture all this richness, computer graphics uses geometry and radiometry/photometry (explicit modeling or texturing/BRDF). In this class, we will be talking about appearance and the modeling of appearance in general, with an emphasis on reflection models, transmission, scattering, and participating media (volumetric effects). We will not talk much about color, since it's quite well studied, or about the modeling of geometry.

This subject is interdisciplinary: it is studied from different points of view in such areas as physics, material science, perception in psychology, and art. With computers, however, we can study phenomena that have traditionally been too complicated to model by hand. Despite the richness that computer graphics has achieved, though, the lack of good appearance models has been apperant in rendered images of natural objects: animals, plants, minerals. Other applications of appearance modeling include ceramics, pigments/dyes, building materials, cleaning and polishing, textiles, metals, cosmetics.

This class will cover the 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 latter 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.
- Structural Models (description of structure of materials vs. texture map, for example).
- Phenomenological Models (equations that capture the way things look).

2 Physical Processes

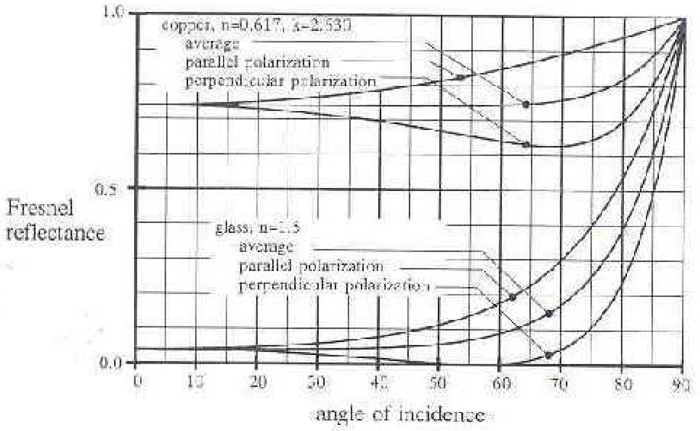

Figure 2: Fresnel Reflectance. Top curves — copper, bottom — glass.

The Fresnel equations describe the surface reflection of pure, smooth materials. Figure 2 shows these reflectance curves for copper and glass. If you look at the glass from different angles, the amount of reflected light will change as the result of processes described by

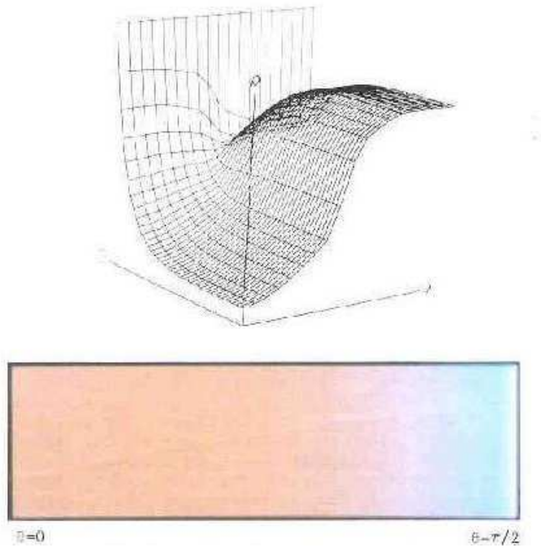

Figure 3: Reflectance and Color of copper mirror.

Fresnel. At grazing angles there is almost total reflection, but at normal incidence very little light is reflected. Also, there is no color shift.

Reflection from metals differs considerably, since the percentage of reflected light changes with wavelength. This can cause a color shift, as illustrated in Figure 3. Classic examples of attempting to model this effect in computer graphics may be found in papers by Pete Shirly and Rob Cook (the Cook and Torrance reflection model, e.g. Figure 4).

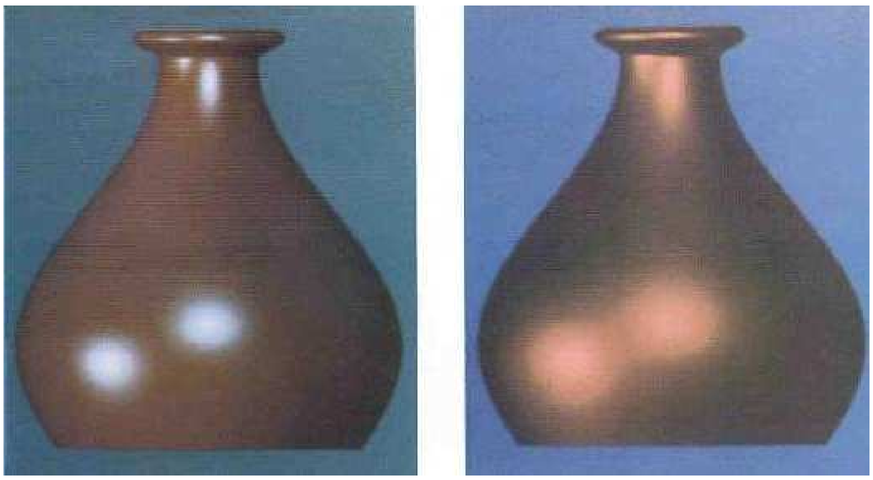

Figure 4: Copper-colored plastic (left) and copper (right) vases. Rendered using the Cook-Torrance reflection model.

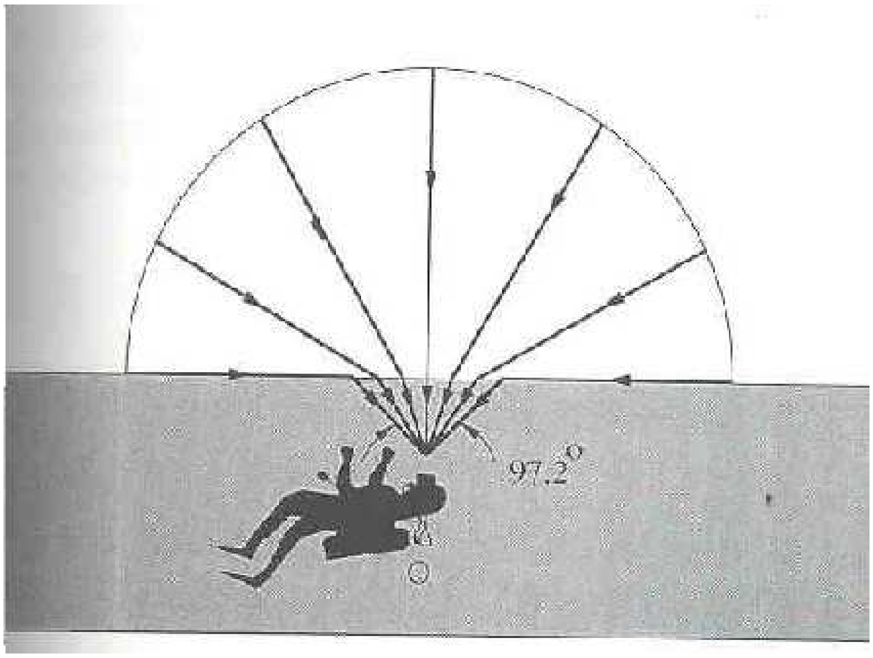

Figure 5: Optical manhole effect.

Another reflection-related phenomenon is total internal reflection, which occurs when light reflects off a boundary from a material with a high index of refraction to a material with a lower index (e.g., water to air). The optical manhole effect (Fig. 5) can be seen by a diver looking up from below the water's surface. He sees the whole sky compressed to a part of the hemisphere around the zenith, and at directions near the horizon there is no light.

The roughness of surfaces at various scales accounts for lots of interesting reflection effects. A classic example is a CD, which displays colorful interference patterns due to small features on its surface (Fig. 6 and 7).

Another example, this time at a larger scale, is reflection of the sun in the sea. If the surface of the sea were perfectly flat, then the reflection would be just a disc; because of waves, the reflection is a very long oval (Fig. 8).

A very important part of appearance is self-shadowing of surface features. You can see this in images of the moon with its highlights and shadows (Fig. 9), but some surfaces, if looked at closely, reveal a similar surface structure with bumps and pits (Fig. 10). The appearance of such bumpy surfaces also changes with view direction.

The measurement of reflection is important for understanding physical processes. Such measurements are made by illuminating a portion of the material from a single direction, then collecting the reflected light as a function of angle. Performing such measurements is difficult, however. One complication that may arise is interreflection from locally-concave portions of the surface.

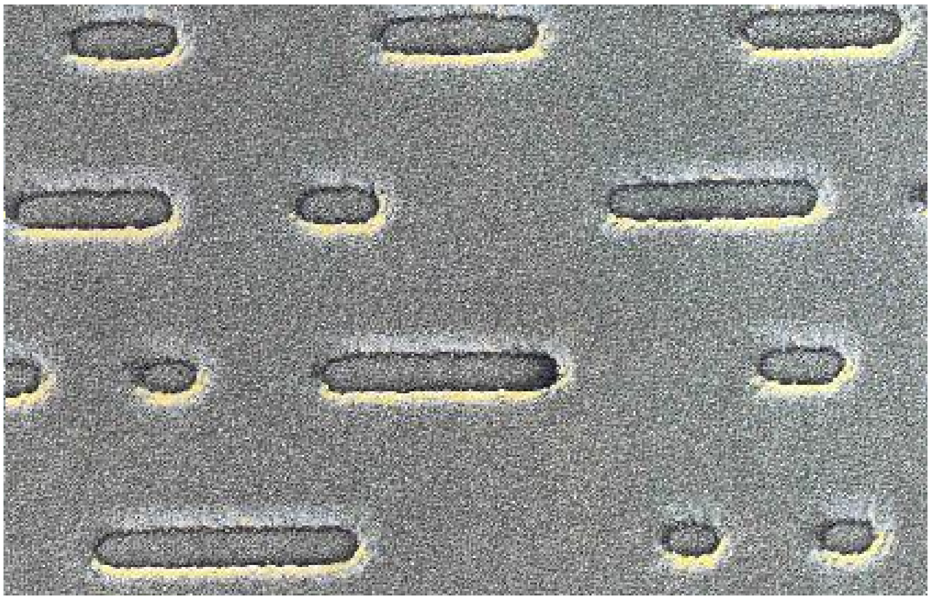

Figure 6: Closeup of CD surface.

Figure 7: Rendered CD from Jos Stam's 1999 SIGGRAPH "Diffraction Shaders" paper.

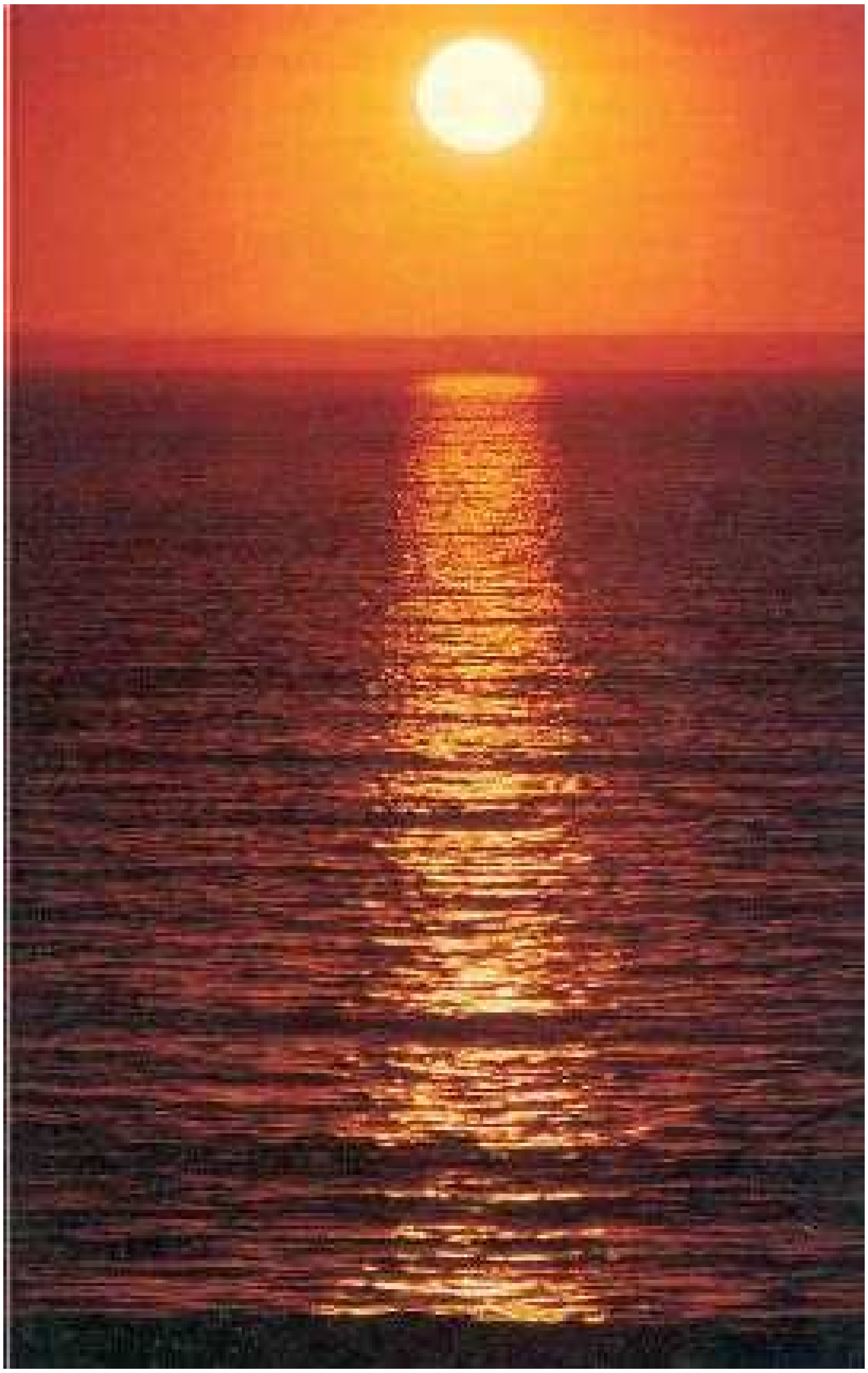

Figure 8: Sunset.

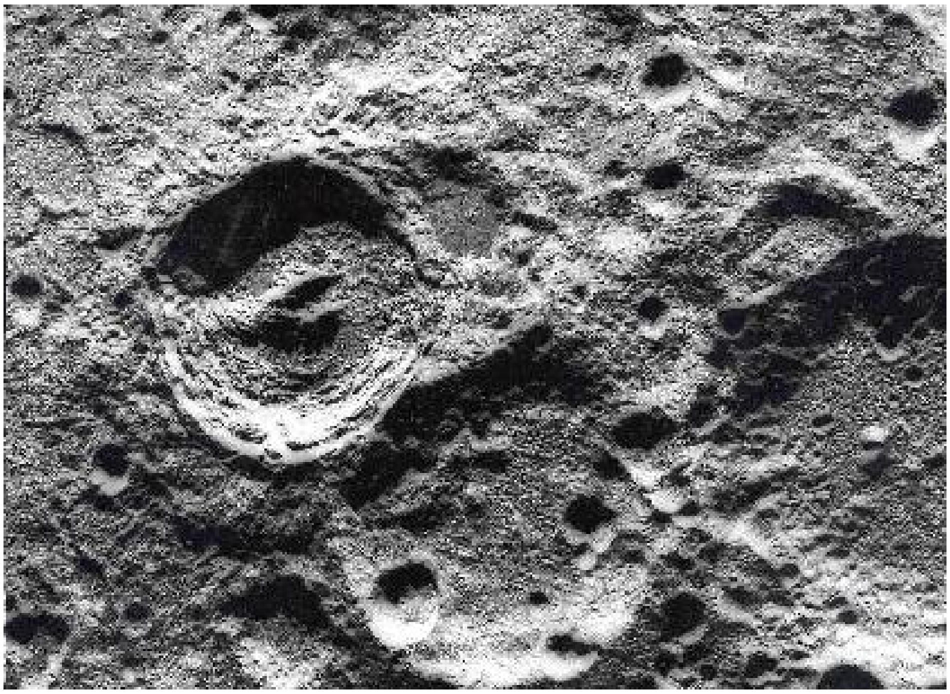

Figure 9: Moon surface.

Figure 10: Painted stucco from "Surfaces" by J. Juracek.

Figure 11: Marble Taiwan Green Dark, from "Surfaces" by J. Juracek.

Figure 12: Yellowstone's Opalescent pool.

One more class of physical phenomena which we will consider is volumetric effects. The appearance of transparent materials and participating media depends on scattering and absorption of light within. For example, the appearance of marble (Fig. 11) is affected by subsurface scattering. You can see very exotic colors in the water of the ponds of Yellowstone (Fig. 12) due to scattering and absorption from minerals and sediments suspended in the water. A striking example of the effect of atmospheric scattering can be seen from pictures taken in an environment without atmosphere (Fig. 13).

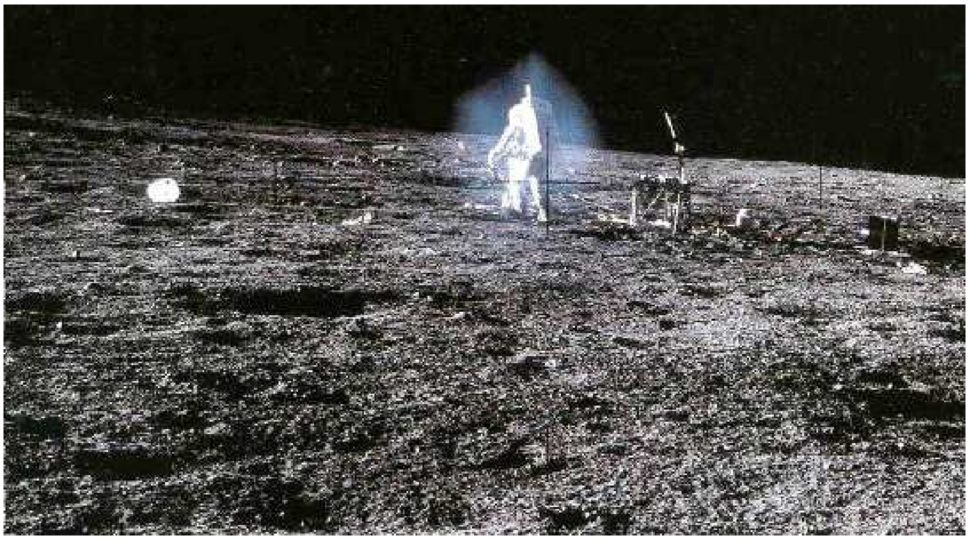

Figure 13: Glow around an astronaut.

When considering the effects of volumetric scattering, it turns out that the important quantity is albedo, which is 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 material is raised, the material looks more white. A classic demonstration of this is described in "The Measurement of Appearance" by Hunter and Harold. Fairly large pieces of green glass are put in a bottle. The glass looks quite green. Then the glass is crushed more and more, and it looks more and more whitish. (Fig. 14).

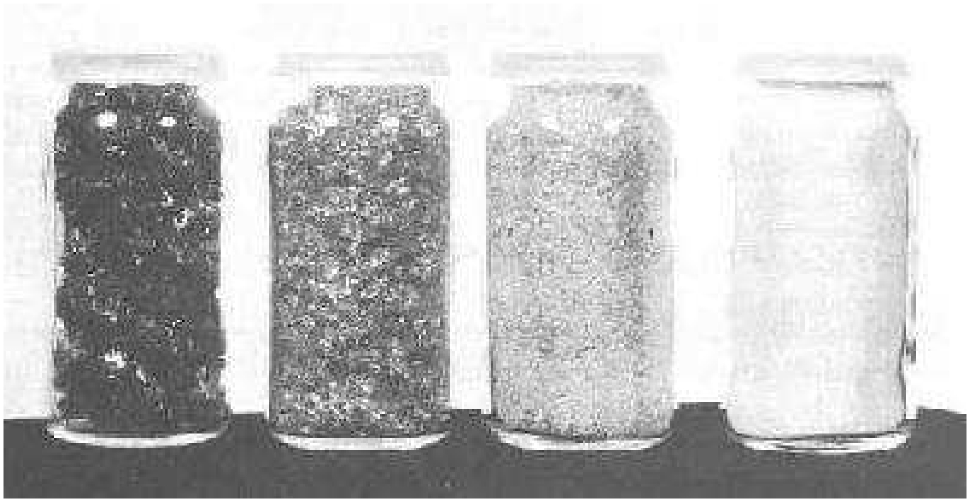

Figure 14: Crushed glass.

The explanation of this phenomenon is that as the number of particles increases and their size decreases, the probability that a ray of light will be scattered increases. Thus, the light is increasingly likely to undergo (spectrally uniform) surface reflection, rather than volumetric attenuation.

Another example is clouds. Absorption is low, but scattering is very high, and so almost all the light that goes in the cloud eventually gets out. The result is a very bright white color. Sometimes you can see black clouds in front of the Sun – this means that little light goes through the cloud, but it is scattered in different directions, rather than being absorbed.

3 Structural Models

The second way of looking at appearance is understanding the structure of materials. It's very hard to model the appearance of things in nature without knowing their microstructure, especially such complex materials as rust, butterfly wing, insect eye, fabric, etc. (Figs. 15, 16)

Some materials, for example patinas (Fig. 17), consist of multiple layers. Modeling such layering is important, since it has a large effect on appearance. Layered reflection models have been used in computer graphics (e.g., Hanrahan and Krueger) to render materials such as skin, leaves, patinas, varnishes, and dust.

Figure 15: Butterfly wing.

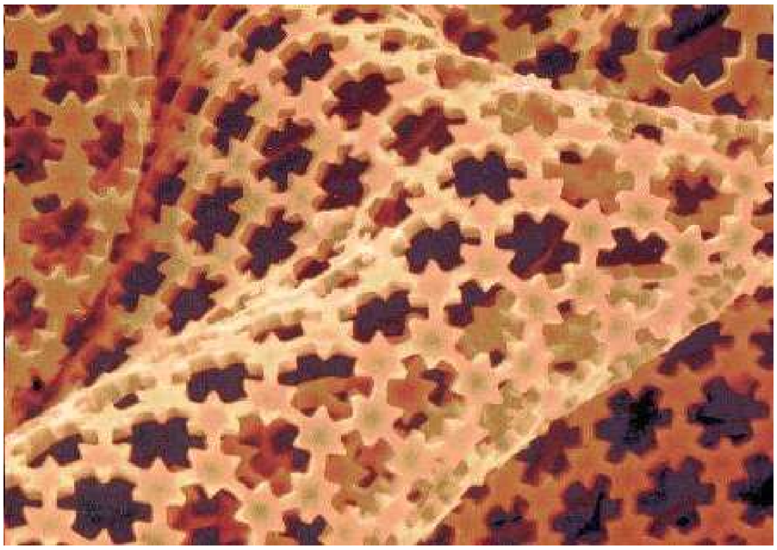

Figure 16: Plastic microfabric.

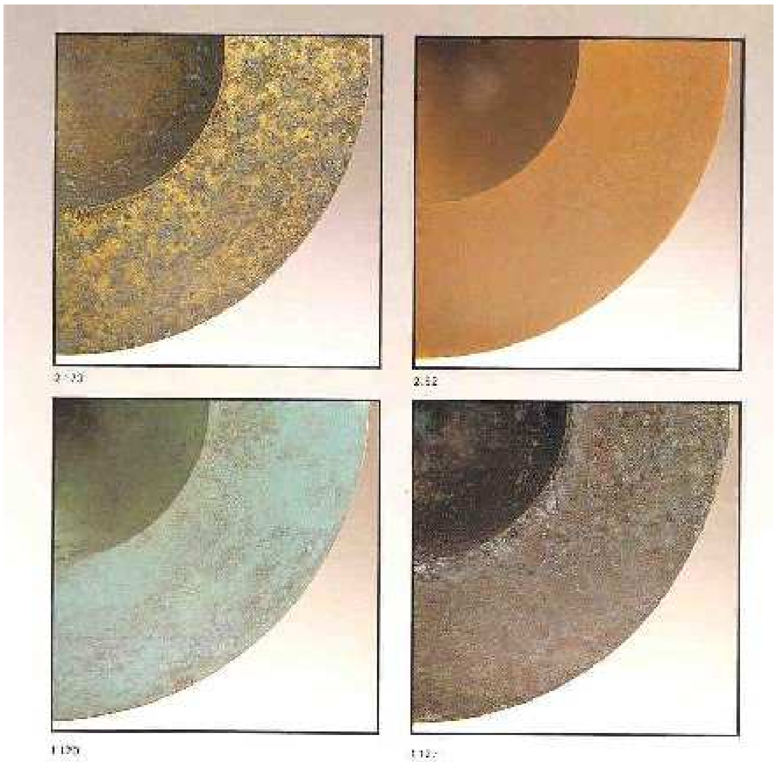

Figure 17: Examples of patinas from "The Colouring, Bronzing and Patination of Metals" by Hughes and Rowe.

A different kind of modeling consists of simulating the history of global effects, rather than just trying to predict appearance based on local phenomena. One example is the work of Hanrahan and Dorsey on modeling weathering effects on the surfaces of buildings and statues. The appearance is modeled by simulating the flow of water on surfaces, and can include such effects as erosion and particle deposition.

4 Phenomenological Models

The third way of simulating appearance is to use phenomenological models. An early example was the Phong model. This model has no physical basis, it just attempts to capture the appearance of highlights on surfaces from point lights (which do not exist but are used in computer graphics) without any of the complexities of physics. According to the Phong model, the value for the spread highlight at particular point is

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

It turns out that this is equivalent to using light source of finite size. Phong's model works in certain situations, but it is wrong: for example, it does not predict many properties of the actual 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, but multiple subsurface and surface scattering can cause materials to appear approximately diffuse.

A third model of this kind is the BRDF — bidirectional reflection distribution function. It is a nice mathematical and physical abstraction that hides the complexity of interaction of light with matter.

It is often useful to introduce simplifying assumptions when trying to come up with a mathematical model of some phenomenon. For example, the Torrance-Sparrow model assumes that surface microfeature consists of V-grooves, and tries to predict reflection from such a surface. Of course, no such surfaces actually exist, but the assumption simplifies the math and makes it possible to get at the heart of what is happening. In addition, the results might adequate for predicting reflection from actual rough surfaces. Other mathematical abstractions include Gaussian rough surfaces, smoothness assumptions (e.g., assumptions that BRDFs may be decomposed using smooth basis functions), and mathematical simplifications of certain phenomena (e.g., Schlick's Fresnel approximation).

We may also apply the concept of phenomenology to the classification of reflectance models. Although it would probably be impossible to create a complete comprehensive single model for every material, it's feasible to build a taxonomy of models. Part of Pixar's RenderMan taxonomy is drawn in Figure 19(a). Plastic, Metal, and Matte materials applied to a vase can be seen in Figure 18. A different, somewhat more natural taxonomy of materials, as in Figure 19(b), might be just as interesting.

Figure 18: Examples of RenderMan materials applied to a vase.

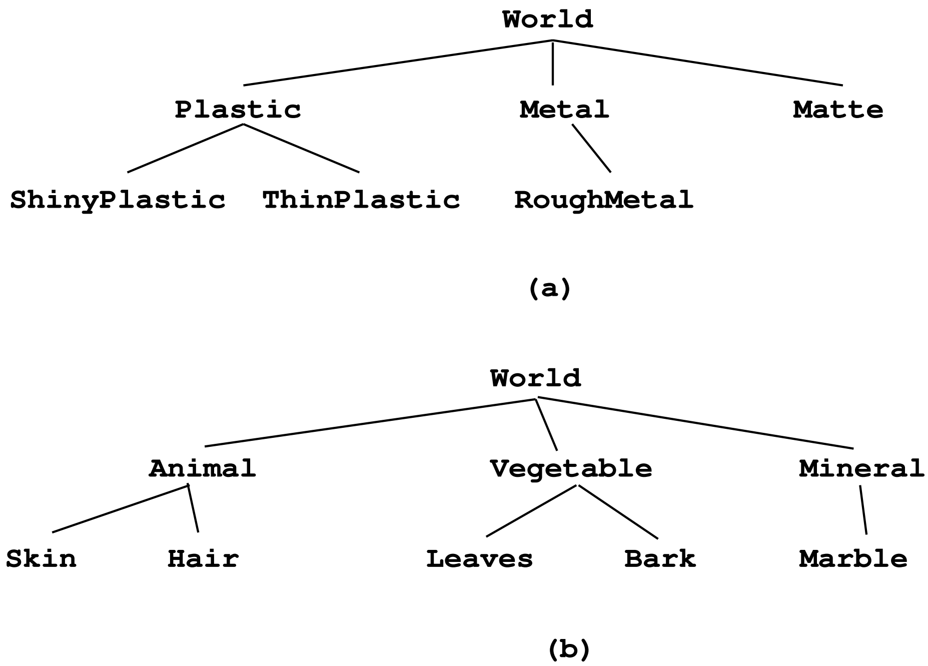

Figure 19: Taxonomy of materials. (a) in RenderMan, (b) natural.