# Digital Materials and

The next step in creating more realistic computer-generated images is the development of better models of the physical structures of materials and their degradation by the environment

by Julie Dorsey and Pat Hanrahan

Computer graphics passed an entertainment milestone in 1995 with the release of *Toy Story,* the first full-length movie animated using computers. But the digitally created characters and sets of such productions generally still have a distinctive look that sets them off from reality: everything is a little too smooth and perfect, a little too clean, as if freshly molded in plastic. What's missing is dirt and dust, cracks and scratches; a dribble of rust down a wall from a leaky pipe; a patchy green patina of oxidation on a copper statue; the salt-crusted, weather-beaten face of an ancient granite sphinx; the fine tones of human skin, complete with freckles, pores, wrinkles and a slight flush of living blood.

The Pixar team, which released *Toy Story 2* late last year, does add weathering effects such as scuffs and dirt by painting patterns onto surfaces, but this process is ad hoc and very time-consuming. More intensive application of these established techniques or brute-force application of greater computing power will not be enough to overcome the cartoonish, waxen look of computer graphics. To produce a simulation that doesn't *look* like one, we must properly model the appearance of materials in all their variety, including realistic wear and grime. Techniques such as ray tracing and radiosity, which simulate lighting, can add to the ambience of virtual scenes with effects such as soft shadows and reflections, but the accuracy and visual complexity of the resulting images also depend crucially on the quality of the underlying material models.
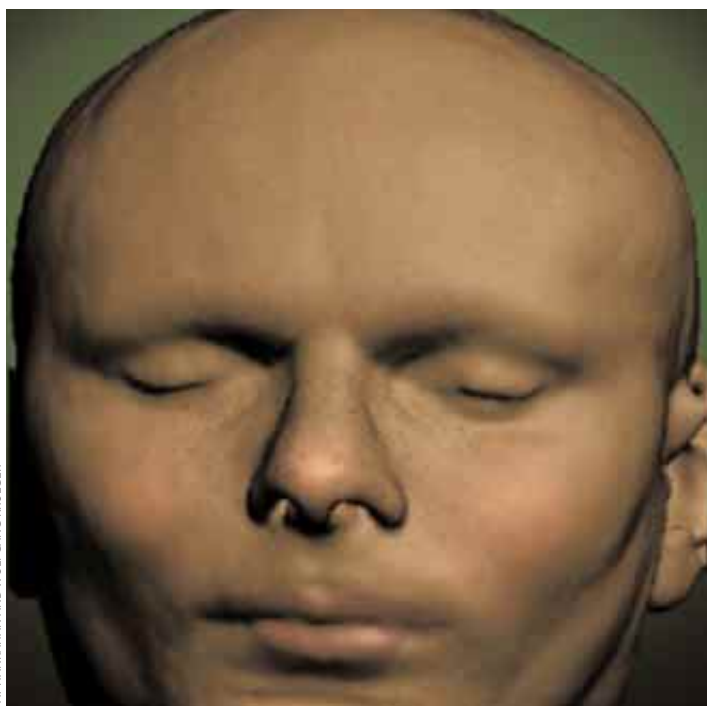
Such models are becoming increasingly realistic. An important feature of them is explicit modeling of a material's

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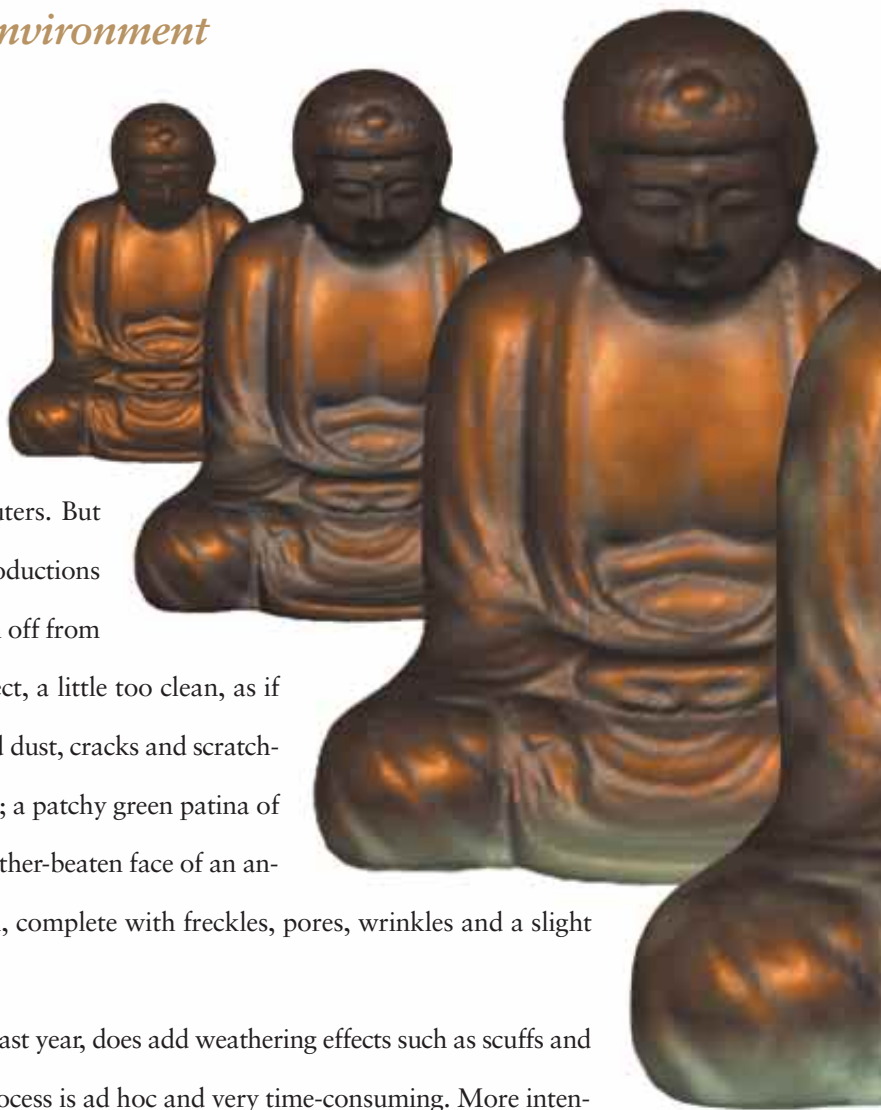
Virtual Weathering

PATINA DEVELOPMENT ON A COPPER BUDDHA is simulated using a series of layers to represent the physical structure of the surface. Different operations oxidize the top layer and remove loose material as if under the action of wind and rain. Interaction of light with the stack of layers determines the resulting appearance.

HUMAN SKIN is among the most challenging appearances to simulate well. This image models the interaction of light with the outer epidermis and the underlying, blood-rich dermis. The lips, for example, are pink because of their thin epidermis. The data for this image were obtained by a medical MRI scan.

internal structure and the simulation of light propagation and scattering beneath its surface. Another is the modeling of how a surface evolves under aging phenomena such as corrosion, which can add irregular layers of oxides and also break away pieces of the surface. An exciting possibility for the future would be a palette of software tools enabling artists to "brush on" physical processes of this kind, in the same way that they can apply "paint" and other coloring effects on screen today.

Such image-making, or rendering, technology is becoming widely used in industry and not merely in animated movies. Boeing used rendering technology for virtual-reality systems to design its 777 aircraft. Architecture firms and city planners use rendering to assess the visual impact of proposed buildings on neighborhoods.
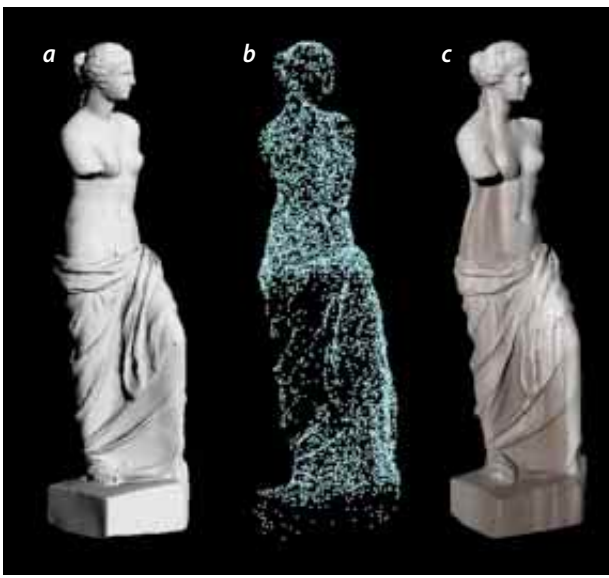
Ray Tracing, Reflection and Texture

Scientists and artists have long theorized about the causes of appearance in the natural world. During the 17th century, Rembrandt and other Dutch and Flemish artists reproduced natural skin tones in their lifelike portraits by applying multiple layers of paint and lacquer. In the 19th century Lord Rayleigh used principles of physics to explain the sky's blue color, the iridescence in butterfly wings and the shine of polished surfaces. Today we can use such theories and insights to create practical computer simulations of the mechanisms that generate different appearances.

The rendering of realistic computer images requires simulating light and its interaction with the environment, which includes objects (such as sets, props and characters), lights that shine on them and a virtual camera that observes the scene. The objects are defined by their shapes, positions, orientations and materials. Once the scene has been modeled, the rendering program computes the paths that light follows from the light sources to the camera [*see upper illustration on page 70*].

Several techniques may be used to simulate light propagation. The radiosity method models how light reflected from a matte surface illuminates the surrounding area. Ray tracing

tracks rays of light one bounce at a time. The current state-of-the-art technique is stochastic ray tracing: rays hitting a surface are reflected randomly in different directions according to probabilities that may depend on properties of the surface or other parts of the environment. This technique can reliably simulate the interaction of light with a wide variety of complex shapes and materials.

The basic methods for rendering were developed during a few groundbreaking years in the 1970s at the University of Utah. These early shading models were hybrids, combining aspects of lighting simulation, reflection models and interpolation. Shapes were often approximated by a mesh of triangles. Henri Gouraud developed a method whereby the vertex of each triangle was lit and the color of the reflected light was interpolated across the triangle. Lance Williams and Edwin Catmull (later a co-founder of Pixar) first proposed texture mapping, in which the color of an object is controlled by an image that is mapped onto the three-dimensional shape of the object's surface, similar to the pasting of a decal on a plastic toy.

The earliest computer graphics models of how light reflects from objects tried to capture the major aspects of appearance by simple formulas, without drawing on physical principles to simulate the interaction of light with matter. These phenomenological reflection models, as they are called, use a mathematical function called the bidirectional reflectance distribution function, or BRDF [*see box on page 69*]. Types of BRDFs range from those of matte materials such as cardboard, which scatter light equally in all directions (Lambert's Law of Reflection), to those of perfect mirrors, which reflect a ray of light in a single direction [*see lower illustration on page 70*]. Between these extremes, shiny surfaces produce a distribution of reflected light roughly centered in one direction. Such surfaces are typically modeled by adjusting the size of the shiniest spots of reflected light.

In computer graphics, texture and reflection are considered separate aspects of appearance. In fact, visual texture is more distinctive than the reflective property for most materials, so generating and using textures to control the reflective properties at different points on the surface is an important ability. Two techniques are widely used to create combinations of texture and reflection: procedural models based on shading and direct three-dimensional painting. These two approaches represent different ends of the spectrum, one highly programmed and the other highly interactive.

A procedural model requires a computer program to generate the desired pattern. For example, a wood pattern can be defined by an algorithm that creates a solid texture of 3-D concentric rings. The ring pattern then controls the color and intensity of light reflected from pieces such as table legs carved from the wood. At the other extreme, in direct 3-D painting the artist applies simulated paint to a 3-D shape. The paint's properties determine the material's appearance, and patterning is obtained by applying different strokes on different parts of the shape. Because the 3-D painting metaphor is natural and intuitive to an artist and because such systems give the user immediate feedback by instantly displaying chang-

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EFFECTS OF RAINWATER and dirt on a replica of the Venus de Milo (*above, a*) were simulated using a model of individual raindrops (*b*) to yield a dirt-streaked statue (*c*). A similar process simulated the effects of rainwater flows on a building facade (*right*).

es, they are widely used in the entertainment industry.

Although these approaches are very powerful, they have several limitations. First, they are often tedious and labor-intensive: imagine painting a complex stone pattern on a building. Clearly, algorithmic techniques could help with this process. Second, as the use of computer-generated images becomes more widespread, a greater range of appearances must be simulated. Ad hoc techniques that work well enough for specific objects and applications soon run up against their limits. The desire to go beyond these limits has spurred a new trend in image-synthesis techniques: the inclusion of more information about material structure and the interaction of light with matter.

Roughing It Up

The roughness of a surface is a good example of a material structure that affects appearance. Metal that has been brushed or machined often contains microgrooves etched into its surface. Materials such as cloth contain cross-hatched fibers (the warp and woof) that create bumps and valleys. The features of a surface can also change over time; for instance, when a surface is polished, bumps are removed, making it shinier.

The microgeometry of a rough surface may be modeled by a height field that perturbs the position of the surface by a small amount at each location. These displacements may be given by a random function with specified statistical properties or by a detailed map of the microscopic structures on the surface.

Reflection from rough surfaces was first studied by scientist Pierre Bouguer during the Enlightenment. He assumed that a surface was made up of many "microfacets" (he called them "micro faces"). The amount of light reflected toward a viewer was determined by the proportion of microfacets that were aligned to reflect light directly from the source to the viewer. Bouguer hoped to explain Lambert's Law, which describes the appearance of matte surfaces, by constructing an arrangement of microfacets that would reflect light equally in

all directions, but this was eventually proved to be impossible.

For specular or glossy surfaces, however, microfacets have become the most widely used model. Computer graphics simulations of reflection can directly specify the distribution of microfacet alignments. Typically a simple distribution is used, with a roughness parameter defining how much the microfacets deviate from the main surface shape.

Microfacet distributions have their limits even for glossy surfaces. For example, when light strikes a rough surface from a low angle, the high peaks will shadow the valleys, dramatically changing the appearance of the surface. Unfortunately, computing such "self-shadowing" effects for microfacet distributions is very difficult. An even more complex problem arises when the wavelength of light is comparable to the size of the surface undulations; then Bouguer's simple model of reflection does not apply, and wave effects such as diffraction and interference can come into play.

More Than Skin Deep

Surprisingly, the physical process of reflection from many materials does not result from light interacting with the surface itself, that is, with the infinitesimal interface between the air and the medium. Instead interactions occur inside the material. This phenomenon, subsurface scattering, is common in organic materials, as well as plastics and other composite materials. The relevant depth can range from microns in the case of paint or other coatings to millimeters in the case of skin or marble.

In subsurface reflection, light crosses the interface into a material. Inside, the light is scattered and absorbed by the con-
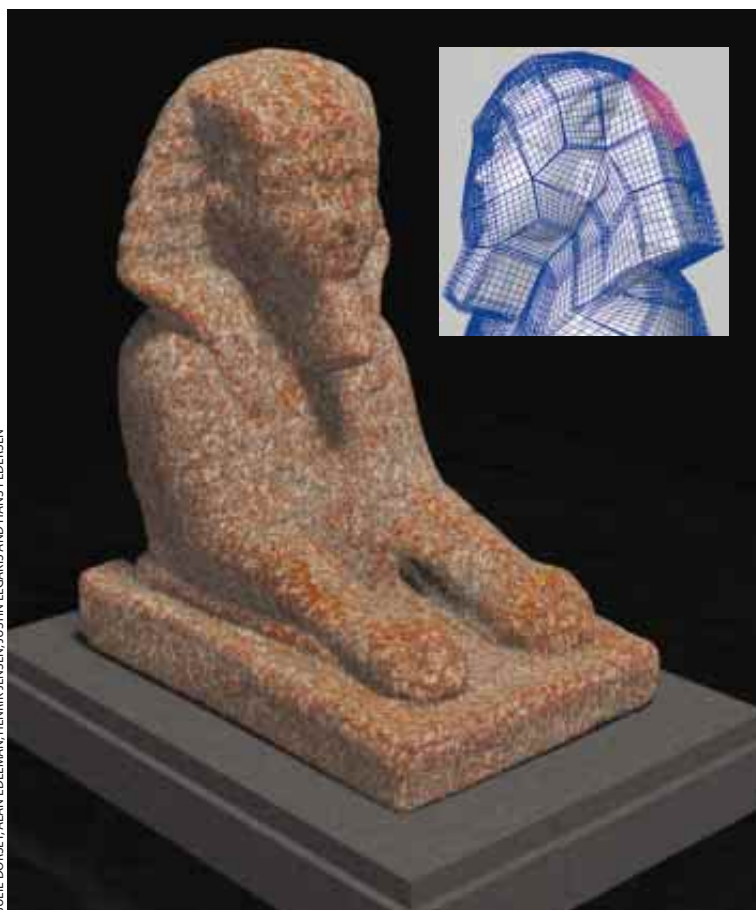
WEATHERING OF A GRANITE SPHINX is simulated using a three-dimensional shell (*inset*) that extends from the stone surface into the interior. Water and contaminants invade this shell, inducing chemical changes and producing decayed minerals, recrystallized salts and an eroded crust.

the light's direction account for the matte appearance.

To create a colored paint, a small amount of pigment is added to the white paint and mixed. These pigments are chemicals that selectively absorb certain wavelengths. Because the pigment particles are suspended in a nearly perfect scattering media, eventually the light interacts with a pigment particle and is partially absorbed; the exiting light takes on the color of those wavelengths that are not absorbed. A model for this process was originally introduced by P. Kubelka and F. Munk in 1931. They assumed that the medium contains particles that scatter and absorb light equally in all directions, and they deduced the color and intensity of the light returning from the medium as a function of its thickness and the concentrations of pigment particles. Their model can be used to simulate the color changes caused by varying the thickness of the coat of paint or by mixing different pigments together. They also showed how to calculate the effects of multiple layers of paint, each with a different color or composition.

The Kubelka-Munk model is the simplest and most widely used model for subsurface reflection. But because it assumes that the particles scatter light equally in all directions, it works only for matte materials. Subsurface reflection can also distribute light in preferred directions, as occurs with glossy surfaces, and models have been devised to account for these effects. The basic idea of these models is to allow directional scattering by the particles. The returning light is approximated by dividing it into two parts: the first is light that exits the material after a single sharp scattering event, and the second is the remaining light that is scattered many times. As in the Kubelka-Munk model, the multiply scattered light is assumed to obey Lambert's Law, but the light from single scattering events is distributed according to the scattering function of the relevant particle.

We have applied these ideas to model the appearance of skin, which has long been a key material that computer graphics systems have striven to simulate, without much success. Skin is particularly challenging both because it has a complicated structure and because our human visual systems are highly tuned toward perceiving faces. Subsurface scattering from multiple layers turns out to be quite effective at meeting these challenges.

Human skin consists of two major layers: the inner dermis and the outer epidermis. The dermis is rich in blood, making it red. The epidermis is thinner than the dermis but contains melanin—increasing concentrations of melanin makes the epidermis brown or black. Also, the epidermis may be covered by oil, dirt or cosmetics.

To generate realistic images of faces, we can control the simulated concentrations of blood and melanin and also the relative thicknesses of the dermis and epidermis. For example, because the lips contain only a very thin layer of epidermis, they look redder than the rest of the face. Freckles are modeled by splotches of additional melanin scattered randomly on the cheeks [*see illustration on page 66*].

Early computer graphics models were idealized: by default,

stituents of the medium, such as individual atoms or molecules, similar to how light might interact with a misty cloud of water vapor. Scattered light can travel back to the surface and exit the medium, appearing to the observer as reflected light. Most of the scattering events in the medium are like glancing blows that deflect the light by less than 90 degrees, and so it can take many such collisions to redirect light back toward the outside. As more deflections occur, the directions of light propagation become randomized. This process, which predicts that light may exit the material in a random direction, is thought to be the mechanism that gives rise to Lambert's Law.

The theory of scattering in a layered media was originally developed to explain radiative transport—the movement of heat and light by radiation—in planetary and solar atmospheres. It has been further developed by researchers interested in the appearance of paint, skin, vegetation and the ocean. Such models have recently been adapted to computer graphics. Interestingly, a clean painted wall and the fine skin tones of a person's face, which are respectively among the simplest and most challenging of appearances to model, are both well described by subsurface scattering.

As anyone who has gone to the hardware store to buy a can of paint knows, the paint mixer starts with white paint. The paint's whiteness comes from titanium dioxide, which is an almost perfect scatterer and does not absorb any light. When light falls on a surface painted matte white, the light enters the coat of paint and is scattered many times by the suspended titanium dioxide particles, ultimately exiting the paint and returning to the environment. The whiteness of the surface occurs because very little light is absorbed, and all the visible wavelengths of light are returned equally. The multiple scattering inside the paint and the resulting randomization of

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Modeling Reflection

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The reflection of light from a surface may be characterized by the BRDF, or bidirectional reflectance distribution function. This mathematical function specifies the percentage of light arriving from each incoming direction that is reflected in each outgoing direction.

The oldest reflection model is the Law of Reflection, known to the ancient Greeks, that says the angle of reflection is equal to the angle of incidence. For a given incoming direction, this is described by a BRDF that is zero in all directions except in the single outgoing direction where all the light goes.

Another reflection model is Lambert's Law, which states that light reflects equally in all directions, independent of the incoming direction. Lambert's Law is a good example of a phenomenological model, because it nicely captures the appearance of matte materials such as cardboard, without describing a physical mechanism that would cause light to be equally reflected in any direction. In fact, explaining Lambert's Law from underlying principles has been a challenge to researchers throughout history. Between the extremes of mirrors and matte surfaces, shiny surfaces have BRDFs that describe a distribution of reflected light roughly centered in one direction.

The BRDFs of materials have been measured directly for many years by optical and radar engineers and others interested in the properties of exotic materials. Such measurements were no doubt important in designing stealth aircraft. BRDFs also interest scientists doing remote sensing of the earth's surface from satellites: the appearance of forest, crops and so on varies according to the angle of the sun and the satellite's viewing angle. This problem is the inverse of simulating the look of a material: deducing a material based on its appearance.

An instrument designed to measure BRDFs is shown at the left. In the instrument, constructed at Stanford University, a small sample is placed in the center, a light source shines on the sample, and a photometer systematically moves to different positions on the hemisphere, measuring the light reflected in each of those directions. The measurements are repeated with the light source moved to all positions on the hemisphere to acquire the material's entire BRDF. Measured BRDFs have yet to find wide use in computer graphics, but several groups are pursuing this approach.   —*J.D. and P.H.*

LAMP
CAMERA

Measuring an object's reflectance.

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they assumed the materials to be in pristine condition. In reality, of course, all materials change when exposed to the surrounding environment. Some of the richest appearances in the real world—mellowed brickwork, rusty metal, moss-covered stone, seasoned timber—arise from physical processes such as corrosion, erosion, biological growth and sedimentation. A material's tendency to weather is closely linked to its structure. Stone, wood and metals weather quite differently because of their distinct structures. Methods of preparation such as quarrying, polishing and staining are also important. We have recently begun to develop models for some of these processes that affect appearance, first identifying the basic physical phenomena that underlie a specific change in appearance and then developing the appropriate computer models.

Simulating Corrosion

Metallic patinas are a classic case of appearances that develop when materials interact with their environment. A patina is a film or encrustation on a surface that is produced by chemical alteration or by the addition or removal of material. Patinas can develop naturally through atmospheric corrosion or artificially through painting or other craft processes. A patina's composition and rate of development depend on the surrounding environment. For example, patinas generally develop more rapidly in urban settings than in rural areas because city air has higher concentrations of sulfur. Rainwater and other factors also play an important role in the formation of patinas.

We have developed a phenomenological model for the development of copper patinas. The surface is represented as a series of layers, and patinas are formed by applying a collection of intuitive operators, such as "coat," "erode" and "pol-

ish," to the layered structure. For instance, applying "coat" to a region adds some oxide to the top layer. "Erode" simulates the removal of loose material through the action of wind or rain. To simulate detailed variations in thickness over time, we have experimented with a series of models for use with the layer structure in which a patina grows across the surface in a fractal pattern. (Fractals have been put to great use in computer graphics, such as the generation of realistic-looking terrain, vegetation and so on.) The final appearance of the copper patina depends on how light interacts with the stack of layers, for which we use the Kubelka-Munk model [*see illustration on pages 64 and 65*].

The flow of rainwater is one of the most important and pervasive natural forces contributing to the weathering of materials, producing distinctive patterns. Water may clean some areas by washing dirt away, while staining other areas by depositing dirt and other substances. To simulate these processes we have developed a simple "particle" model of water flow.

Each particle represents a drop of water. The motion of each particle is controlled by factors such as gravity, friction, wind, roughness and constraints that keep the particles in contact with the surface. A set of equations govern the chemical interaction of the water and the surface materials: they describe the rate at which the surface absorbs water and the rate of solubility and sedimentation of deposits on the surface. The illustration on page 67 shows the result of applying the model to simulate washing and staining patterns produced on a facsimile of the classic Venus de Milo statue.

We began with a uniform coating of dirt on the statue and then ran a flow simulation to wash the surface. The flow produced noticeable streaks in the dirt patterns, along with a randomness because of the individual particles. Dirt accumulated where the surface was protected from the path of the
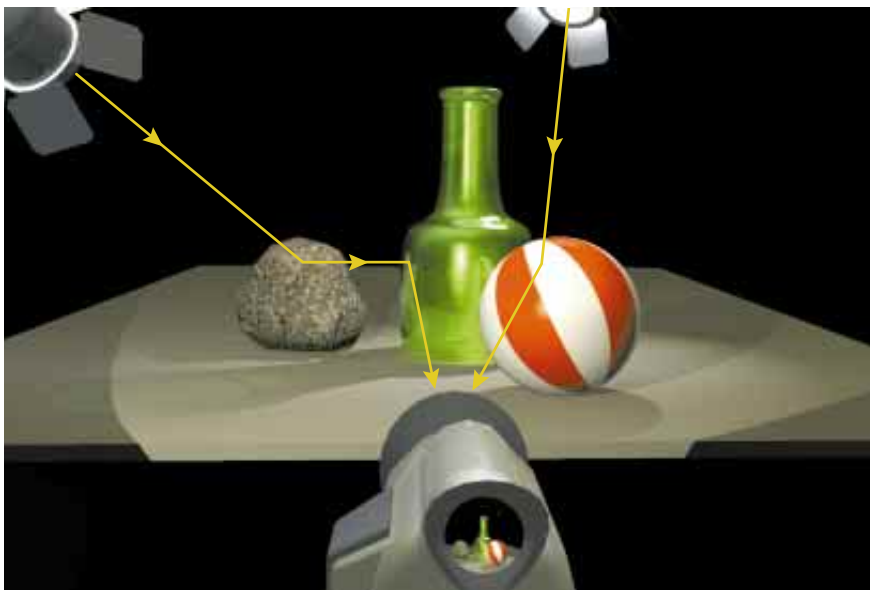
flow, such as under the arm. The dirt pattern conformed to the folds in the fabric; for example, the upper surfaces of the convex parts of the folds were clean, whereas the lower surfaces were dirty. The pattern is more uniform on the base of the statue and closer to the ground, because less water reached those areas. The illustration on page 67 also shows the results of such water flows applied to a building facade.

Both the copper patinas and the "particle" model of water flow simulate only surface effects; that is, the changes in appearance involve just a thin skin near the actual surface. More recently, we have begun investigating models and processes that are more volumetric in nature, such as the erosion of stone. Stone consists of one or more minerals joined together in a tight fabric. The arrangement of this fabric characterizes the type of stone and partly determines its physical and chemical properties, including its strength, color and durability.

Rocks of Ages

Like metals, stone exposed to the environment is attacked by atmospheric contaminants such as the oxides of carbon, sulfur and nitrogen that in water form the infamous acid rain. Instead of being confined to the surface, this solution penetrates some distance into the stone. The penetrated rock can be changed chemically, and recrystallization can produce a crust that is typically more fragile than the native fabric of the stone. Eventually pieces of the crust break off, exposing fresh stone to further attack. Thus, the net effects of stone weathering include color changes, formation of dirty crusts, erosion of surfaces and structural damage such as cracking.

The illustration on page 68 shows a simulation of a small red granite sphinx that has been exposed to such processes. We model the statue as a shell of stone at the statue's surface that extends a significant thickness into the interior. A three-dimensional function describes which minerals are present throughout the stone fabric of this "volumetric surface." The environmental model includes sources of water and contaminants, and these induce reactions on the surface and inside the shell. In this way, the model generates a complicated surface microgeometry and an intricate volumetric mixture of minerals. To render the translucency and coloration caused by the minerals near the surface, we simulate the scattering of light inside the stone using stochastic ray tracing.

A difficult problem, one that occurs generally in computer graphics, is to avoid having to do an excessive number of computations without compromising the quality of the image. For example, for scenes in which an eroded statue appears in the background, it may be appropriate to replace bump maps (which simulate small geometric irregularities of the surface) with a distribution of microfacets that produce the right texture with a much lower computational overhead. As the camera's viewpoint shifts and the statue moves into the fore-

a   SPECULAR REFLECTION

b   DIFFUSE REFLECTION

c   SUBSURFACE SCATTERING
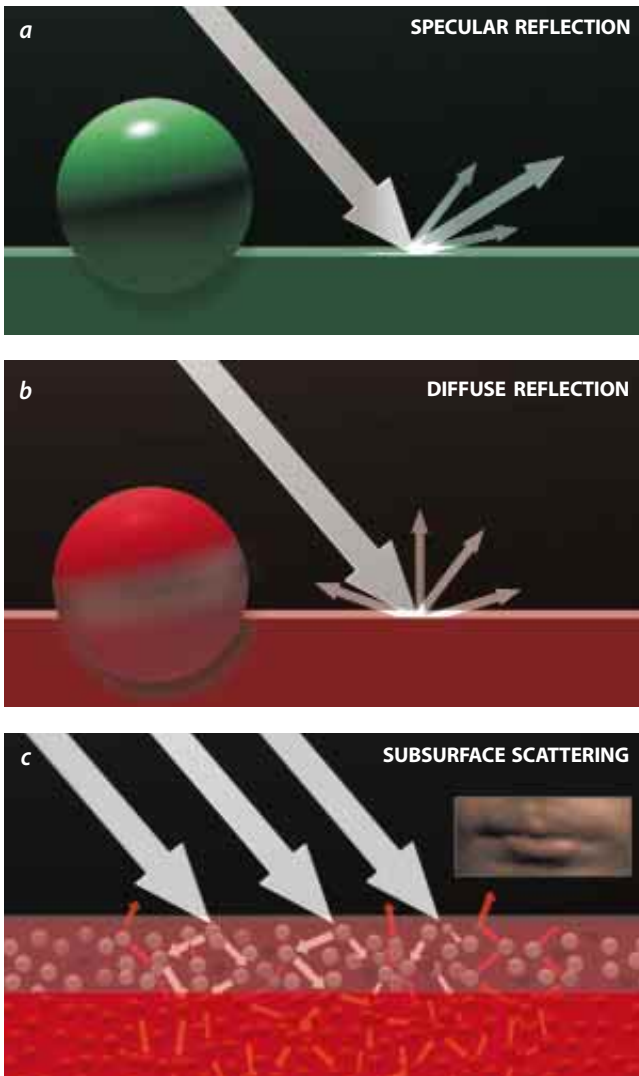
REFLECTIONS FROM SURFACES are a crucial element of image-rendering systems. Specular reflections (*a*) produce shiny surfaces with highlights. Simple matte materials such as cardboard can be modeled using diffuse reflections (*b*) that scatter light equally in all directions. In many materials, subsurface interactions (*c*) play an important role in generating the appearance.

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ground, however, a detailed map of the surface becomes essential for producing a realistic effect [*see box at right*].
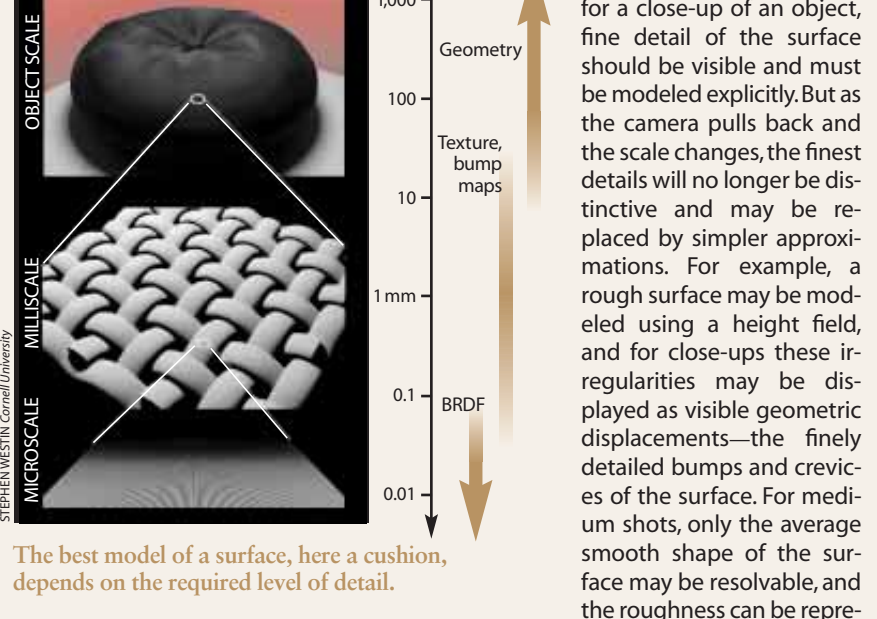
Challenges

The development of material models for computer graphics is only just beginning, but it has already raised some key issues about the models' limitations and trade-offs. Many aspects of appearance are not well understood from physical principles. The corrosion of metals, for example, has tremendous scientific interest and obvious practical importance, but scientists' understanding of the process is far from complete. In addition, the variety of applications that make use of rendering technology places different demands on the accuracy of the models. For instance, in movie production work, appearances merely need to look right—physical accuracy is of secondary importance. In some engineering and scientific applications, however, physical accuracy is critical—creating a different set of expectations for the underlying models. We can see this trade-off in the skin model: although it is convincing enough for many applications, it does not include such elements as hair follicles, pores and oil glands, which would probably be of interest to dermatologists or biologists.

The problem of creating physically based models of materials that can incorporate variations over time is an important challenge for computer graphics. What is needed is a more comprehensive set of models of materials and the processes that affect their appearance. Ideally, computer scientists could create broad taxonomies of materials for easy access by an array of users—much the way people use clip art today. As researchers gain insight into the structure of materials and develop new computer models, a host of new design and engineering applications could reap the benefits. Automobile designers might study various coatings applied to virtual cars to understand the structure, appearance and performance of coatings over time. Architects and conservators might be able to simulate the long-term durability of materials and study the different ways to preserve them. Finally, computer models of materials could even help designers create entirely new appearances—an accomplishment that would beautify the world, not just imitate it.

Levels of Detail

Computer graphics systems must cope with scenes containing millions of basic geometric shapes, and they often must perform millions of BRDF calculations to make a single image. The use of material models in real applications therefore requires skill to minimize the number of computations. This can be as simple as computing or approximating reflection functions during a preparatory process and saving the results for quick lookup during the actual rendering.

Another key technique is to introduce a hierarchy of abstractions and to use the right one at the right time. If the camera has zoomed in for a close-up of an object, fine detail of the surface should be visible and must be modeled explicitly. But as the camera pulls back and the scale changes, the finest details will no longer be distinctive and may be replaced by simpler approximations. For example, a rough surface may be modeled using a height field, and for close-ups these irregularities may be displayed as visible geometric displacements—the finely detailed bumps and crevices of the surface. For medium shots, only the average smooth shape of the surface may be resolvable, and the roughness can be represented merely through subtle variations in the shading and perhaps some patches of self-shadowing. On long shots, a microfacet distribution might be sufficient.

The best model of a surface, here a cushion, depends on the required level of detail.

Automatically changing the representation and computation of material properties as we zoom in and out is a challenging problem of great current interest. How can we produce a computer program that switches automatically to the appropriate level of detail? The scenes in today's applications are extremely complex, often containing tens of millions of surfaces, so for computational efficiency it is crucial to use the simplest possible approximation for each element.
—*J.D. and P.H.*

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Further Information

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Further information and images are available on the Web at http://graphics.lcs.mit.edu/materials/