1.6 Rough Surface Scattering Applications

1.6.1 Computer Graphic Shading and Rendering

At optical frequencies, nearly every object in our everyday existence has electromagnetically significant roughness. The basic theory of rough surfaces developed in this section can help to understand the optical properties and behaviors that these objects possess. Furthermore, an understanding of rough surface scattering is important to the field of computer graphics for the lifelike rendering of complicated three-dimensional scenery.

Consider the physical diagram of Figure 1.5, which illustrates the composition of a typical object surface at the microscopic level. Many objects possess a glossy veneer that undulates very slightly across the surfaces. Incident light – whether from a coherent or incoherent source – would partially reflect and partially transmit through this first interface. The transmitted portion of the light then travels through the dielectric surface to the much rougher material interface below. This surface, usually regarded as Lambertian, then scatters the light in nearly every direction (as well as coloring the light with frequency-selective absorption). The diffusely scattered light then partially transmits back into the scene from the surface. Thus, there are two potential components to the light emanating from a surface at optical frequencies: a near-specular component and a diffuse, Lambertian component.

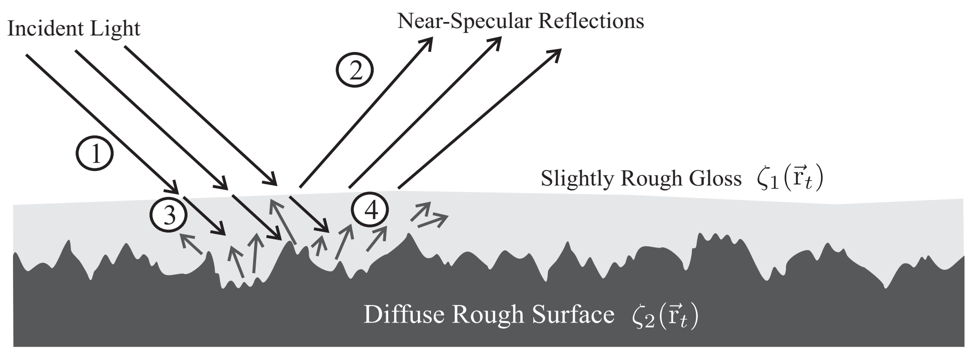

Figure 1.5. Physics of light interaction on a surface: 1) incident light partially reflects off a 2) smooth, slightly undulating surface. Then 3) transmitted light enters the second medium and strikes the Lambertian surface which re-radiates diffuse power away from the surface in all directions.

The basic physical model of Figure 1.5 helps to explain why objects look the way they do to our eyes. First of all, the diffuse scattering of light allows us to see surfaces even when angle-of-observation is not equal to angle-of-incidence to a light source. However, there can be a strong near-specular component present, which provides a glossy sheen and acts as an imperfect mirror for any image that falls upon the surface. Capturing this behavior is the key part of realistic computer graphic rendering for digital art, web illustrations, and video games.

In light of our knowledge of rough surface scattering, we will parse one of the most famous empirical models in computer graphics – the *Phong reflection model*. This reflection model estimates the light intensity contribution I (in Watts) at observation point ($\vec{r}$) due to a surface point $\vec{r}_s$ in a scene may be computed with the following summation over the light sources present:

$$I(\vec{r}) = \sum_{m=1}^{\substack{\#\text{ of}\\\text{sources}}} \Big(\underbrace{\kappa_a}_{\text{ambient}} + \underbrace{\kappa_d \cos\theta_{nm}}_{\text{diffuse}} + \underbrace{\kappa_s \cos^{\alpha}\theta_{rm}}_{\text{specular}} \Big) \, I_m \tag{1.6.1}$$

$$\cos\theta_{rm} = \hat{k}_{rm} \cdot \frac{(\vec{r} - \vec{r}_s)}{\|\vec{r} - \vec{r}_s\|} \qquad \cos\theta_{nm} = \hat{n} \cdot \frac{(\vec{r}_m - \vec{r}_s)}{\|\vec{r}_m - \vec{r}_s\|}$$

where

I_m	-	intensity of the mth light source
κ_a	-	ambient coefficient due to multiple diffusely scattered waves
κ_d	-	diffuse scattering coefficient due to Lambertian roughness
κ_s	-	specular reflection coefficient from glossy layer
α	-	shininess factor (0 is pure Lambertian, ∞ is a perfect mirror)
$\vec{r}$	-	point of observation
$\vec{r}_s$	-	surface point under observation
$\vec{r}_m$	-	location vector of the mth source
$\hat{n}$	-	surface normal vector
$\hat{k}_{rm}$	-	direction of specular reflection due to mth source

The geometry used for these terms is summarized in Figure 1.6.

The model described by Equation (1.6.1) breaks down the optical contribution of a point on a surface into specular, diffuse, and ambient components.

- **Ambient Term:** This term is physically linked to the "ambient" light in the environment which is mostly due to light that has already diffusely scattered from a source. This component provides a dull, soft illumination of a surface point from nearly every direction and to every direction. Though we would expect the reflection of ambient illumination to vary across a realistic scene, the omnipresence of diffuse scattering at optical frequencies allows us to approximate ambient illumination as uniform. Captured by a single coefficient κ_a, this model of ambient illumination – the most empirical part of the Phong reflection model – provides enough realism for most graphics applications. In Equation (1.6.1), the ambient contribution will scale with the total intensity of the sources in the scene.

- **Specular Term:** This component imparts a rough, mirror-like sheen to points on the surface of an object. In addition to the material-dependent coefficient κ_s, which measures overall intensity of the specular reflection, there is a shininess term α. When $\alpha = 0$, the specular reflection takes on a pseudo-Lambertian pattern where light reflects equally in all directions. When α

becomes very large, this reflection contribution *only* occurs in specular directions. In our rough surface analysis, we would describe the glossy layer surface displacement function $\zeta_1(\vec{r}_t)$ as having increasing wavenumber content as α decreases.

- **Diffuse Term:** This component is due to the underlying, highly rough reflective layer under any glossy veneer. Its surface displacement function, $\zeta_2(\vec{r}_t)$ would have near-uniform wavenumber content over the interval $\|\vec{k}\| < \frac{4\pi}{\lambda}$. The scattering in this case is near-Lambertian and radiates as a function of observation angle with respect to the surface normal.

These terms are often applied for each color of light in an illumination spectrum. Although the Phong reflection model is highly empirical, it is easy to see how it approximately reproduces the physical behavior in the electromagnetic interactions of a realistic rough surfaces. Because the eye is very forgiving, the approximate behavior is sufficient for many types of realistic scene renderings.

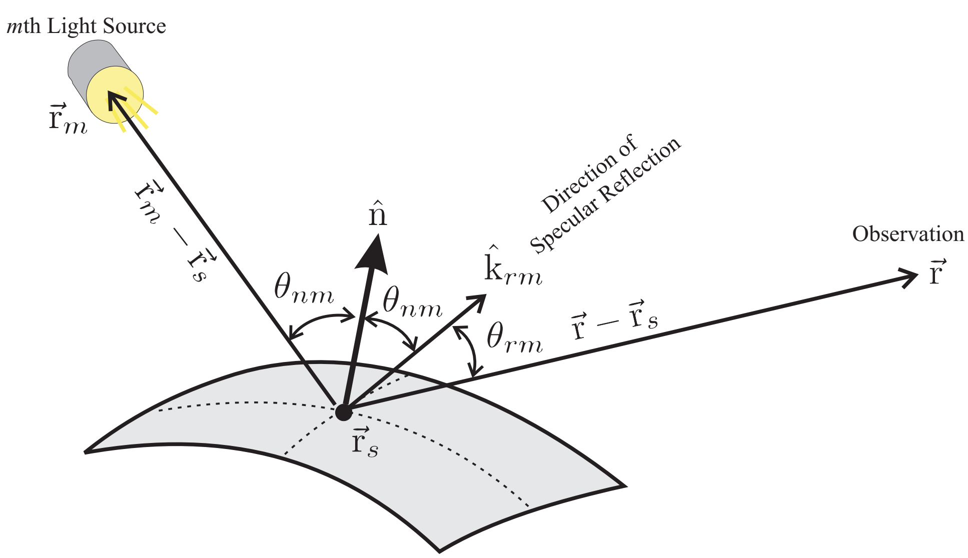

Figure 1.6. Geometry used in the Phong reflection model.

Note: Bui Tuong Phong (1942-1975)

Bui Tuong Phong invented what would become widely known as the Phong reflection model in his 1973 Ph.D. dissertation [Pho73]. The model's popularity in computer graphics derived from its beautiful balance of simplicity and eye-insensitive approximations. Many other optical reflection models followed. Interestingly, an early method for interpolating optical behavior across a curved surface in the Phong reflection model became known as *Phong shading* in computer parlance. Though not invented by Phong, the *Phong shading* algorithm is in wide use today – even when it is applied to models other than Phong reflection!

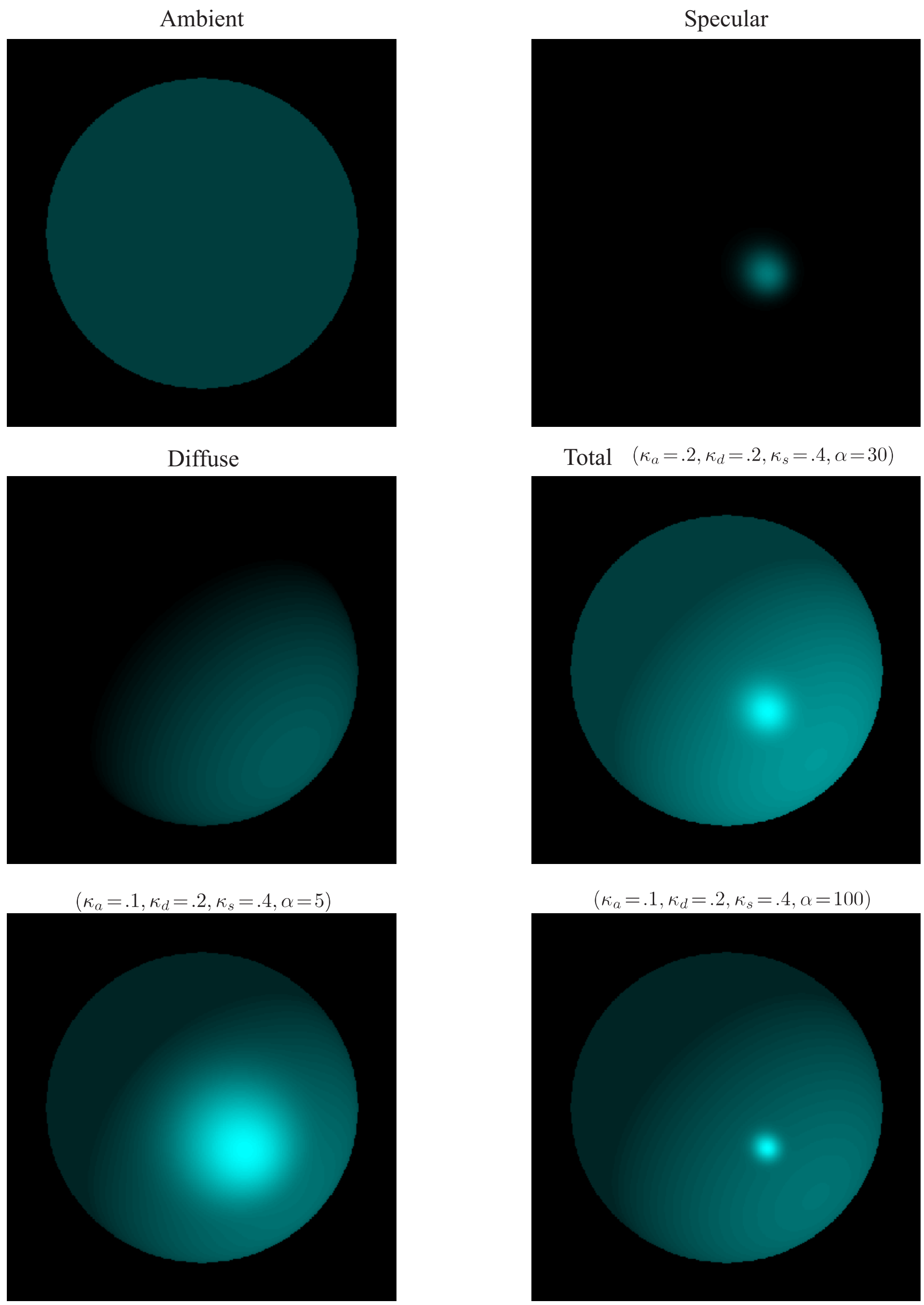

Figure 1.7. Example of ambient, specular, and diffuse components for a sphere rendered using the Phong reflection model. Increasing the shininess factor α allows the sphere to reflect the point source of light more cleanly.