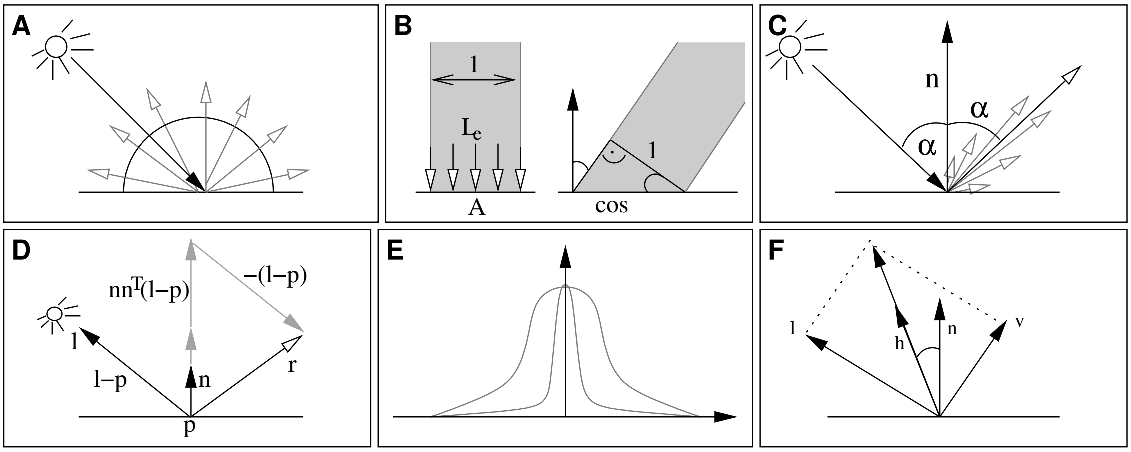

Figure 2.16: Lighting: (a) diffuse reflection, (b) light energy, (c) specular reflection, (d) reflected vectors, (e) shininess, (f) Phong-Blinn approximation.

where φ is the angle between surface normal and light ray. This means, the energy exposed to this square unit is

$$E = \frac{L_e}{A} = L_e \cdot \cos\varphi$$

The amount of diffusely reflected light is proportional to the cosine of the angle between surface normal and light direction (*Lambertian reflection*). For a light source at position l emitting the light C_l onto a surface point p with normal n and diffuse material property matrix α_d, we get for the diffuse component:

$$C_d(p, n, l) = \alpha_d \cdot C_l \cdot \cos\varphi = \alpha_d \cdot C_l \cdot \frac{n^T(l-p)}{\|l-p\|}.$$

Specular Lighting

The specular component models the reflection that occurs on shiny surfaces: if a light ray hits the surface with an angle φ to the surface normal, it is reflected with the same angle (cf. Fig. 2.16c). This reflected light vector can be computed as $r = (2nn^T - I)(l - p)$ (cf. Fig. 2.16d).

Intuitively, the closer the viewing ray $v - p$ is to this reflected vector r, the higher the specular intensity. As we deviate from r, the intensity gets smaller. This effect is again modeled by a cosine factor, this time taking the angle between r and $v - p$ into account.

$$C_{sp}(p, n, l, v) = \alpha_{sp} \cdot C_l \cdot \left(\frac{r^T(v-p)}{\|r\| \, \|v-p\|} \right)^s$$

Depending on the material (roughness/shininess) not all energy is reflected into the direction r, but some of the energy is still scattered. This is modeled by the *shininess* exponent s (cf. Fig. 2.16e): The higher s is, the less light is reflected into directions deviating from r. For large values of s, the light is almost completely reflected into the direction r (perfect/complete reflection). The shininess s therefore controls the size of the specular highlights (cf. Fig. 2.15c).

Phong-Blinn Approximation

Calculating the specular component using the above formula is computationally quite costly. Therefore, an approximation to this formula by Phong and Blinn is normally used. This approximation is based on the *halfway vector* h of l and v (cf. Fig. 2.16f):

$$h = \frac{(l-p)+(v-p)}{\|(l-p)+(v-p)\|}$$

The angle between h and n is a good approximation to the angle between r and v. Hence, we can simplify the formula for specular lighting as follows:

$$C_{sp}(p,n,l,v) \approx \alpha_{sp} \cdot C_l \cdot \left(n^T h\right)^s .$$

Using this approximation yields very similar visual results in most cases, but requires substantially less calculations.

2.3.2 Other Lighting Effects

Attenuation We have not yet discussed one important physical property of light: *attenuation*. It can be observed that light intensity decreases with increasing distance between surface and light source. We need to take this effect into account in order to create realistic images.

A light source emits light equally in all directions. At distance r from the light source the light's energy is distributed on a sphere of radius r. Since the surface of this sphere grows quadratically with increasing radius, the light intensity decreases quadratically as we move away from the light source.

Unfortunately, using quadratic attenuation together with the approximations inherent in the Phong model simply does not look well. Instead we will use an additional linear attenuation factor and get:

$$\text{att}(p,l) = \frac{1}{att_{lin} \cdot \|p-l\| + att_{quad} \cdot \|p-l\|^2}$$

The two coefficients att_{lin} and att_{quad} give the relative weighting of the linear and quadratic attenuation terms, respectively.

Spotlight Another effect to be taken into account is that light can be directional. The light sources we considered so far emit light equally into all directions.

In case of a spotlight, a light source is associated with a direction d into which it emits the most light. Its intensity decreases with increasing deviation from that direction. Therefore, we need another factor, called *spotlight-factor*, that models this effect. Similar to the diffuse and specular term, the directional attenuation can be expressed in terms of a cosine, leading to

$$spot(p,l) = \left(\frac{d^T(p-l)}{\|p-l\|}\right)^f$$

Here, d denotes the direction of the spotlight, and f is a light source property similar to the specular shininess: the larger f is, the more spotty is the light source, i.e. more light is emitted into the direction d and less is emitted into other directions.

Depth Cueing If we want to model large outdoor scenes, we also have to take atmospheric effects into account. With growing distance to the viewer, the environment seems to merge with the atmosphere, i.e. the colors fade to some grey-blue. This effect is modeled by the so-called *depth cueing*: a gray-bluish atmosphere color C_{dc} is blended into the color from the previous steps, depending on the distance to the viewer (represented by the factor b):

$$C_{\text{final}} = b \cdot C_{phong} + (1-b) \cdot C_{dc}.$$