Advanced Material Appearance Models

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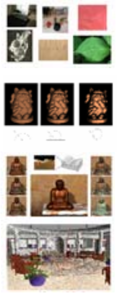
2008
Crete, Greece
April 14-18
EUROGRAPHICS '08

In these course notes we present principles of defining numerical models to be used in rendering realistic imagery of physical materials. Additional information on research in rendering and materials can be found at http://graphics.cs.yale.edu/. Updates or corrections to these notes will be posted at this site. The in person presentation of this course varies from these notes in the interest of timeliness, and considering the fact that "fair use" materials can not be posted for distribution to non-course attendees.

These notes build on introductory information on material modeling that was presented in a SIGGRAPH course in 2005 and 2006. Notes and presentations from these courses can be accessed by ACM Digital Library subscribers.

These notes also draw on the text "Digital Modeling of Material Appearance" that we have published with Morgan-Kaufmann/Elsevier. Attendees interested in a more thorough discussion of the topics presented here may with to consult that work.

Advance Material Appearance Models



1. Introduction

2. Background

3. Specialized Material Models
- **Common themes**
- **Natural Materials**
- **Manufactured/Processed Materials**

4. Aging and Weathering Processes
- **Taxonomy**
- **Simulation Methods**
- **Capture Approaches**

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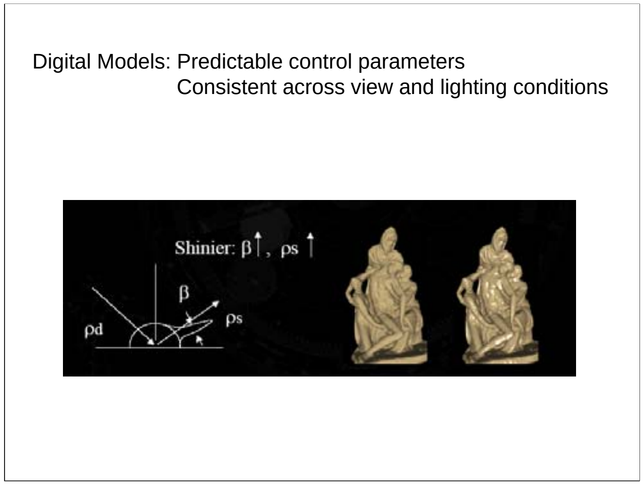
1. INTRODUCTION

Digital Modeling of the Appearance of Materials:

Art or Science??

The materials here are rendered with models. Artists conceived the shape, and selected materials to construct such objects in the physical world. A purely artistic approach could be used to digitally paint the shades of light and dark on the digital shapes to give the illusion of translucent stone or shiny gold metal. However, to generate these images material models are expressed numerically and rendered using lighting simulations. That is their appearance – the colors, shades of light and dark, were computed, rather than being digitally painted on the model.

There are many ways in which compelling visual images can be generated of the world. Different approaches can be used to create images, all of which are valid in some set of circumstances. To define our approach in this course we distinguish between the use of digital models to define materials, and the use of artistic techniques. Broadly, by digital models we mean a quantitative approach to rendering that intends to simulate realistic appearance.



Digital Models: Predictable control parameters
Consistent across view and lighting conditions

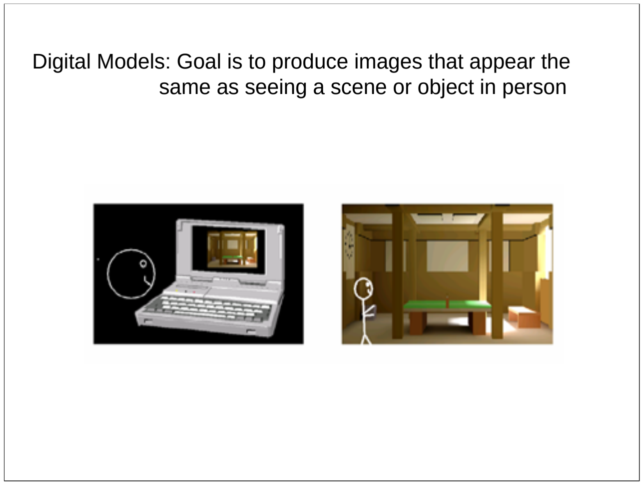
We define a model as taking a physically measurable input and producing a predictive output that can be

verified by physical measurement. A model of a material makes possible the reliable rendering of the

appearance of that material in any geometric and lighting conditions. An artistic technique as takes

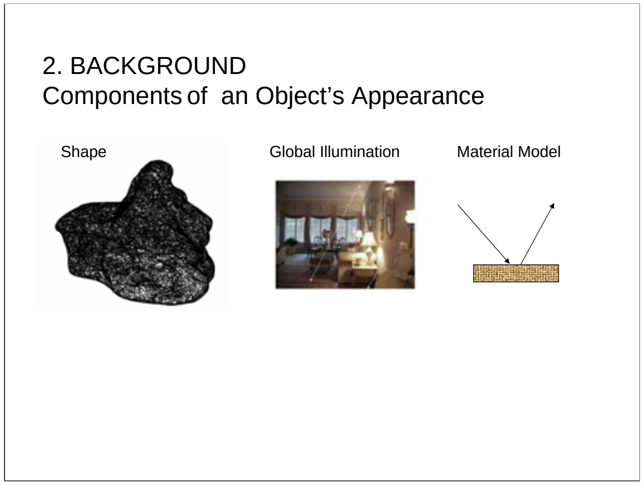
an input which is not necessarily measurable, and produces an output that may or may not reproduce the

appearance of an object under arbitrary circumstances. Human judgment is required to use an artistic technique, and to evaluate its success.



Digital Models: Goal is to produce images that appear the same as seeing a scene or object in person

Our goal is to make predictive images that give a view of a scene or object that is the same as if the person were viewing it directly. Material modeling is one aspect of this. We need to consider the object’s shape, and the light incident on it. We also need to take into account how the incident light is perceived by humans. Perception is a complex phenomenon, but some simple understanding of it makes modeling easier. The complexity of human perception is what makes digital imaging even possible. It is a remarkable fact that vastly different arrays of incident light, if adjusted properly, give us the same visual impression.



2. BACKGROUND
Components of an Object’s Appearance

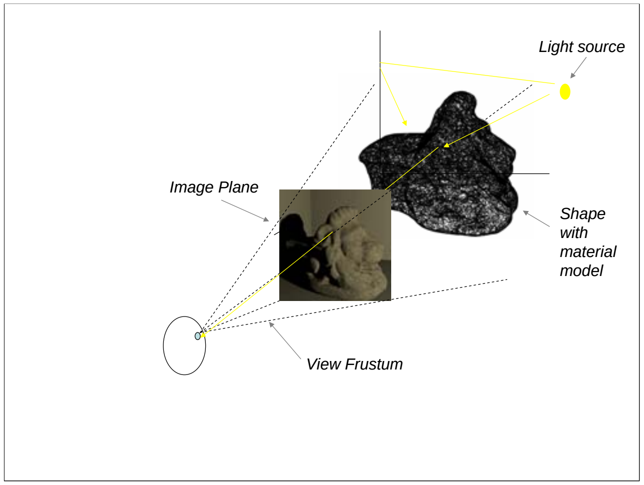
Shape

Global Illumination

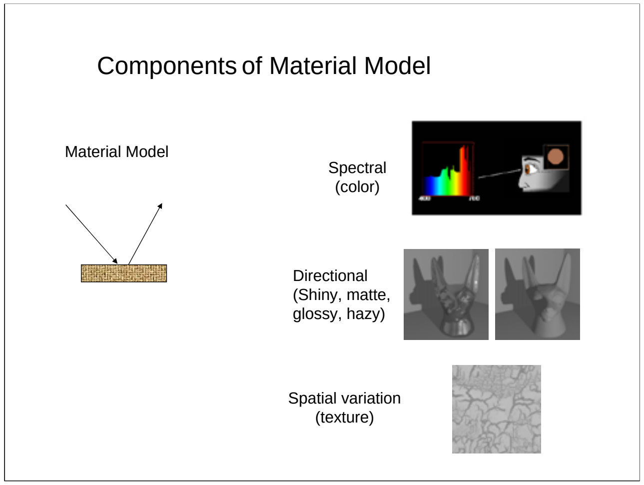
Material Model

Shape is the large scale form or geometry of the object. The shape is needed to place the image of the object correctly with respect to other objects in the scene, to determine which other objects are occluded by the object, and what areas are cast into shadow by the object. Fine scale geometric variations in the object we define as part of the object’s material from the point of view of creating digital models in computer graphics. For a close view of a tree branch, a leaf is defined by a flat shape, with the number of lobes or points depending on the type of tree. In an aerial photograph, a leaf is a small facet in a tree canopy material that covers the terrain. Many methods can be used to represent shape. The area of computer-aided geometry is devoted to the study of shape representation, and extensive descriptions of representations such as NURBs (non-uniformrational B-splines), triangle meshes, subdivision surfaces and implicit surface are documented at length in references such as **Farin *Curves and Surfaces for Computer-Aided Geometric Design: A Practical Code*. Academic Press, Inc., 1996.**

Many methods can be used to compute the interreflections of light between objects in an environment. These methods, referred to as “global illumination” methods, include ray tracing, radiosity, photon mapping and hybrids of these various approaches. Thorough discussions of these methods can be found in **Dutre, Bekaert and Bala, *Advanced Global Illumination*. AK Peters Limited, Wellesley, MA, 2003.** For rendering appearance, the essential feature of a global illumination method is that for a given ray direction the quantity of light from that direction at a particular point can be efficiently computed.



An environment consists of a set of objects, each defined by a shape and material description, and at least one light source. An infinite number of images could be created of such an environment, and to specify a particular image a viewpoint, view direction and view frustum (i.e. field of view) need to be specified. The image is formed by projecting the objects in the environment seen through the frustum onto an image plane that spans the field of view and is perpendicular to the view direction. In a digital image, the image is discretized into pixels, and the display values for that pixel are set by determining the light that would arrive at the viewer from the object visible through that pixel.



Components of Material Model

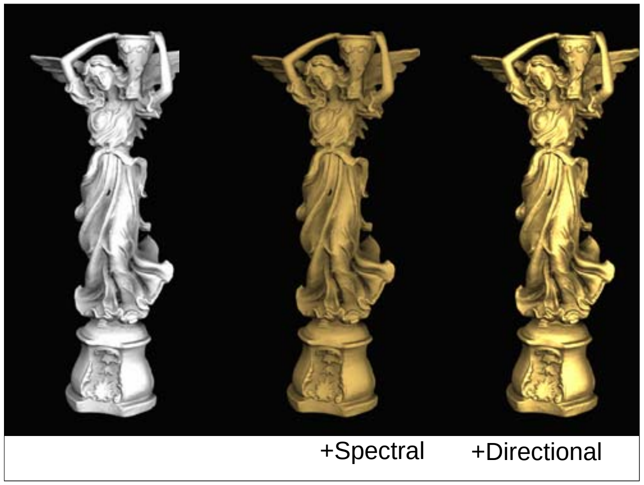
Material Model

Spectral (color)

Directional (Shiny, matte, glossy, hazy)

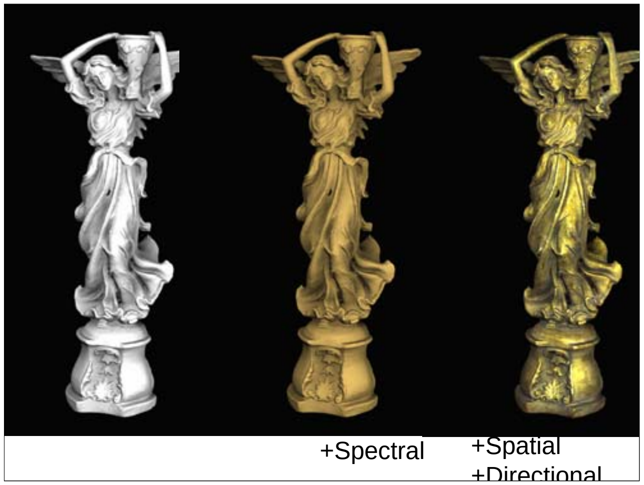
Spatial variation (texture)

There are three important components of a material model that allow us to recognize a material – spectral, directional and spatial. We notice the color of an object (resulting from the spectral composition of light), its directionality (hazy, glossy, shiny,) and small spatial variations (textures formed by light and dark, or little bumps.)



Example of introducing spectral and directional variations

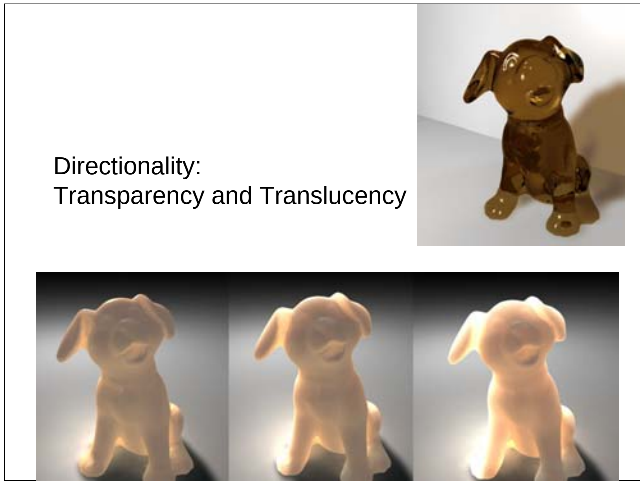
Introducing spatial variations



+Spectral

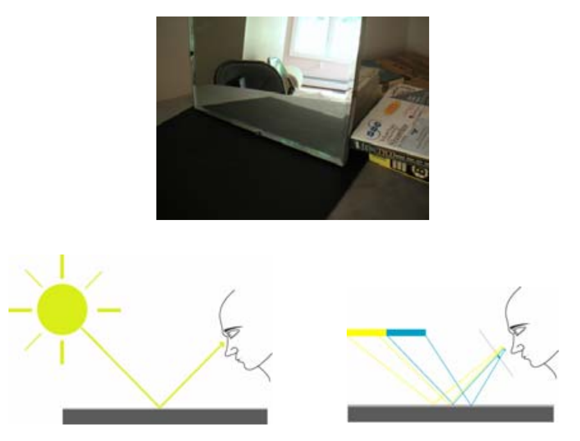
+Spatial
+Directional

Spatially varying spectral and directional variations to make this look like a worn,dirty metallic object.

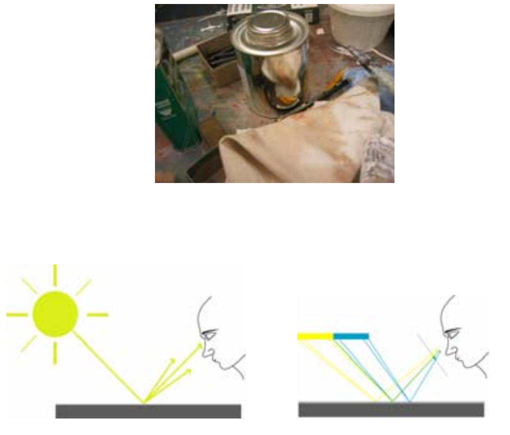


Directionality:
Transparency and Translucency

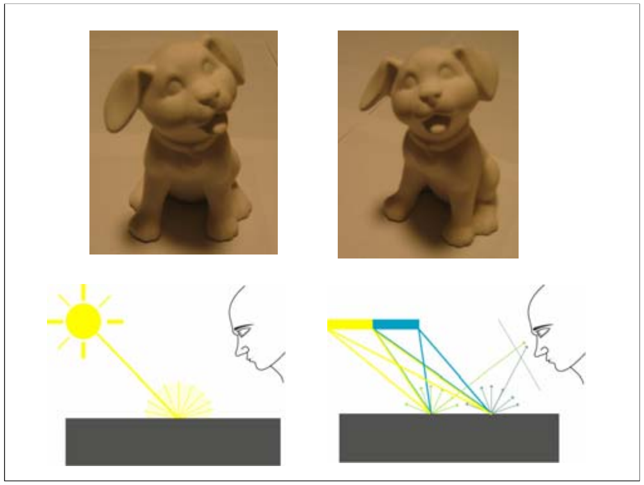
Examples of directionality beyond directional reflectance



The most familiar and basic light scattering is regular or “mirror-like” reflection, as shown in the photo at the top. Light rays reflect into one single direction, and that direction forms the same angle to the surface normal as the incident direction, as shown on the lower left. Because the reflected rays stay organized as they were when they left the previous objects, a sharp image is formed just as though you were looking directly at the objects. This regular, or mirror-like reflection is referred to as pure or ideal specular reflection.



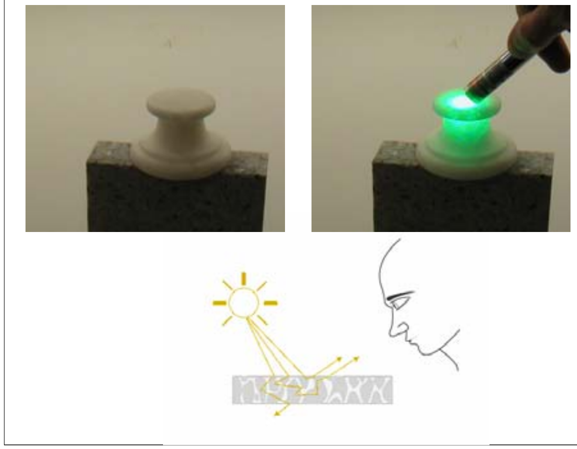
Many materials are shiny or glossy, but not purely specular. In these materials, incident beams of light are distributed into a cone or lobe of directions centered around the specular, or mirror direction. The result of this is when you are looking at such materials the light reflected from each point of the surface includes light from an a range of surfaces in the environment, instead of just reflecting one point. Instead of seeing sharp edges reflected, everything looks blurred. By observing the reflections in the paint can in the image, you can see that how blurred things look depends on how close the objects being reflected are to the glossy surface. If they are relatively close, the cross section of the cone from which a point is reflecting light is relatively small, and lines like that between the yellow and blue surfaces above are only blurred a bit. As the objects get further away, the cross section of the cone becomes large, and can include entire objects which then do not appear with any detail when reflected in the glossy surface.



Objects that appear to have the same pattern of light and dark regardless of how you view them (as long as you don't block a significant source of light from the environment as you move to another view) are diffuse. An ideal diffuse (also referred to as Lambertian) object reflects an incident beam of light as light rays of much lower magnitude in all directions. The light coming from any point on the object in any direction is a product of light coming from many different sources in the environment. The contribution of each source in the environment varies very slowly from point to point on the object, so the amount of light varies slowly from point to point, and there no clear images of the environment can be seen in the object.

In addition to the reflectance that depends on material microstructure and chemical composition, the appearance depends on small scale geometric structure. Just as some materials are characterized primarily by the spatial variations in reflectance, other materials are characterized primarily by their small scale geometric structure. “Small” is defined as orders of magnitude smaller than the overall object. The image above shows a piece of plastic with a pattern pressed into it that changes the surface from smooth to bumpy. The small scale geometric structure shown here is characteristic of leather material, and this fact is used in the production of physical materials to make a plastic look like leather.

The variation of light and dark in the image of the plastic is not due to spatial changes in reflectance, but to the change of surface orientation caused by the small scale geometry. Even small indentations can cause large changes in the surface normal. The surface normal, rather than the absolute surface position, determines in which direction incident light will be reflected.



Some materials don’t just reflect light from the surface, or just transmit the light. In some cases light penetrates the material and scatters in the interior. This is referred to as subsurface scattering, and can occur in dielectrics, not metals. Under normal room illumination, surfaces which allow subsurface scattering often do not look dramatically different from completely opaque surfaces. The image on the right though shows an extreme example of illumination. A green laser is directed at the top of a small piece of stone. Besides being reflected from the top, the light is scattered in the material and is visible emerging from the sides of the stone.

Terminology and Mathematical Descriptions

Key quantities:

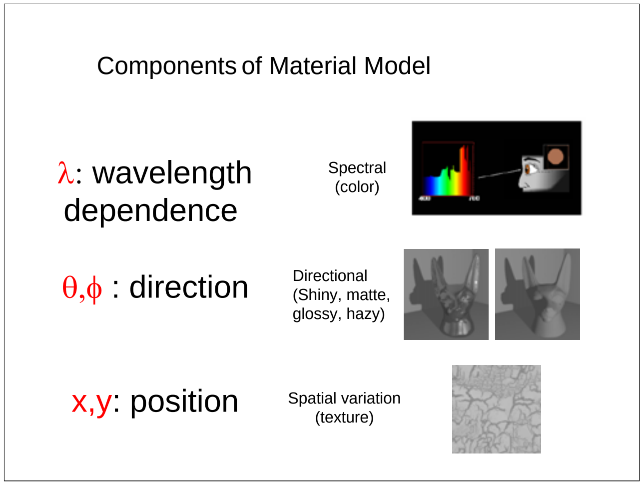
Radiance L

Bidirectional Reflectance Distribution Function (BRDF) f_r :

An explanation of the mathematics of light transport isn’t possible in a brief lecture. However, a couple of key points are:

-- a lot of the notation in light transport is just denoting that quantities vary with color (spectral dependance l), direction (given by angles q and f) and position (x,y)

-- there are two quantities that are key, but which take some getting used to . One is the quantity of light we want to compute, the radiance L. The other is the function telling how a surface scatters light, the BRDF fr.



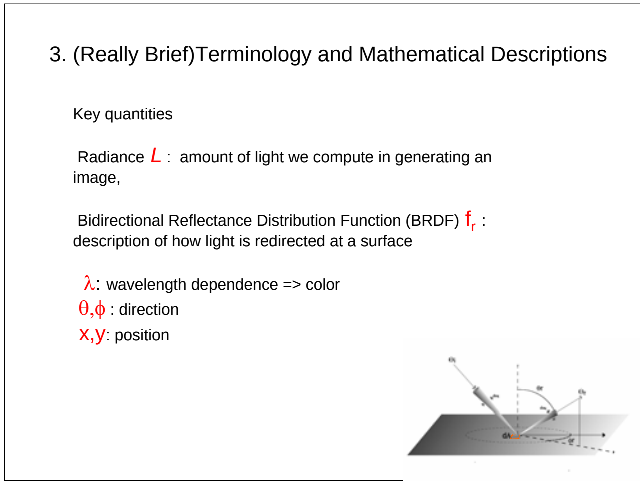
Components of Material Model

λ: wavelength dependence — Spectral (color)

θ,ϕ : direction — Directional (Shiny, matte, glossy, hazy)

x,y: position — Spatial variation (texture)

There are three important components of a material model that allow us to recognize a material – spectral, directional and spatial. We notice the color of an object (resulting from the spectral composition of light), its directionality (hazy, glossy, shiny,) and small spatial variations (textures formed by light and dark, or little bumps.)



3. (Really Brief)Terminology and Mathematical Descriptions

Key quantities

Radiance L : amount of light we compute in generating an image,

Bidirectional Reflectance Distribution Function (BRDF) f_r : description of how light is redirected at a surface

λ: wavelength dependence => color
θ,ϕ : direction
x,y: position

An explanation of the mathematics of light transport isn't possible in a brief lecture. However, a couple of key points are:

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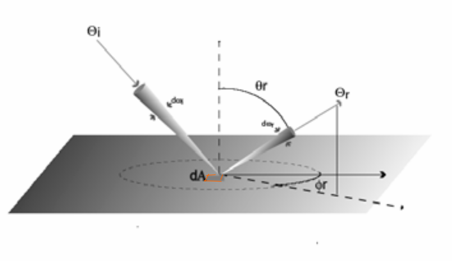
Bidirectional reflectance distribution function, BRDF

$$f_r(\Theta_i, \Theta_r, x, y, \lambda) = \frac{d^2 L_r(\Theta_r, x, y, \lambda)}{L_i(\Theta_i, x, y, \lambda) \cos\theta_i dA d\omega_i}$$



The key quantity we use to define how a surface redirects light is the BRDF, which relates incident and reflected radiance for two given directions. The BRDF is a distribution function, not a fraction from zero to one. It can take on values from zero to infinity. To conserve energy, the integral of the BRDF over all reflected directions must be less then or equal to one.

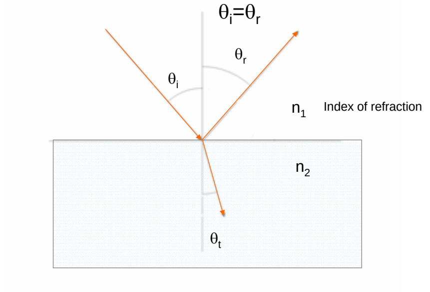
Common Reflectance Models

- “Named” models generally after the people who developed the models
- No compliance standards for claiming that a “named” model is being used

Reflectance Models

- Smooth Surfaces
  - Fresnel Equations
- Empirical
  - Lambertian, Phong, Ward, Lafortune, Ashikhmin-Shirley
- First Principles
  - Blinn, Cook-Torrance, Oren-Nayar
- Wave Optics
  - He-Torrance

Reflection and Transmission



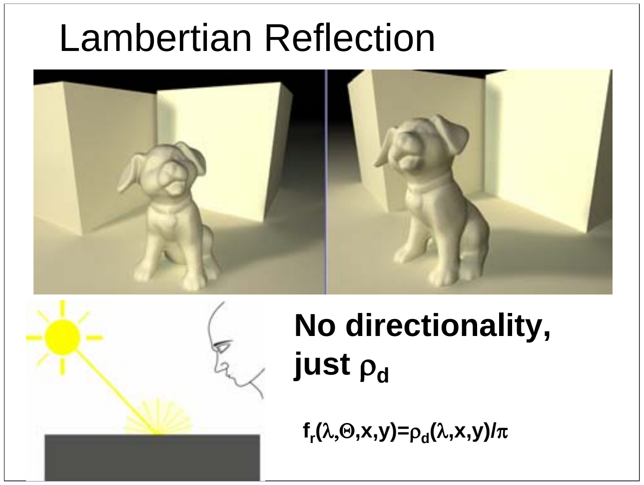
$\sin\theta_i / \sin\theta_t = n_2/n_1$

Snell's Law

The directionality of transmission is a bit more complicated. First, most metals have a high tendency to absorb electromagnetic energy, so transmission of visible light is not observed. For dielectrics, the change in the speed of light in the material causes a change in the direction. This change in direction is called refraction, and is expressed by Snell's Law as shown above. Unlike the direction of reflection, the direction of refraction depends on the properties of the materials.

Since light is electromagnetic energy, its interaction is governed by the properties that quantify the material's interaction with electric and magnetic fields. In the solution to Maxwell's equations these properties are expressed as the index of refraction *n* and a coefficient that captures the tendency to absorb electomagnetic waves k . The value of *n* is the ratio of the speed of light in a vacuum to the speed of light in the material. The value of k is zero for dielectrics, which do not conduct electricity, and greater than zero for metals, which do. Values of k and *n* are found by measurement and can be looked up in handbooks or online resources. Generally understanding and applying the results of the smooth surface solution requires only knowing

some rough estimates of typical values of these constants for common materials.



Lambertian Reflection

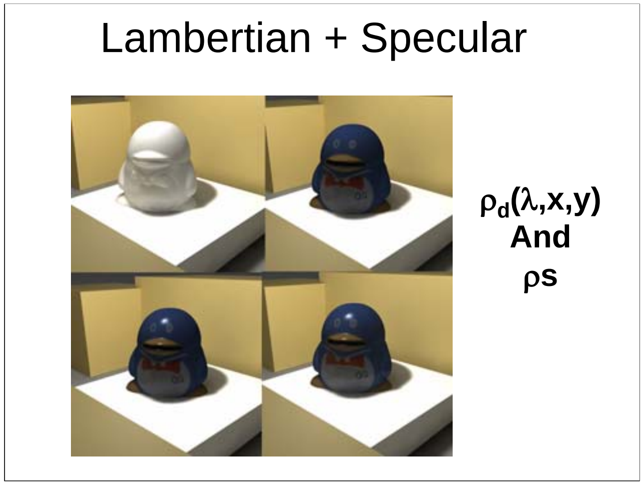
No directionality, just ρ_d

$f_r(\lambda,\Theta,x,y)=\rho_d(\lambda,x,y)/\pi$

Lambertian, or “ideal diffuse” reflectance is in a sense the opposite of

specular reflection. Instead of all light being reflected in a single direction, it is reflected in all directions with the same radiance. Unlike specular reflection, this is not the result of solving Maxwell’s equations for some particular surface configuration. It is an approximation of the observed behavior of many materials. While real materials usually deviate from Lambertian for angles of view or incidence greater than 60 degrees, the Lambertian model is used for its computational simplicity. For measurement purposes, some materials have

been designed that are very close to being to Lambertian, such as Spectralon® from Labsphere Inc.



Lambertian + Specular

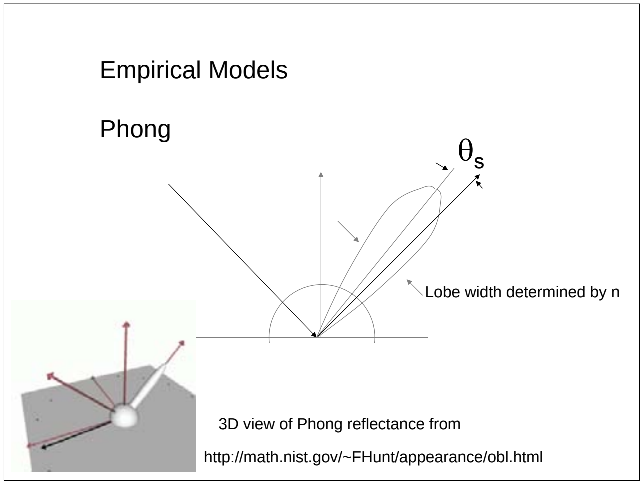
$\rho_d(\lambda,x,y)$
And
ρs

Materials can be modeled as a combination of Lambertian and mirror-like reflectance. The material can also have spectral values that vary with position. Here a scanned object is shown as white Lambertian (upper left), spectrally varying with position (upper right), with mirror-like reflection of the light source (lower left), and with mirror-like reflection of the entire environment.

Metal vs. Dielectric Specular Color

Metal highlights the same color of the metal

Dielectric Highlights (e.g. a plastic Or clear coat) Have white highlights



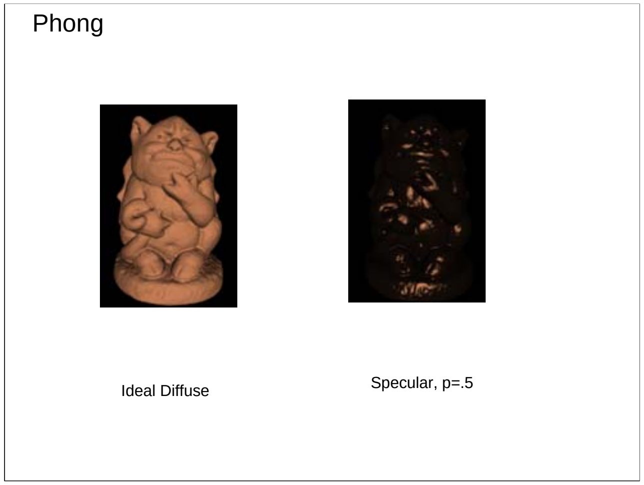
Empirical Models

Phong

3D view of Phong reflectance from

http://math.nist.gov/~FHunt/appearance/obl.html

The original Phong reflectance model is described in the classic paper: **Bui Tuong Phong "Illumination for computer generated pictures" *Communications of the ACM*, v.18 n.6, p.311-317, June 1975** . It was expressed as reflectance function for light intensity, rather than as a BRDF for computing radiance. However, it was inspired by physical observation. The effect of the model in rendering a sphere is compared to a photograph of a real sphere in the paper. The fuzziness of the specular reflection is computed as a function of the angle a between the reflected direction and the mirror reflection angle: reflectance = ρd (cos qi) + rs (cos a)n



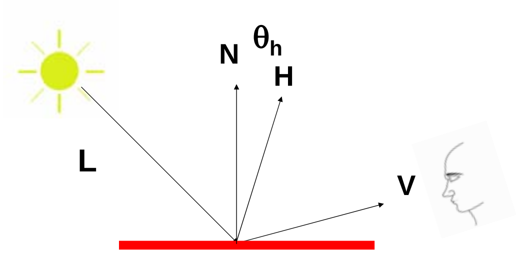
Phong

Ideal Diffuse

Specular, p=.5

In contrast to diffuse reflection, the specular component concentrates the reflected light. The larger the value of n, the smaller the specular highlights formed by the reflection of the light source. (Images generated using GLView http://home.snafu.de/hg/)

Alternate measure of “closeness” to specular reflection



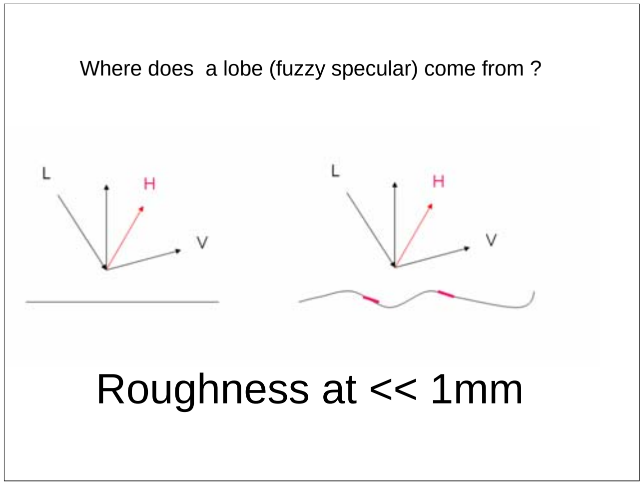
The specular lobe in the Phong model is taking into account roughness at a very small scale. At a small scale parts of a surface are oriented to reflect into directions that aren’t the mirror direction for the flat surface.

H is the “half way” vector, the direction a surface normal would need to be pointing for a mirror reflection to be visible for a given pair of light L and view V directions. Many reflectance models are computed in terms of this half way vector.

Blinn-Phong
(using θh instead of θs)

Increasing p →

$$\rho_d + \rho_s \cos^p \theta_h$$



Where does a lobe (fuzzy specular) come from ?

Roughness at << 1mm

The specular lobe in the Phong model is taking into account roughness at a very small scale. At a small scale parts of a surface are oriented to reflect into directions that aren’t the mirror direction for the flat surface.

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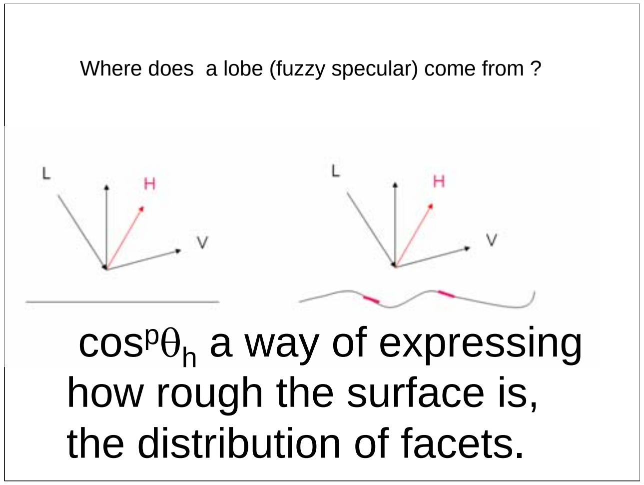

Where does a lobe (fuzzy specular) come from ?

$\cos^p\theta_h$ a way of expressing how rough the surface is, the distribution of facets.

The specular lobe in the Phong model is taking into account roughness at a very small scale. At a small scale parts of a surface are oriented to reflect into directions that aren’t the mirror direction for the flat surface.

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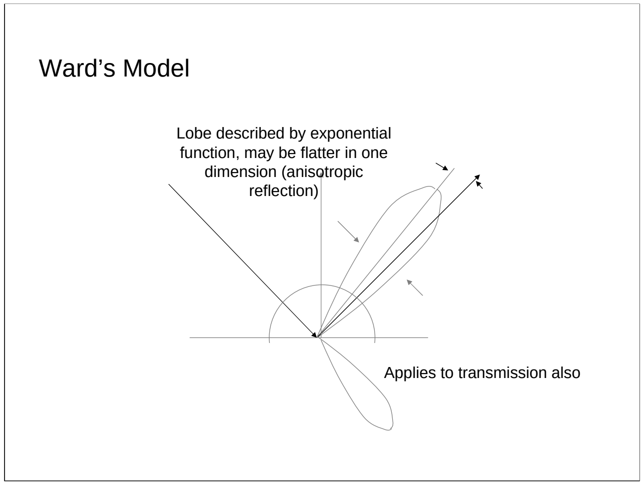
mirror

crumpled foil

A macroscopic example of the spreading effect of a rough surface. For a surface that is somewhat rough at a microscopic level, some portions of the surface are oriented in the direction of the halfway vector even when the halfway vector isn't the same as the main surface normal.



Ward's Model

Lobe described by exponential function, may be flatter in one dimension (anisotropic reflection)

Applies to transmission also

The Ward reflectance model is similar to the Phong model except it is expressed in physical terms – it expresses the relationship between incident and reflectance radiance and conserves energy. Rather than using the cosine term to a power, it uses an exponential function, parameterized by an average slope, to express the shape of the specular lobe. Furthermore, the specular lobe can be anisotropic – by expressing different slopes for different directions on a surface (e.g. for a set of grooves the slope is zero along the grooves, and potentially steep perpendicular to the grooves). This results in the width of the lobe being different in the direction out of the page than it is in the page. Further, the model can be applied to regular and diffuse transmission through a thin surface. The BRDF is given by fr = pd + ps exp (). The model is fully described in as described in **Ward Larson and Shakespeare, *Rendering with radiance: the art and science of lighting visualization* (Morgan Kaufmann, 1998)**

Ward


Ideal Diffuse


Diffuse plus white glossy specular


Diffuse plus white anisotropic glossy specular

Since the Ward model is developed in physical terms of incident and reflected radiance, it works (by design) in a system that simulates physically accurate global illumination. These variations were rendered using the Radiance software system, as described in Ward Larson and Shakespeare, ***Rendering with radiance: the art and science of lighting visualization*** (Morgan Kaufmann, 1998) A point to remember is that physically accurate material models only create realistic appearance when used in the context of a physically accurate global illumination system.

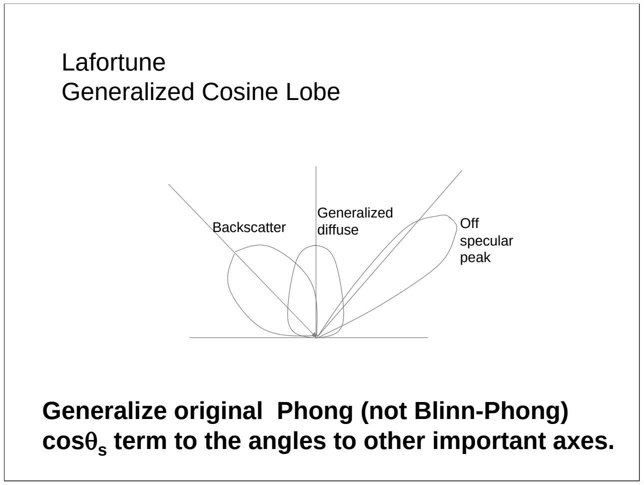
Ward


Metal, isotropic glossy


Metal, anisotropic (horizontal)glossy


Metal, anisotropic (vertical)glossy

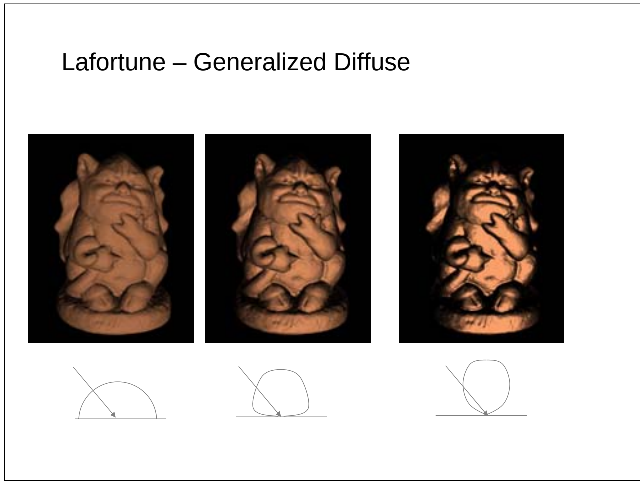
Anisotropic reflection has a significant impact on appearance, but for a complicated object its effect is only clear when the effect of isotropic, or anisotropic reflection with a different orientation is displayed.



Lafortune
Generalized Cosine Lobe

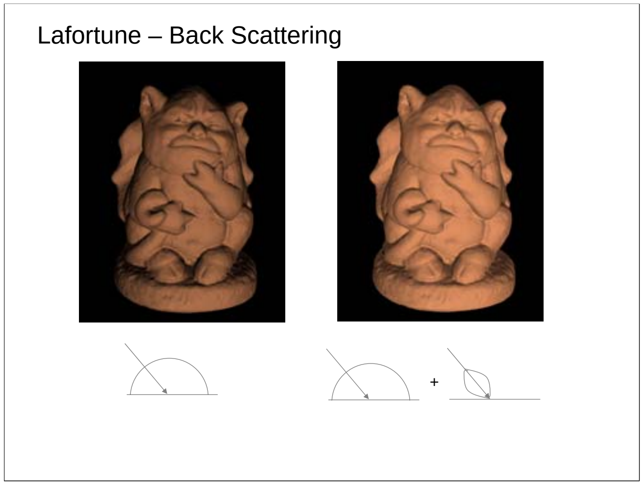
Generalize original Phong (not Blinn-Phong) $\cos\theta_s$ term to the angles to other important axes.

The generalized cosine lobe model described in **Lafortune, Foo,Torrance, and Greenberg "Non-linear approximation of reflectance functions" In *Proceedings of the 24th annual conference on Computer graphics and interactive techniques* (1997, ACM Press/Addison-Wesley Publishing Co., pp. 117–126.)** Gives a different generalization of the Phong model. Like the Ward model, it is formulated in physical terms. It conserves energy. Instead of just describing peaks of reflection around the specular direction, it allows the definition of lobes (possibly anisotropic) around any axis defined with respect to the surface. Important other axes are just off the specular direction, the normal direction and the direction of the source (for backscatter). The general form of the reflectance is fr = C(u) (Cxuxvx+Cyuyvy+Czuzvz)n where u and v are vectors in the incident and reflected directions, Cx,Cy are coefficients determining the direction and shape of the lobe, n defines how narrow it is, and C(u) is a normalizing function to insure the function conserves energy. Sets of functions of this form can be summed to form the BRDF for a single material.



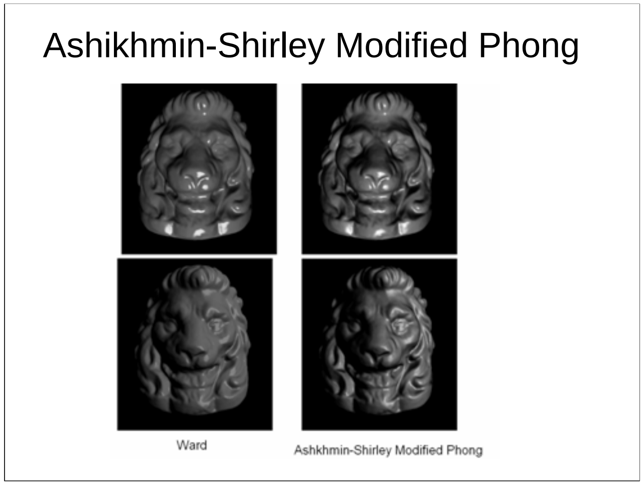
Lafortune – Generalized Diffuse

An example of a BRDF that the Lafortune model can represent that previous models could not is generalized diffuse reflectance. In general, even surfaces that appear matte or diffuse don't reflect radiance evenly in all directions – the reflection may peak in the direction of the surface normal and fall off at near grazing viewing angles. The effects shown here are found using Cx=Cy=0, Cz=1, n equal to zero, 0.5 and 2 respectively. (Rendered by a customized local illumination implementation of Lafortune model.)



Lafortune – Back Scattering

The Lafortune model, unlike Phong or Ward, also provides a mechanism for defining back scatter. In this case a sum of two Lafortune lobes is used. With summing functions, there become a large number of parameters Cx,Cy,Cz and n to be defined for specifying reflectance. This makes the model inconvenient for user interfaces. The Lafortune model is popular though for fitting masses of measured BRDF data into a compact representation.



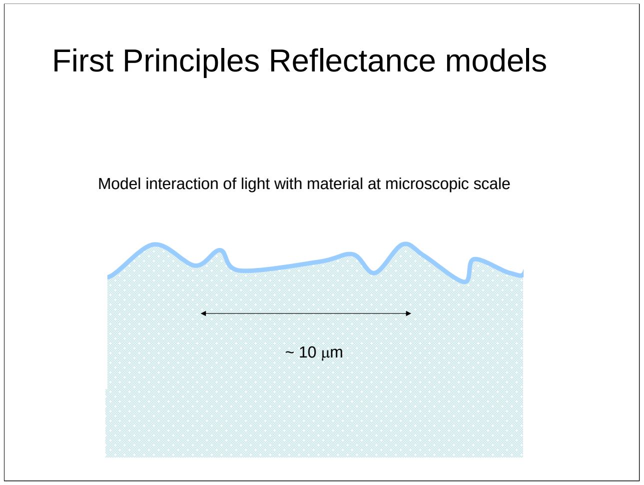
Ashikhmin-Shirley Modified Phong

Ward

Ashkhmin-Shirley Modified Phong

The Ashikhmin-Shirley modification of Phong reflectance *(Ashikhmin and Shirley, An Anisotropic Phong BRDF Model" Journal of Graphic Tools, 5,2, (2000), pp.25-32)* has the feature that it includes an explicit term for the Fresnel reflectance. The specular reflectance increases as the angle of incidence increases. The diffuse component is appropriately reduced at these angles to maintain energy conservation. The formulation also maintains reciprocity, and allows for anisotropy. The Fresnel component is computed with Schlick's

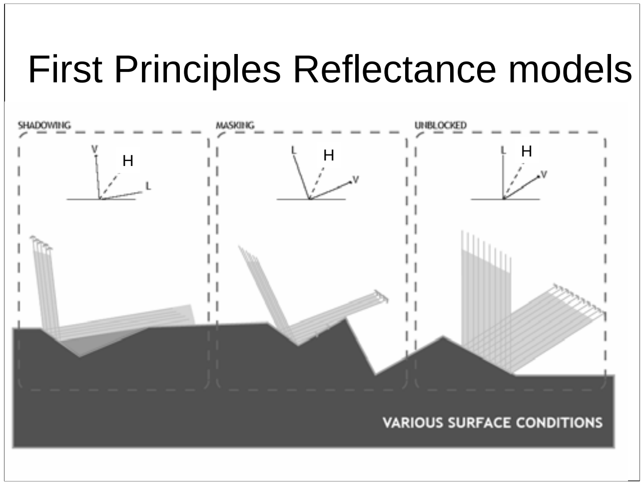
approximation. In the examples shown above, the decrease of the diffuse component with view angle relative to the ideal diffuse component used in the Ward model can be observed.



First Principles Reflectance models

Model interaction of light with material at microscopic scale

In contrast to empirical methods that look for convenient functional forms, first principles methods model the interaction with light with a mathematical model of material defined at a microscopic scale. The most frequently used first principles models use as a mathematical model a statistical distribution of surface facets to describe the details of the boundary between a material and air. The most popular methods model this interaction with geometric optics, which requires that the surface being modeled be “large” with respect to the wavelength of light (which is 0.4 to 0.7 microns) Some more complex models use wave optics to capture of the effects of diffraction at the surface.

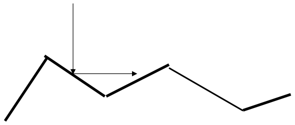


First Principles Reflectance models

First principles models account for the effects that facets can have on one another – they may block light incident on another facet, making it appear darker, or they may block light leaving the facet before it reaches a viewer, again resulting in a darker appearance. Even unblocked, the orientation of the facets results in light being scattered in a much different directional pattern than from a smooth surface.

First Principles Reflectance models

Blinn,
Cook-Torrance



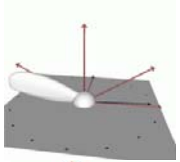
Fresnel, Distribution, Shadowing

$$f_r(\Theta i,\Theta r)=\frac{F(\theta_h)D(\theta_h)G(\theta_i,\theta_r)}{\pi\cos\theta_i\cos\theta_r}$$

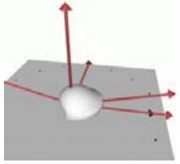
Two popular first principles models are Blinn, *“Models of light reflection for computer synthesized pictures,” SIGGRAPH 1977, pp. 192-198.* and Cook-Torrance, *Cook and Torrance “A reflectance model for computer graphics”. ACM Transactionson Graphics 1, 1 (Jan. 1982), 7–24*

They are both based on specular reflections of distributions of facets. The difference between them is the distribution of the facets assumed.

Major Features: First Principles Reflectance models



Cook-Torrance
Predicts off specular peaks

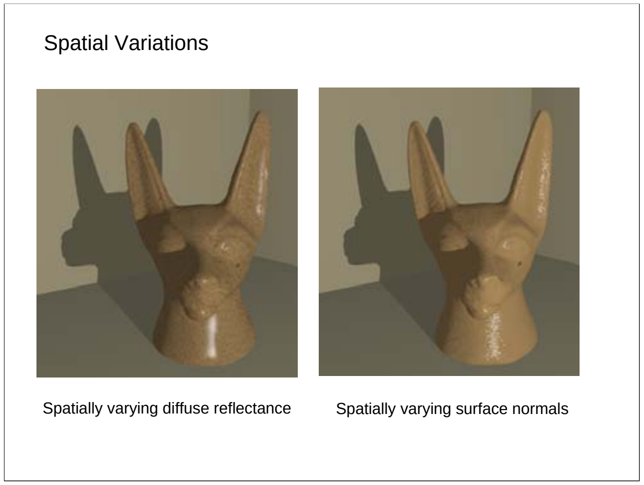


Oren-Nayar

Predicts back-scatter

3D views: http://math.nist.gov/~FHunt/appearance/obl.html

The principle feature of the Cook-Torrance model is the prediction of off specular peaks, that are the consequences of shadowing and masking causing asymmetries. The principle feature of the Oren-Nayar model is the prediction of back scattering, that is a consequence of facets oriented towards the light source diffusely reflect some light back to the source. The result in each case are BRDF functions with lobes in the specular and backscatter directions that have more complicated structure than those used in the empirical models. The BRDF for these models is specified by giving parameters for the microscopic surface geometry. However, since the microstructure is rarely known, the facet distribution parameters are normally treated as parameters similar to n in the Phong and Lafortune models for controlling the shape of these complicated distributions.

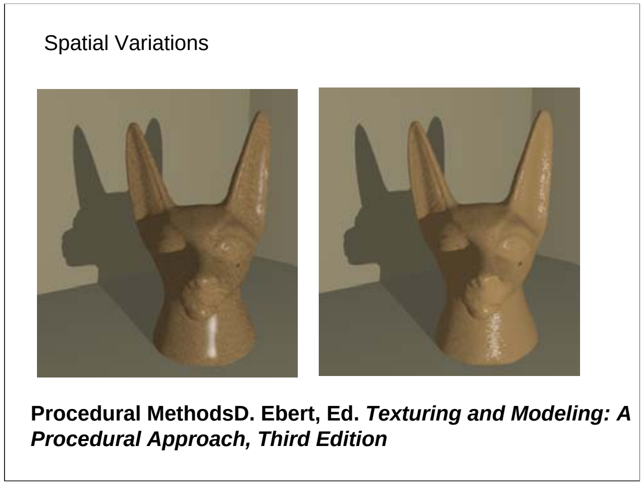


Spatial Variations

Spatially varying diffuse reflectance

Spatially varying surface normals

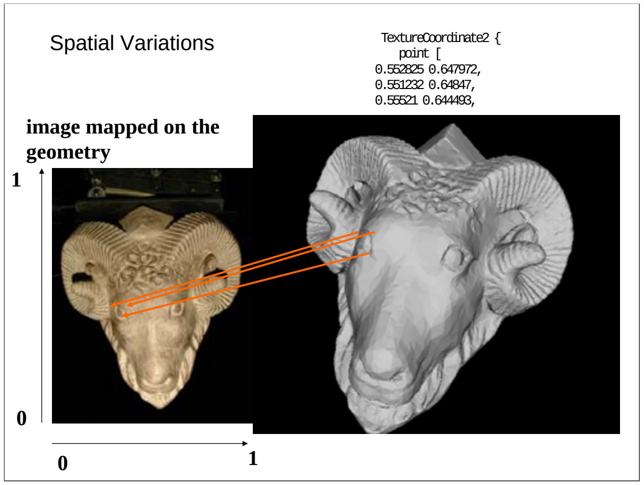
The two renderings above were performed with *Radiance* with procedural textures rather than image maps to define spatial variations on the surface (**e.g. see D. Ebert, Ed. *Texturing and Modeling: A Procedural Approach, Third Edition*. Morgan Kaufmann, San Francisco, CA, 2002**.) The same spatial frequency has different visual impact depending on whether the fraction of light is modulated, or the direction of the surface normals.



Spatial Variations

Procedural MethodsD. Ebert, Ed. *Texturing and Modeling: A Procedural Approach, Third Edition*

The two renderings above were performed with *Radiance* with procedural textures rather than image maps to define spatial variations on the surface (**e.g. see D. Ebert, Ed. *Texturing and Modeling: A Procedural Approach, Third Edition*. Morgan Kaufmann, San Francisco, CA, 2002**.) The same spatial frequency has different visual impact depending on whether the fraction of light is modulated, or the direction of the surface normals.



Spatial Variations

```
 TextureCoordinate2 {
    point [
0.552825 0.647972,
0.551232 0.64847,
0.55521 0.644493,
```

image mapped on the geometry

A basic mechanism for representing spatial variations that characterize a material is to use images mapped to the surface. Each pixel in the map may store simply a diffuse color, or a BRDF, a normal, a displacement, or a BTF (a virtual BRDF that includes the effect of small scale geometry). The mapping is done by storing coordinate of a location in an image with each vertex used to define a geometric model.

Mapping to a geometry requires that the geometry be parameterized (i.e. a two dimensional coordinate system must be defined on the surface), a topic which is studied extensively in computer aided geometric design. Parameterization is one of the topics considered in the course in SIGGRAPH 2005 **14. Discrete Differential Geometry: An Applied Introduction** Full-Day, Sunday, 31 July, 8:30 am - 5:30 pm lecturers Eitan Grinspun , Mathieu Desbrun, Peter Schröder

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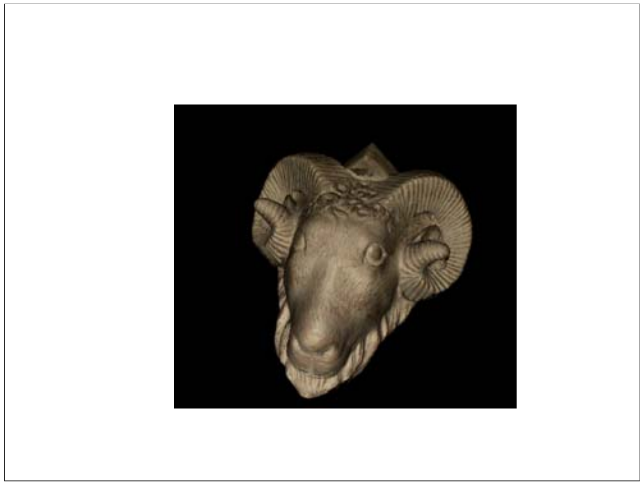

Result of mapping image on geometry.

Effects that Require Advanced Models

- Polarization

There are some optical effects that are important for small classes of materials. One is polarization. General references for this include:

David C. Tannenbaum, Peter Tannenbaum, and Michael J. Wozny. Polarization

and birefringency considerations in rendering. In *Proceedings of the 21st annual conference on Computer*

graphics and interactive techniques, pages 221–222. ACM Press, 1994.

Alexander Wilkie, Robert F. Tobler, and Werner Purgathofer. Combined rendering of

polarization and fluorescence effects. In *Proceedings of the 12th Eurographics Workshop on Rendering*,

pages 197–204, 2001.

Lawrence B. Wolff and David J. Kurlander. Ray tracing with polarization

parameters. *IEEE Comput. Graph. Appl.*, 10(6):44–55, 1990.

Effects that Require Advanced Models

- Diffraction and Interference

Another classes of effects is interference and diffraction. General references for these phenomena that require modeling the wave nature of light include:

Brian E. Smits and Gary W. Meyer. Newton’s color: Simulating interference

phenomena in realistic image synthesis. In Kadi Bouatouch and Christian Bouville, editors, *Rendering*

Techniques ’90, Eurographics, pages 185–194. Imprimerie de l’universit´e de Rennes, 1990. Proc. 1st

Eurographics Rendering Workshop, Rennes, France, June 11–13, 1990.

Yinlong Sun, F. David Fracchia, ThomasW. Calvert, and Mark S. Drew. Deriving spectra

from colors and rendering light interference. *IEEE Comput. Graph. Appl.*, 19(4):61–67, 1999.

Jos Stam. Diffraction shaders. In *Proceedings of the 26th annual conference on Computer*

graphics and interactive techniques, pages 101–110. ACM Press/Addison-Wesley Publishing Co., 1999.

Yinlong Sun, F. David Fracchia, Mark S. Drew, and Thomas W. Calvert. Rendering

iridescent colors of optical disks. In *Proceedings of the Eurographics Workshop on Rendering Techniques*

2000, pages 341–352, London, UK, 2000. Springer-Verlag.

3. SPECIALIZED MATERIAL MODELS

Common themes
Natural Materials
Manufactured/Processed Materials

Fibers

Many materials are composed of bundles of long thin fibers. The appearance of the bulk material is modeled by first account for reflection and transmission from individual strands. Hair, textiles and finished wood are all examples of materials modeled based on the light interactions of individual fibers.

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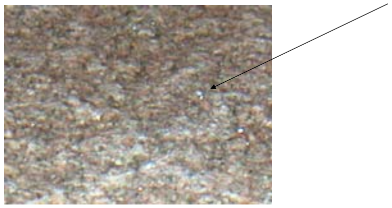
3. SPECIALIZED MATERIAL MODELS

Common themes
Natural Materials
Manufactured/Processed Materials

Sparkles

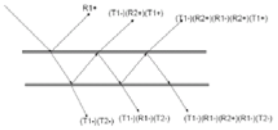


Either naturally by design many materials have the appearance of “sparkles” – small flecks of material that have a high specular reflectance. A challenge is to model where the sparkles appear in a way that is consistent frame to frame in animated sequences. Materials in which sparkles appear include automotive paint, man-made carpet fibers and snow.

3. SPECIALIZED MATERIAL MODELS

Common themes
Natural Materials
Manufactured/Processed Materials

Thin Layer/ Volumes



Many materials have sense of depth because they are composed of multiple layers of material that transmit and reflect light. This effect occurs in materials as diverse as paints and the human eye.

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3. SPECIALIZED MATERIAL MODELS

Common themes
Natural Materials
Manufactured/Processed Materials

Captured Data

With inexpensive digital cameras now widely avaiable,many material models are built around data that can readily acquired.

3. SPECIALIZED MATERIAL MODELS

Common themes
Natural Materials
Manufactured/Processed Materials

Hair and Fur:
Same stuff, hair on people, fur on other animals.

People: vellus and terminal hairs.

An individual hair consists of a core medulla, the cortex and exterior cuticle. The cuticle consists of lapped cells on the outside of the hair.

Coloration: granules of the melanin pigment, either eumelanins or pheomelanins . Hair with no pigment granules appears white.

Two different types of hair – vellus hairs and terminal hairs. Terminal hairs are those typically found on the scalp. Vellus hairs are unpigmented narrow (4 micron diameter), short (1mm) hairs that grow nearly all over the body.

Some stats:

Scalp hairs on humans are 50 micron to 90 micron diameter, may be circular or ellipsoidal, with curlier hair more ellipsoidal in cross section.

Beard and moustache (rather than scalp) hair may have triangular cross section.

Eyelashes, are 20 to 120 micron in diameter.

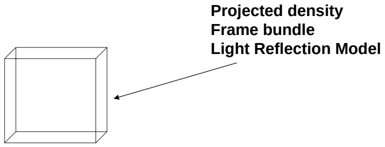
A person has about 175 to 300 terminal hairs per *cm*2, for a total of on the order of 100,000 hairs on the typical human scalp.

Foxes and rabbits: average diameter 20 to 30 micron, and approximately 4000 hairs per *cm*2

Goats and badgers :average diameter 70 to 80 micron and approximately 100 to 200 hairs per *cm*2).

General References on types of hair and fur:

Surface and volumetric properties of hair are combined in the *texel* data structure (Kajiya and Kay)



Projected density
Frame bundle
Light Reflection Model

A volumetric approach for rendering fur was presented in:

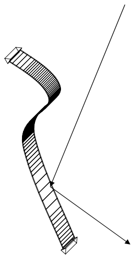
J. T. Kajiya and T. L. Kay. Rendering fur with three dimensional textures. In

Proceedings of the 16th annual conference on Computer graphics and interactive techniques, pages 271–

280. ACM Press, 1989.

This is different from pure volume rendering because the structure of individual strands must still be visible.

Surface and volumetric properties of hair are combined in the *texel* data structure (Kajiya and Kay)

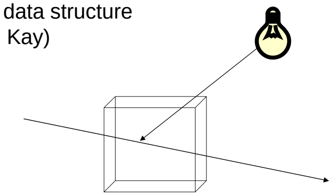


$$\Psi_d = K_d sin\theta_i$$

$$\Psi_s = K_s(cos\theta_i cos\theta_r + sin\theta_i sin\theta_r)^p$$

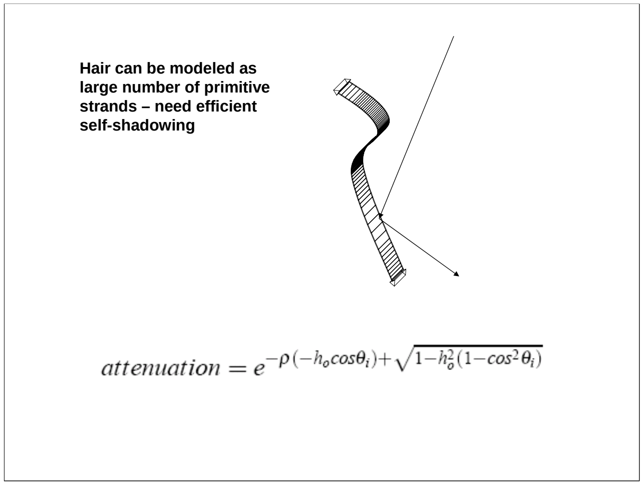
Reflectance from a 1-D fiber

Surface and volumetric properties of hair are combined in the *texel* data structure (Kajiya and Kay)



$$L = \Sigma_{t=t_{near}}^{t=t_{far}} e^{-\tau \Sigma_{u=t_{near}}^{u} \rho(u)} \rho(t) \Sigma_i L_i(t) \Psi(t)$$

Light from a volume of fibers

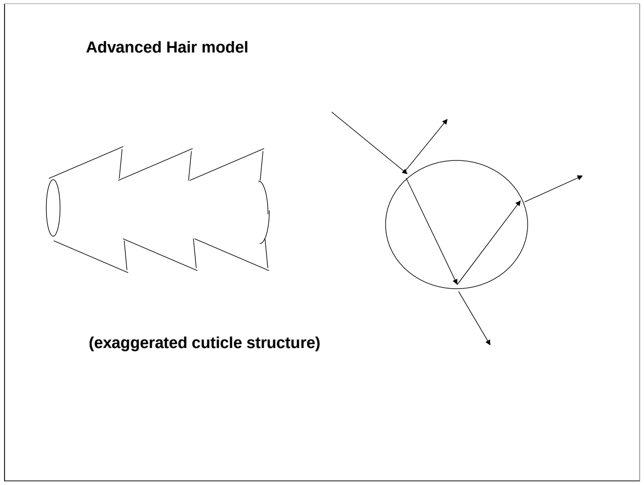


Hair can be modeled as large number of primitive strands – need efficient self-shadowing

$$attenuation = e^{-\rho(-h_o cos\theta_i)+\sqrt{1-h_o^2(1-cos^2\theta_i)}}$$

An example of modeling with strands (rather than texels): Aslan in Narnia

Brad Hiebert, Jubin Dave, Tae-Yong Kim, Ivan Neulander, Hans Rijpkema, and Will Telford. The chronicles of Narnia: the lion, the crowds and rhythm and hues. In *SIGGRAPH '06: ACM SIGGRAPH 2006 Courses*, page 1, New York, NY, USA, 2006. ACM Press.



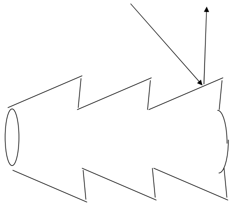
Advanced Hair model

(exaggerated cuticle structure)

An advanced model for hair accounts for the detailed geometry of hair cuticles, and the path of light through hairs.

Stephen R.Marschner, HenrikWann Jensen, Mike Cammarano, SteveWorley, and Pat Hanrahan. Light scattering from human hair fibers. *ACM Trans. Graph.*, 22(3):780–791, 2003.

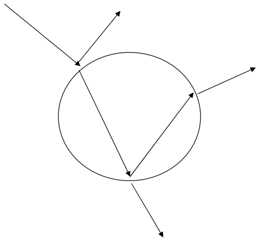
Advanced Hair model



Results in directionality of reflection.

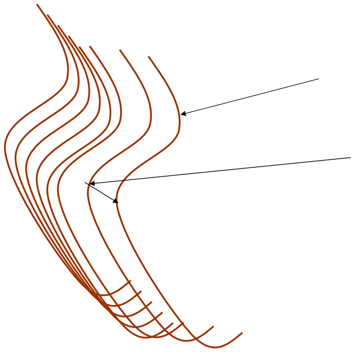
(exaggerated cuticle structure)

Advanced Hair model



Results in secondary highlights

Self shadowing and interreflections have a significant effect on hair appearance



Jonathan T. Moon and Stephen R. Marschner. Simulating multiple scattering in hair using a photon mapping approach. In *SIGGRAPH ’06: ACM SIGGRAPH 2006 Papers*, pages

1067–1074, New York, NY, USA, 2006. ACM Press.

Tom Lokovic and Eric Veach. Deep shadow maps. In *SIGGRAPH ’00: Proceedings of the 27th annual conference on Computer graphics and interactive techniques*, pages 385–392, New York, NY, USA, 2000. ACM Press/Addison-Wesley Publishing Co.

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3. SPECIALIZED MATERIAL MODELS

Common themes
Natural Materials
Manufactured/Processed Materials

Vellus Hairs

Asperity scattering

$$f_r(\Theta_i \rightarrow \Theta_r) = \frac{\frac{\sigma_s d}{4\pi}}{cos\theta_i cos\theta_r}$$

The scattering from short vellus hairs on the rest of the body is similar to the scattering of fuzz on a peach. A simple function for simulating this effect, which softens the look of a surface is described in

J. Koenderink and S. Pont. The secret of velvety skin. *Machine Vision and Applications*, 14(4):260–268, 2003.

3. SPECIALIZED MATERIAL MODELS

Common themes
Natural Materials
Manufactured/Processed Materials

Skin

Human skin:

-- varies in thickness varying from 0.1 to more than 0.5 cm.

-- has three layers :

The epidermis is the thin outside layer, that includes the exterior layer of “dead cells” (the stratum cornuem)

The dermis is thicker, and includes the vessels that carry blood.

The hypodermis connects the skin to the rest of the body.

A general reference:

Kenneth A. Walters. *Dermatological and Transdermal Formulations*. Marcel Dekker Incorporated, 2002.

Skin – Model Components

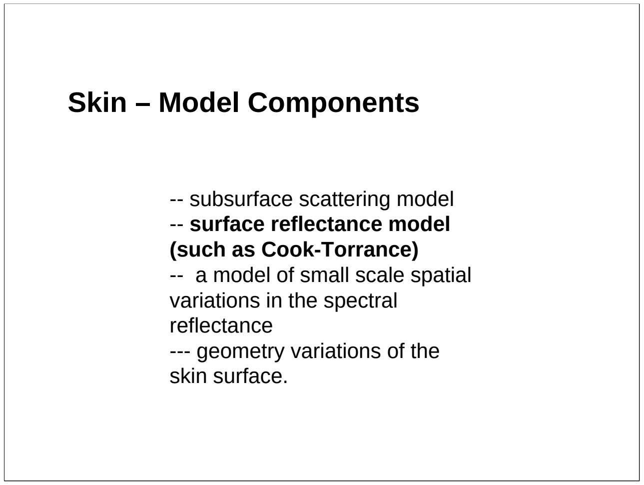
-- subsurface scattering model
-- surface reflectance model (such as Cook-Torrance)
-- a model of small scale spatial variations in the spectral reflectance
--- geometry variations of the skin surface.

The need to account for subsurface scattering in skin models was first noted in:

Pat Hanrahan and Wolfgang Krueger. Reflection from layered surfaces due to subsurface scattering. In *Proceedings of the 20th annual conference on Computer graphics and interactive techniques*, pages 165–174. ACM Press, 1993.

And more recent methods have estimated a subsurface scattering model from measurements:

Tim Weyrich, Wojciech Matusik, Hanspeter Pfister, Bernd Bickel, Craig Donner, Chien Tu, Janet McAndless, Jinho Lee, Addy Ngan, HenrikWann Jensen, andMarkus Gross. Analysis of human faces using a measurement-based skin reflectance model. In *SIGGRAPH ’06: ACM SIGGRAPH 2006 Papers*, pages 1013–1024, New York, NY, USA, 2006. ACM Press.



Skin – Model Components

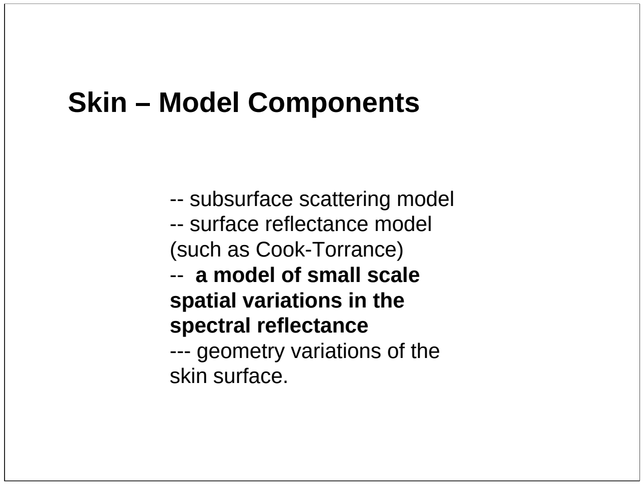
-- subsurface scattering model
-- **surface reflectance model (such as Cook-Torrance)**
-- a model of small scale spatial variations in the spectral reflectance
--- geometry variations of the skin surface.

Surface reflectance models have been fit to captured data including fitting the Lafortune model used in:

Stephen R. Marschner, Brian K. Guenter, and Sashi Raghupathy. Modeling and rendering for realistic facial animation. In *Proceedings of the Eurographics Workshop on Rendering Techniques 2000*, pages 231–242, London, UK, 2000. Springer-Verlag.

And Cook-Torrance model used in:

Athinodoros S. Georghiades. Recovering 3-d shape and reflectance from a small number of photographs. In *EGRW '03: Proceedings of the 14th Eurographics workshop on Rendering*, pages 230–240, Aire-la-Ville, Switzerland, Switzerland, 2003. Eurographics Association.



Skin – Model Components

-- subsurface scattering model
-- surface reflectance model (such as Cook-Torrance)
-- **a model of small scale spatial variations in the spectral reflectance**
--- geometry variations of the skin surface.

Spatial coloring variations are due to freckles and age spots, and temporary effects such as blushing.

A full first principles model of skin including prediction of color due to detailed composition including blood flow is the BioSpec

Model:

A. Krishnaswamy and G.V.G. Baranoski. A Biophysically-Based Spectral Model of Light Interaction with Human Skin. *Computer Graphics Forum*, 23(3):331–340, 2004.

Skin – Model Components

-- subsurface scattering model
-- surface reflectance model (such as Cook-Torrance)
-- a model of small scale spatial variations in the spectral reflectance
--- geometry variations of the skin surface.

Details of pores from molding compound used on skin:
Stephen R. Marschner, Brian K. Guenter, and Sashi Raghupathy. Modeling and rendering for realistic facial animation. In *Proceedings of the Eurographics Workshop on Rendering Techniques 2000*, pages 231–242, London, UK, 2000. Springer-Verlag.

Generic wrinkle patterns are modeled in:
L. Boissieux, G. Kiss, N. Magnenat-Thalmann, and P. Kalra. Simulation of skin aging and wrinkles with cosmetics insight. *Computer Animation and Simulation 2000*, pages 15–27, 2000.

Applying wrinkles from scanned data:

lovinskiy et al., 2006] Aleksey Golovinskiy, Wojciech Matusik, Hanspeter Pfister, Szymon Rusinkiewicz, and Thomas Funkhouser. A statistical model for synthesis of detailed facial geometry. In SIGGRAPH '06: ACM SIGGRAPH 2006 Papers, pages 1025–1034, New York, NY, USA, 2006. ACM Press.

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3. SPECIALIZED MATERIAL MODELS

Common themes
Natural Materials
Manufactured/Processed Materials

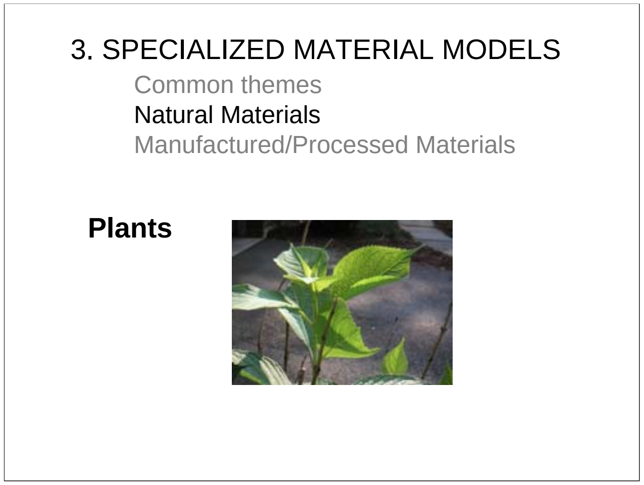
Eyes

Eyes have a complex appearance due to a complex layered structure. An approximation of this structure based on the manufacture of artificial eyes is given by:

Aaron Lefohn, Brian Budge, Peter Shirley, Richard Caruso, and Erik Reinhard. An ocularist's approach to human iris synthesis. *IEEE Comput Graphics Appl*, 23(6):70–75, November/
December 2003.

A detailed biological model is described in:

Michael W.Y. Lam and Gladimir V.G. Baranoski. A predictive light transport model for the human iris. *Computer Graphics Forum*, 25(3):359–368, 2006.



3. SPECIALIZED MATERIAL MODELS

Common themes

Natural Materials

Manufactured/Processed Materials

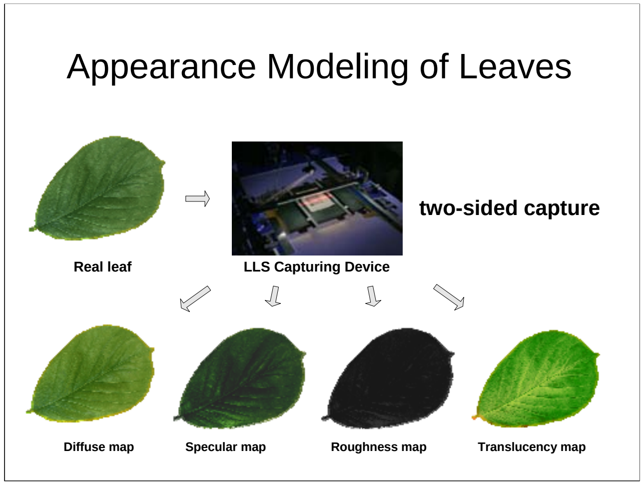
Plants

Physically detailed models of leaves are given in:

G. V. G. Baranoski and J. G. Rokne. An algorithmic reflectance and transmittance model for plant tissue. *Computer Graphics Forum*, 16(3):141–150, August 1997. ISSN 1067-7055.

Gladimir V. G. Baranoski and Jon G. Rokne. Efficiently simulating scattering of light by leaves. *The Visual Computer*, 17(8):491–505, 2001.

Lifeng Wang, Wenle Wang, Julie Dorsey, Xu Yang, Baining Guo, and Heung-Yeung Shum. Real-time rendering of plant leaves. In *SIGGRAPH '05: ACM SIGGRAPH 2005 Papers*, pages 712–719, New York, NY, USA, 2005. ACM Press.

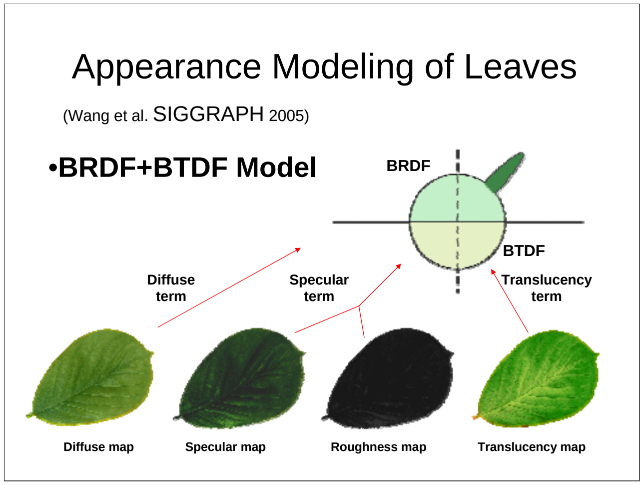


Appearance Modeling of Leaves

two-sided capture

The spatial variation of reflectance and transmittance can be measured.

Lifeng Wang, Wenle Wang, Julie Dorsey, Xu Yang, Baining Guo, and Heung-Yeung Shum. Real-time rendering of plant leaves. In *SIGGRAPH '05: ACM SIGGRAPH 2005 Papers*, pages 712–719, New York, NY, USA, 2005. ACM Press.



Appearance Modeling of Leaves

(Wang et al. SIGGRAPH 2005)

- **BRDF+BTDF Model**

BRDF

BTDF

Diffuse term

Specular term

Translucency term

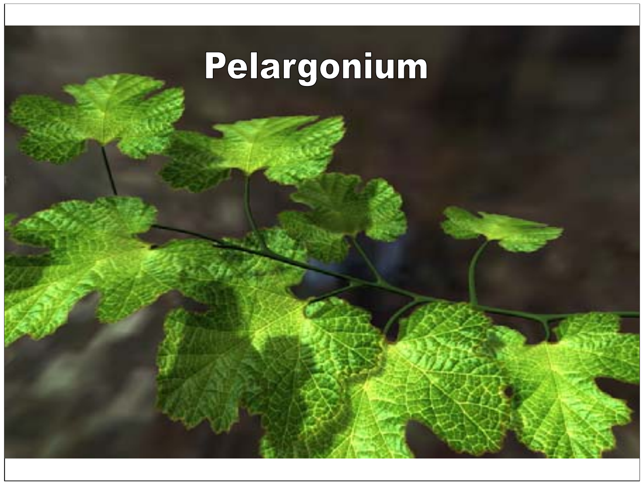
Diffuse map

Specular map

Roughness map

Translucency map

The observations can be encoded in terms of models.



Pelargonium

3. SPECIALIZED MATERIAL MODELS

Common themes
Natural Materials
Manufactured/Processed Materials

Birds/Insects

Bird feather patterns are modeled in:

Wen-Kai Dai, Zen-Chung Shih, and Ruei-Chuan Chang. Synthesizing feather textures in galliformes. *Computer Graphics Forum*, 14(3):407–420, August 1995. ISSN 1067-7055.

Structure of Bird feathers are modeled in:

Yanyun Chen, Yingqing Xu, Baining Guo, and Heung-Yeung Shum. Modeling and rendering of realistic feathers. In *Proceedings of the 29th annual conference on Computer graphics and interactive techniques*, pages 630–636. ACM Press, 2002.

L. Streit and W. Heidrich. A biologically-parameterized feather model. *Computer Graphics Forum*, 21(3):565–565, 2002.

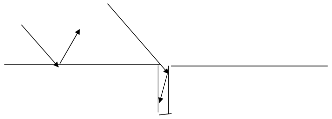
Iridescent effects typical in feathers and insects are modeled based on rigorous physical models translated to RGB renderers in:

Yinlong Sun. Rendering biological iridescences with rgb-based renderers. *ACMTrans. Graph.*, 25(1):100–129, 2006.

3. SPECIALIZED MATERIAL MODELS

Common themes
Natural Materials
Manufactured/Processed Materials

Porous



Light incident on porous materials undergoes interreflections within pores causing darkening:

S.Merillou, J.-M. Dischler, and D. Ghazanfarpour. A BRDF postprocess to integrate porosity on rendered surface. *IEEE Transactions on Visualization and Computer Graphics*, 6(4):306–318, October 2000.

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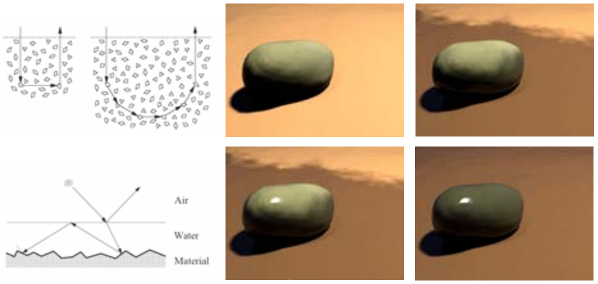
3. SPECIALIZED MATERIAL MODELS
Common themes
Natural Materials
Manufactured/Processed Materials

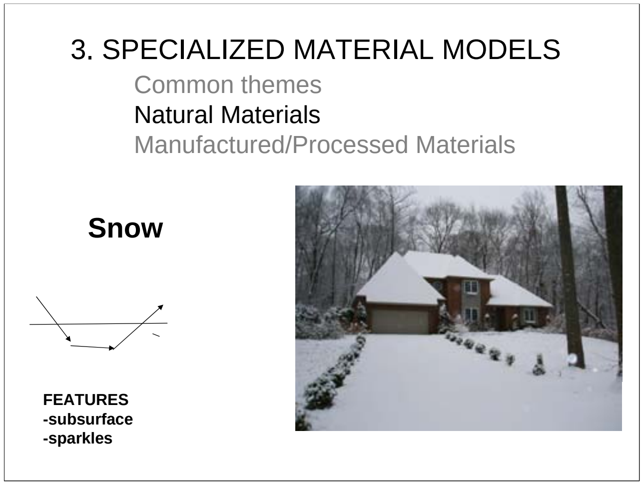
Wet Materials



Wet material appears different because of the change in the index of refraction of the medium between particles in the material, and because of the smooth surface formed by a water layer.

Henrik Wann Jensen, Justin Legakis, and Julie Dorsey. Rendering of wet material. In Lischinski and Larson [1999], pages 273–282. Proc. 10th Eurographics Rendering Workshop, Granada, Spain, June 21–23, 1999.

H.B. Mall Jr and N. da Vitoria Lobo. Determining wet surfaces from dry. *Computer Vision, 1995. Proceedings., Fifth International Conference on*, pages 963–968, 1995.



3. SPECIALIZED MATERIAL MODELS

Common themes

Natural Materials

Manufactured/Processed Materials

Snow

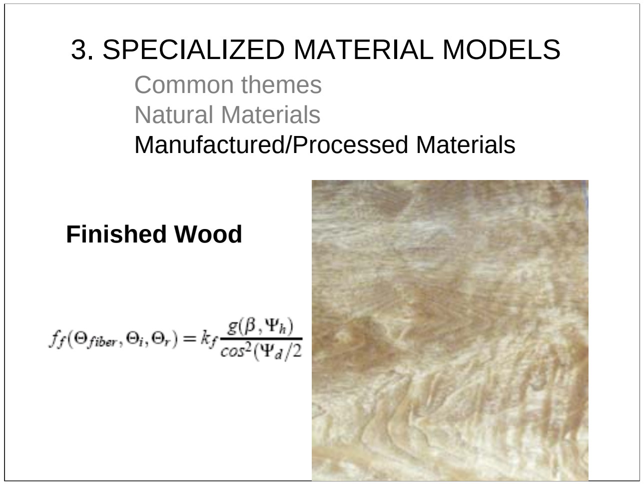
FEATURES
-subsurface
-sparkles

Important features in realistic snow are subsurface scattering within snow, and the sparkles caused by mirror reflections from individual crystals.

T. Nishita, H. Iwasaki, Y. Dobashi, and E. Nakamae. A modeling and rendering

method for snow by using metaballs. *Computer Graphics Forum*, 16(3):357–364, August 1997. ISSN

1067-7055.



3. SPECIALIZED MATERIAL MODELS

Common themes

Natural Materials

Manufactured/Processed Materials

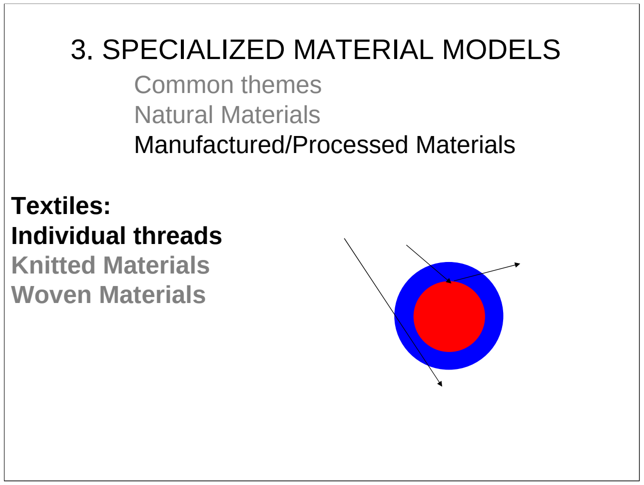
Finished Wood

$$f_f(\Theta_{fiber},\Theta_i,\Theta_r) = k_f \frac{g(\beta,\Psi_h)}{cos^2(\Psi_d/2}$$

Finished wood can have a lustrous appearance that results from the internal orientation of the wood fibers, combined with the reflection and transmission from the smoothed finished top surface. Marschner et al. modeled this reflectance as a Gaussian function g that depends on parameters Psi that depend on the orientation of the wood fibers and the surface normal.

Stephen R. Marschner, Stephen H. Westin, Adam Arbree, and Jonathan T. Moon.

Measuring and modeling the appearance of finished wood. *ACM Trans. Graph.*, 24(3):727–734, 2005.



3. SPECIALIZED MATERIAL MODELS

Common themes
Natural Materials
Manufactured/Processed Materials

Textiles:
Individual threads
Knitted Materials
Woven Materials

The structure of individual threads may be designed to give particular optical effects, such as looking a different color from different view angles.

B. Rubin, H. Kobsa, and S. M. Shearer. Prediction and verification of an iridescent synthetic fiber. *Appl. Opt.*, 36:6388–6392, 1997.

3. SPECIALIZED MATERIAL MODELS

Common themes
Natural Materials
Manufactured/Processed Materials

Textiles:
Individual threads
Knitted Materials
Woven Materials

Specialized volumetric structures have been proposed to model the fuzzy nature of knitwear:

Eduard Groeller, Rene T. Rau, and Wolfgang Strasser. Modeling and visualization of knitwear. *IEEE Transactions on Visualization and Computer Graphics*, 1(4):302–310, 1995.

Ying-Qing Xu, Yanyun Chen, Stephen Lin, Hua Zhong, Enhua Wu, Baining Guo, and

Heung-Yeung Shum. Photorealistic rendering of knitwear using the lumislice. In *Proceedings of the 28th*

annual conference on Computer graphics and interactive techniques, pages 391–398. ACM Press, 2001.

3. SPECIALIZED MATERIAL MODELS

Common themes
Natural Materials
Manufactured/Processed Materials

Textiles:
Individual threads
Knitted Materials
Woven Materials

The reflectance of individual threads, effect of light going through threads and weaving patterns need to be accounted for in realistically rendering woven materials

Neeharika Adabala, Guangzheng Fei, and Nadia Magnenat-Thalmann. Visualization of woven cloth. *Proceedings of the 14th Eurographics workshop on Rendering*, Leuven, Belgium, 2003. pages 178–185.

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3. SPECIALIZED MATERIAL MODELS

Common themes
Natural Materials
Manufactured/Processed Materials

Automotive Paint

A first principles model for automotive paint, including the “depth” effect given by multiple layers and sparkles caused by reflections off small particles is given in:

Sergey Ershov, Konstantin Kolchin, and Karol Myszkowski. Rendering pearlescent appearance based on paint-composition modelling. *Computer Graphics Forum*, 20(3), 2001. ISSN 1067-7055.

Sergey Ershov, Roman Durikovic, Konstantin Kolchin, and Karol Myszkowski. Reverse engineering approach to appearance-based design of metallic and pearlescent paints. *Vis. Comput.*, 20(8-9):586–600, 2004.

Roman Durikovic and William L. Martens. Simulation of sparkling and depth effect in paints. In *SCCG ’03: Proceedings of the 19th spring conference on Computer graphics*, pages 193–198, New York, NY, USA, 2003. ACM Press

The change of color with angle for metallic car paints is modeled in a system for automotive finish design in:

3. SPECIALIZED MATERIAL MODELS

Common themes
Natural Materials
Manufactured/Processed Materials

Artistic Paints

Paints, particularly water colors, are modeled as particulates carried by a fluid modeled with either a shallow fluid model:

Cassidy J. Curtis, Sean E. Anderson, Joshua E. Seims, KurtW. Fleischer, and David H.
Salesin. Computer-generated watercolor. In *Proceedings of the 24th annual conference on Computer*
graphics and interactive techniques, pages 421–430. ACM Press/Addison-Wesley Publishing Co., 1997.

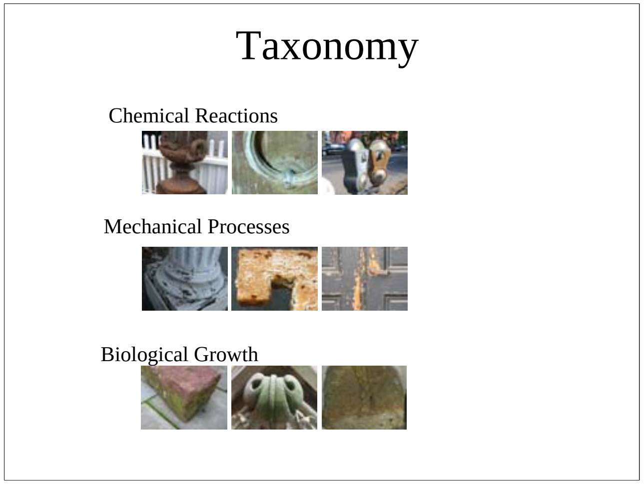
Or a Lattice-Boltzmann model:

Nelson S.-H. Chu and Chiew-Lan Tai. Moxi: real-time ink dispersion in absorbent paper. *ACM Trans. Graph.*, 24(3):504–511, 2005.

4. AGING AND WEATHERING PROCESSES

Taxonomy
Simulation Methods
Capture Approaches

The area of aging and weathering processes is relatively new in material modeling. Many very detailed models have been developed. A general view of the area is given by organizing the detailed models into three general categories.



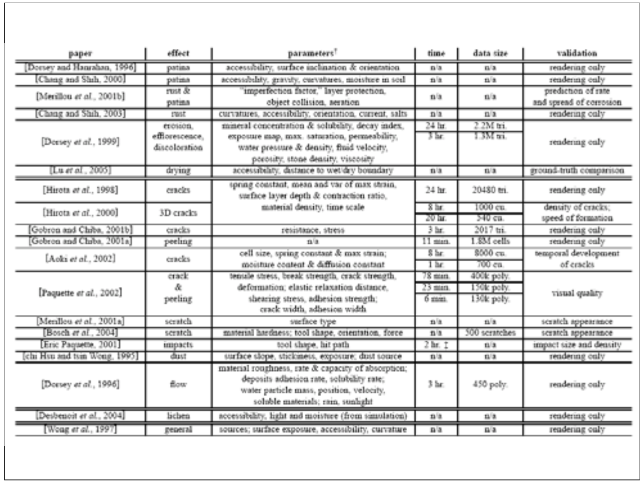
Taxonomy

Chemical Reactions

Mechanical Processes

Biological Growth

- Chemical Reactions like rusting or patination
- Mechanical Processes like paint crackling and peeling
- Biological Growth like algae, moss or mold growing



paper	effect	parameters†	time	data size	validation
[Dorsey and Hanrahan, 1996]	patina	accessibility, surface inclination & orientation	n/a	n/a	rendering only
[Chang and Shih, 2000]	patina	accessibility, gravity, curvatures, moisture in soil	n/a	n/a	rendering only
[Merillou *et al.*, 2001b]	rust & patina	"imperfection factor," layer protection, object collision, aeration	n/a	n/a	prediction of rate and spread of corrosion
[Chang and Shih, 2003]	rust	curvatures, accessibility, orientation, current, salts	n/a	n/a	rendering only
[Dorsey *et al.*, 1999]	erosion, efflorescence, discoloration	mineral concentration & solubility, decay index, exposure map, max. saturation, permeability, water pressure & density, fluid velocity, porosity, stone density, viscosity	24 hr. 3 hr.	2.2M tri. 1.3M tri.	rendering only
[Lu *et al.*, 2005]	drying	accessibility, distance to wet/dry boundary	n/a	n/a	ground-truth comparison
[Hirota *et al.*, 1998]	cracks	spring constant, mean and var of max strain, surface layer depth & contraction ratio, material density, time scale	24 hr.	20480 tri.	rendering only
[Hirota *et al.*, 2000]	3D cracks		8 hr. 20 hr.	1000 cu. 540 cu.	density of cracks; speed of formation
[Gobron and Chiba, 2001b]	cracks	resistance, stress	3 hr.	2017 tri.	rendering only
[Gobron and Chiba, 2001a]	peeling	n/a	11 min.	1.8M cells	rendering only
[Aoki *et al.*, 2002]	cracks	cell size, spring constant & max strain; moisture content & diffusion constant	8 hr. 1 hr.	8000 cu. 700 cu.	temporal development of cracks
[Paquette *et al.*, 2002]	crack & peeling	tensile stress, break strength, crack strength, deformation; elastic relaxation distance, shearing stress, adhesion strength; crack width, adhesion width	78 min. 23 min. 6 min.	400k poly. 150k poly. 130k poly.	visual quality
[Merillou *et al.*, 2001a]	scratch	surface type	n/a	n/a	scratch appearance
[Bosch *et al.*, 2004]	scratch	material hardness; tool shape, orientation, force	n/a	500 scratches	scratch appearance
[Eric Paquette, 2001]	impacts	tool shape, hit path	2 hr. ‡	n/a	impact size and density
[chi Hsu and tsin Wong, 1995]	dust	surface slope, stickiness, exposure; dust source	n/a	n/a	rendering only
[Dorsey *et al.*, 1996]	flow	material roughness, rate & capacity of absorption; deposits adhesion rate, solubility rate; water particle mass, position, velocity, soluble materials; rain, sunlight	3 hr.	450 poly.	rendering only
[Desbenoit *et al.*, 2004]	lichen	accessibility, light and moisture (from simulation)	n/a	n/a	rendering only
[Wong *et al.*, 1997]	general	sources; surface exposure, accessibility, curvature	n/a	n/a	rendering only

Summary table from

Jianye Lu, Athinodoros S. Georghiades, Andreas Glaser, Hongzhi Wu, Li-YiWei, Baining

Guo, Julie Dorsey, and Holly Rushmeier. Context-aware textures. *ACM Trans. Graph.*, 26(1):3, 2007.

4. AGING AND WEATHERING PROCESSES
- Taxonomy
- **Simulation Methods**
- Capture Approaches

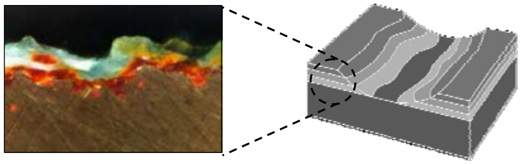
Metallic patinas

natural

artificial

Metals often develop a characteristic patina over time. The patination process, which develops in a series of thin surface layers, is due to the chemical alteration of a surface and results in changes in color. Patination may be the result of deliberately applied craft processes or natural corrosion.

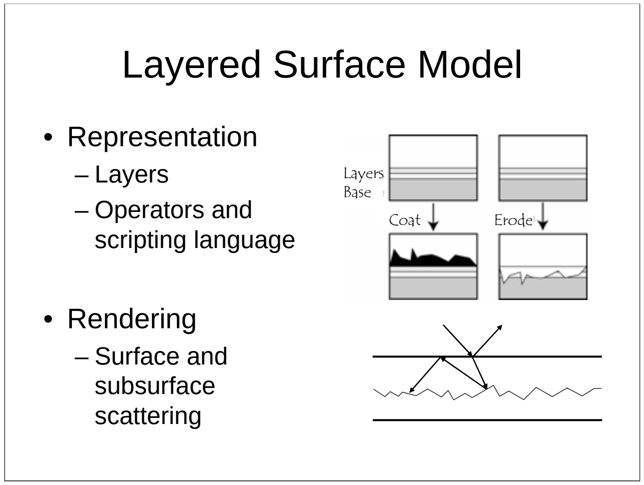
Layers and Materials



copper micrograph

abstraction

To represent surface patinas, we have developed a layered-surface model. We have also developed a simple scripting language, consisting of operators such as “coat” and “erode,” which can be used to specify the evolution of a surface over time.



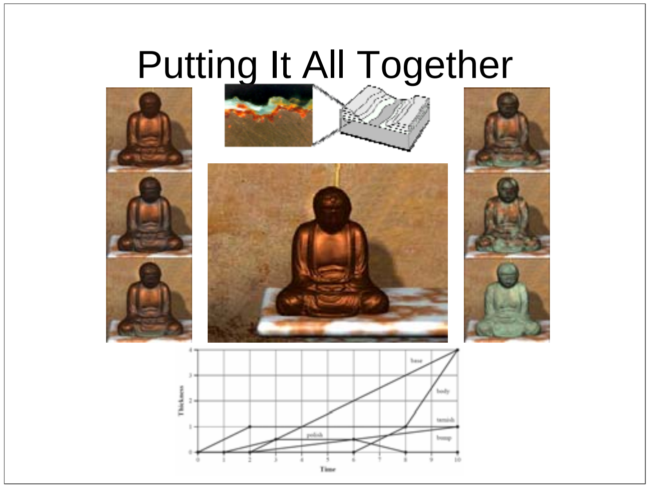
Layered Surface Model

- Representation
  - Layers
  - Operators and scripting language
- Rendering
  - Surface and subsurface scattering

In our work, we've introduced a model for layered surfaces and applied it to a classic example of the aging of a surface: the development of metallic patinas.

This model allows us to program how the surface will change over time in addition to rendering the complex interaction of light with the surface and subsurface of the model.

We have also developed a simple scripting language, consisting of operators such as "coat" and "erode," which can be used to specify the evolution of a surface over time.



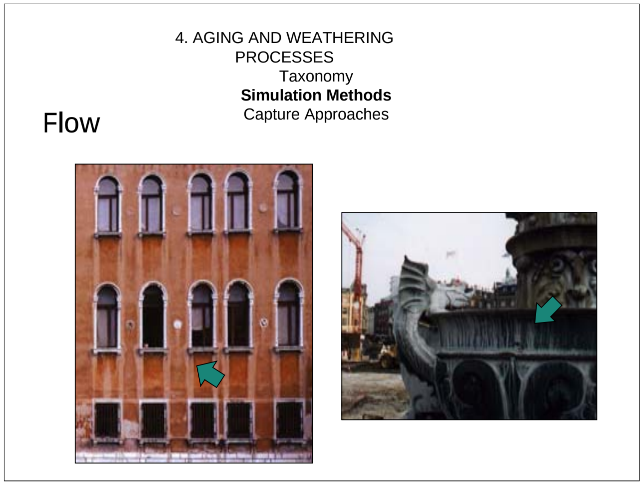
Putting It All Together

Here, you're seeing the build up a patina on a small polygonal statue of a buddha. Our model allows us to control the composition and thickness of the layers in the model and to vary various position-dependent parameters according to the geometry and other factors…

Julie Dorsey and Pat Hanrahan. Modeling and rendering of metallic patinas.

In *Proceedings of the 23rd annual conference on Computer graphics and interactive techniques*, pages

387–396. ACM Press, 1996.



4. AGING AND WEATHERING PROCESSES
Taxonomy
Simulation Methods
Capture Approaches

Flow

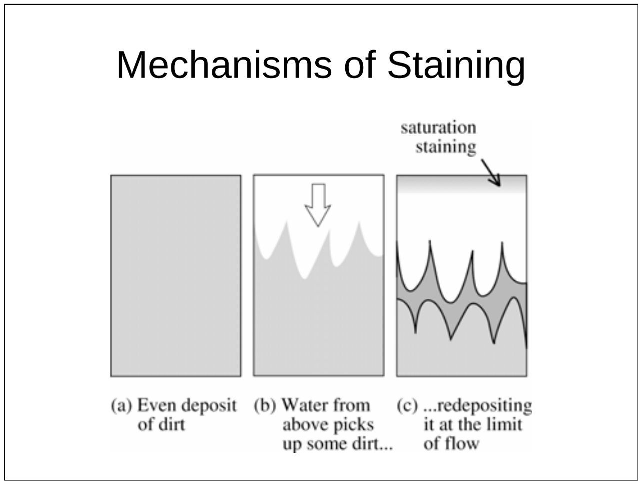
The flow of water is one of the most pervasive and important natural forces involved in the weathering of materials — producing a distinctive set of patterns of washes and stains.

These slides show photographs showing the weathering of various buildings. Looking carefully at these slides, you can see that many of the complex patterns of the surfaces are due to the flow of water.

Water may wash dirt from some areas and clean them;

in other areas dirt and other materials are deposited, creating stains.

The result is a visually rich set of patterns that are difficult to model with current texturing techniques.



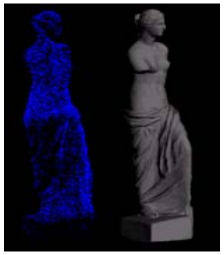
Mechanisms of Staining

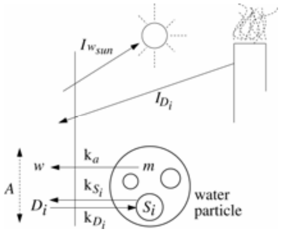
(a) Even deposit of dirt (b) Water from above picks up some dirt... (c) ...redepositing it at the limit of flow

Washing and staining effects:

The key factors are the amount of water that incident on a surface, the geometry of the surface, and the absorption of water by the surface.

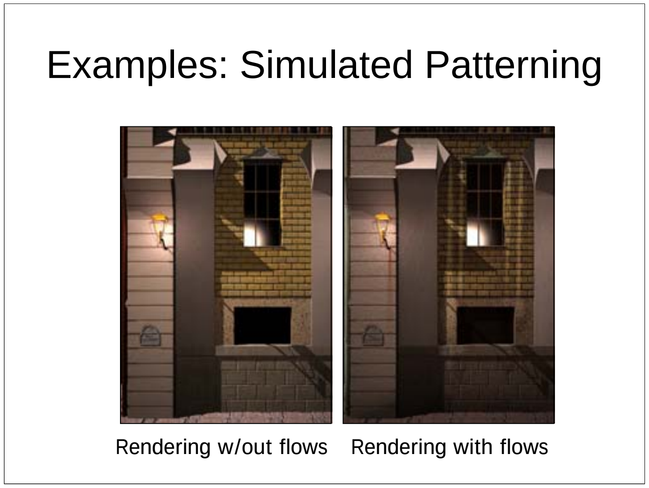
Simulation on a Complex Model





Examples: Simulated Patterning

Rendering w/out flows Rendering with flows



Examples: Simulated Patterning

Rendering w/out flows Rendering with flows

Julie Dorsey, Hans Kohling Pedersen, and Pat Hanrahan. Flow and changes in appearance. In *Proceedings of the 23rd annual conference on Computer graphics and interactive techniques*, pages 411–420. ACM Press, 1996.

4. AGING AND WEATHERING PROCESSES

- Taxonomy
- **Simulation Methods**
- Capture Approaches

Rust

Stephane Merillou, Jean-Michel Dischler, and Djamchid Ghazanfarpour. Corrosion: Simulating and rendering. In *GI 2001*, pages 167–174, June 2001.

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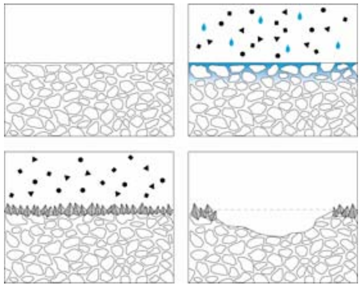
4. AGING AND WEATHERING PROCESSES

Taxonomy

Simulation Methods

Capture Approaches

Erosion



Julie Dorsey, Alan Edelman, Henrik Wann Jensen, Justin Legakis, and Hans Kohling

Pedersen. Modeling and rendering of weathered stone. In *Proceedings of the 26th annual conference on*

Computer graphics and interactive techniques, pages 225–234. ACM Press/Addison-Wesley Publishing

Co., 1999.

Representative Effects I

1908

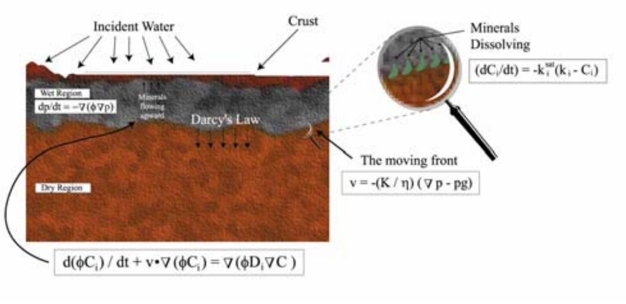
1969

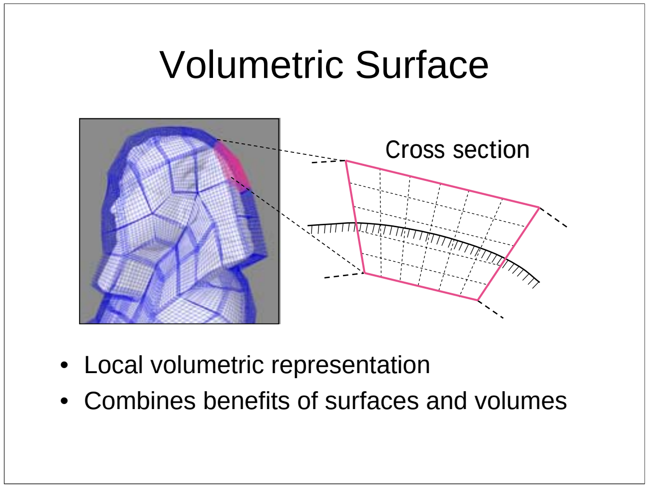
Representative Effects II

Corestone & yellowing

Yellowing

Weathering Simulation

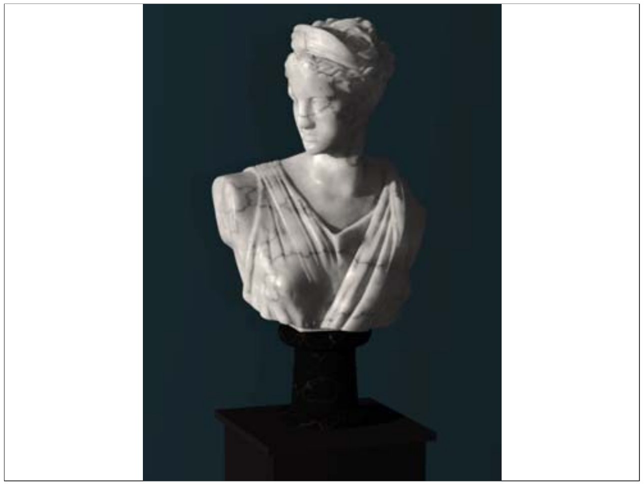


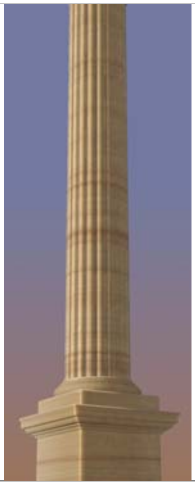


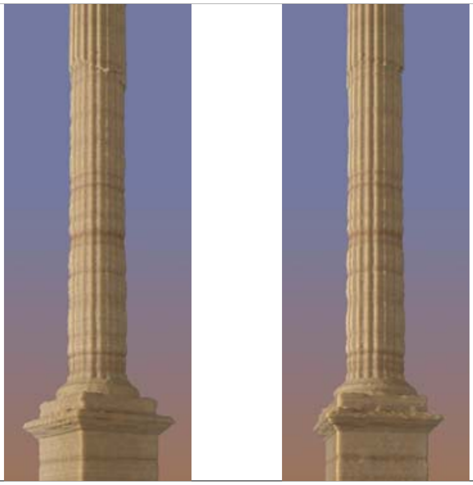
Volumetric Surface

- Local volumetric representation
- Combines benefits of surfaces and volumes

Slabs on a scanned mesh







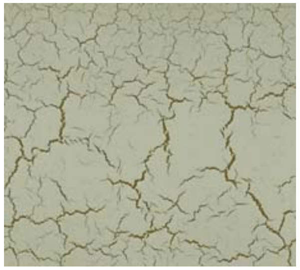
4. AGING AND WEATHERING PROCESSES

Taxonomy

Simulation Methods

Capture Approaches

Cracking



Koichi Hirota, Yasuyuki Tanoue, and Toyohisa Kaneko. Generation of crack patterns with a physical model. *The Visual Computer*, 14(3):126 – 137, 1998.

Koichi Hirota, Yasuyuki Tanoue, and Toyohisa Kaneko. Simulation of threedimensional cracks. *The Visual Computer*, 16(7):371 – 378, 2000.

4. AGING AND WEATHERING PROCESSES

Taxonomy

Simulation Methods

Capture Approaches

Peeling

S. Gobron and N. Chiba. Simulation of peeling using 3d-surface cellular automata.
In *9th Pacific Graphics Conference on Computer Graphics and Applications*, pages 338–347,
Tokyo Japan, Oct 2001. IEEE.

Eric Paquette, Pierre Poulin, and George Drettakis. The simulation of paint cracking and peeling. In *Graphics Interface 2002*, pages 59–68, May 2002.

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4. AGING AND WEATHERING PROCESSES

Taxonomy

Simulation Methods

Capture Approaches

Scratching

S. Merillou, J.M. Dischler, and D. Ghazanfarpour. Surface scratches: measuring, modeling and rendering. *The Visual Computer*, 17(1):30 – 45, 2001.

C. Bosch, X. Pueyo, S. M´erillou, and D. Ghazanfarpour. A physically-based model for
rendering realistic scratches. *Computer Graphics Forum*, 23(3):361–370, 2004.

4. AGING AND WEATHERING PROCESSES

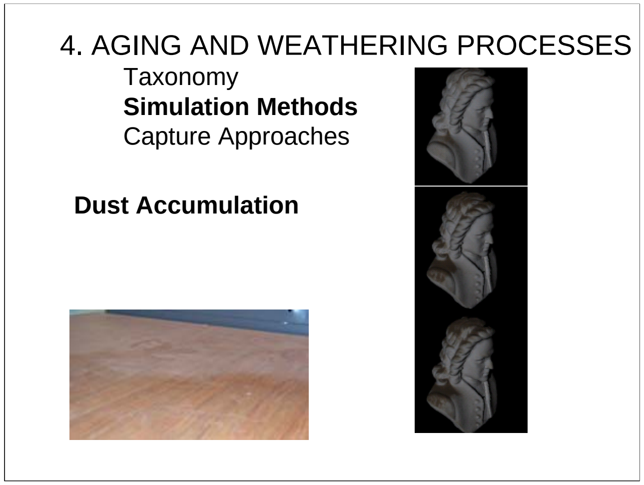
Taxonomy

Simulation Methods

Capture Approaches

Denting and Impacts

George Drettakis Eric Paquette, Pierre Poulin. Surface aging by impacts. In *Graphics Interface 2001*, pages 175–182, June 2001.



4. AGING AND WEATHERING PROCESSES

Taxonomy

Simulation Methods

Capture Approaches

Dust Accumulation

Siu-Chi Hsu and Tien-Tsin Wong. Simulating dust accumulation. *IEEE Comput Graphics Appl*, 15(1):18–22, January 1995.

4. AGING AND WEATHERING PROCESSES

Taxonomy
Simulation Methods
Capture Approaches

Lichen Growth

Brett Desbenoit, Eric Galin, and Samir Akkouche. Simulating and modeling lichen growth. *Computer Graphics Forum*, 23(3):341–350, 2004.

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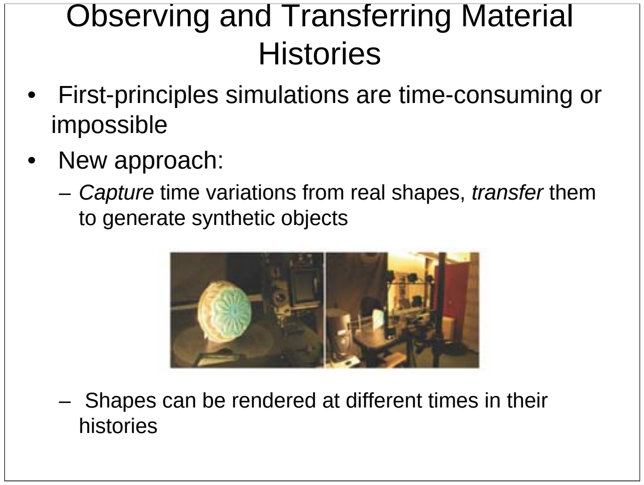
4. AGING AND WEATHERING PROCESSES

Taxonomy
Simulation Methods
Capture Approaches

Capture in Context

-- appearance
--- agent causing change
-- geometry



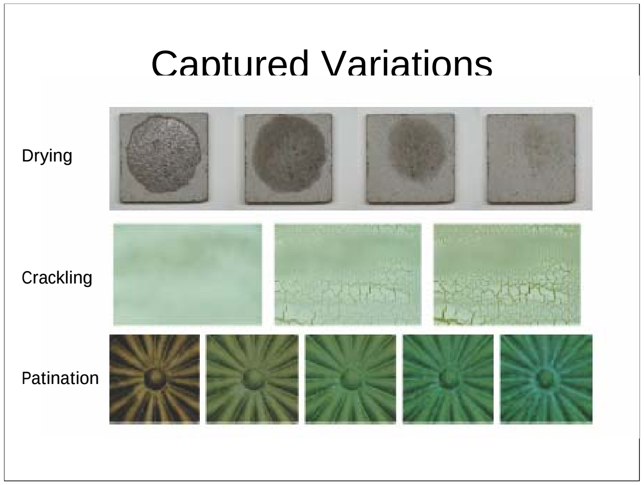
Observing and Transferring Material Histories

- First-principles simulations are time-consuming or impossible
- New approach:
  - *Capture* time variations from real shapes, *transfer* them to generate synthetic objects
  - Shapes can be rendered at different times in their histories

While simulating aging effects produces good results, first-principles simulations are time consuming or, in some cases, impossible because the underlying physics and chemistry are not completely understood.

In recent work, we have explored a new approach to producing weathering effects. Rather than simulating aging effects, we instead capture time variations from real shapes to generate synthetic objects. Using this approach, shapes can be rendered at different times in their histories

This example shows a time series captured from a copper bowl. We applied an artificial patination treatment to the bowl over a two week period and captured the shape and texture variations a frequent time intervals. The bottom row shows the application of this appearance history to a synthetic sea horse model. Note how the appearance variations are linked to the shape.



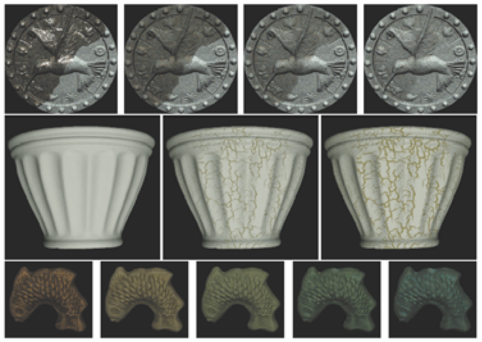
Captured Variations

Drying

Crackling

Patination

Transferred/Synthesized Effects



Jianye Lu, Athinodoros S. Georghiades, Andreas Glaser, Hongzhi Wu, Li-YiWei, Baining

Guo, Julie Dorsey, and Holly Rushmeier. Context-aware textures. *ACM Trans. Graph.*, 26(1):3, 2007.

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4. AGING AND WEATHERING PROCESSES

Taxonomy
Simulation Methods
Capture Approaches

Time Varying

Additional efforts have capture time series of BRDF data

Additional time varying capture:

Jinwei Gu, Chien-I Tu, Ravi Ramamoorthi, Peter Belhumeur, Wojciech Matusik, and

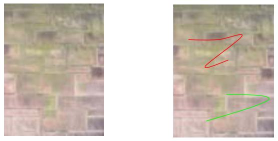
Shree Nayar. Time-varying surface appearance: acquisition, modeling and rendering. *ACM Trans.*

Graph., 25(3):762–771, 2006.

4. AGING AND WEATHERING PROCESSES

Taxonomy
Simulation Methods
Capture Approaches

From Single Example



In some cases weathering effects can be captured by taking data from a single image of a material that has been marked with “fully aged” and “fully new” regions.

Jiaping Wang, Xin Tong, Stephen Lin, Minghao Pan, Chao Wang, Hujun Bao, Baining
Guo, and Heung-Yeung Shum. Appearance manifolds for modeling time-variant appearance of materials.
ACM Trans. Graph., 25(3):754–761, 2006.

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5. FUTURE TRENDS

- Advanced modeling
- Improved capture devices/methods
- Procedural methods