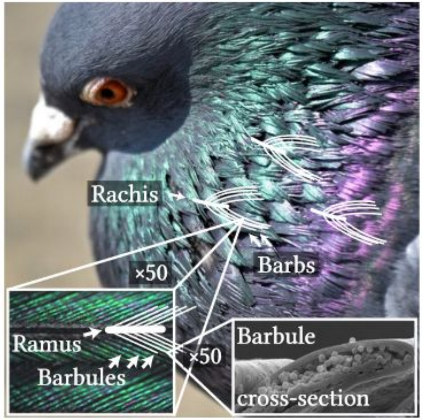
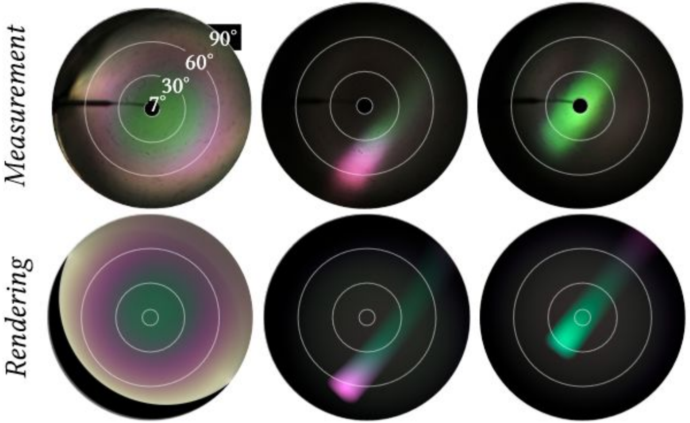
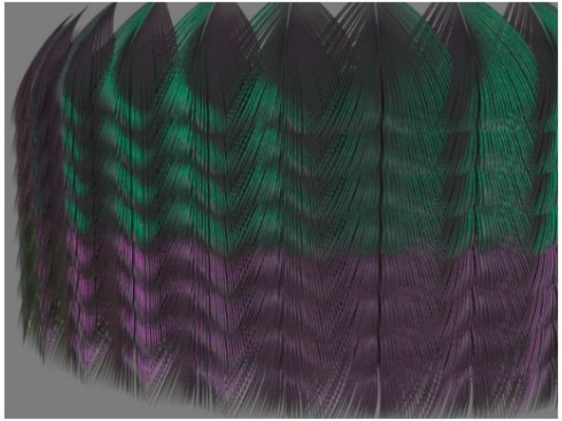
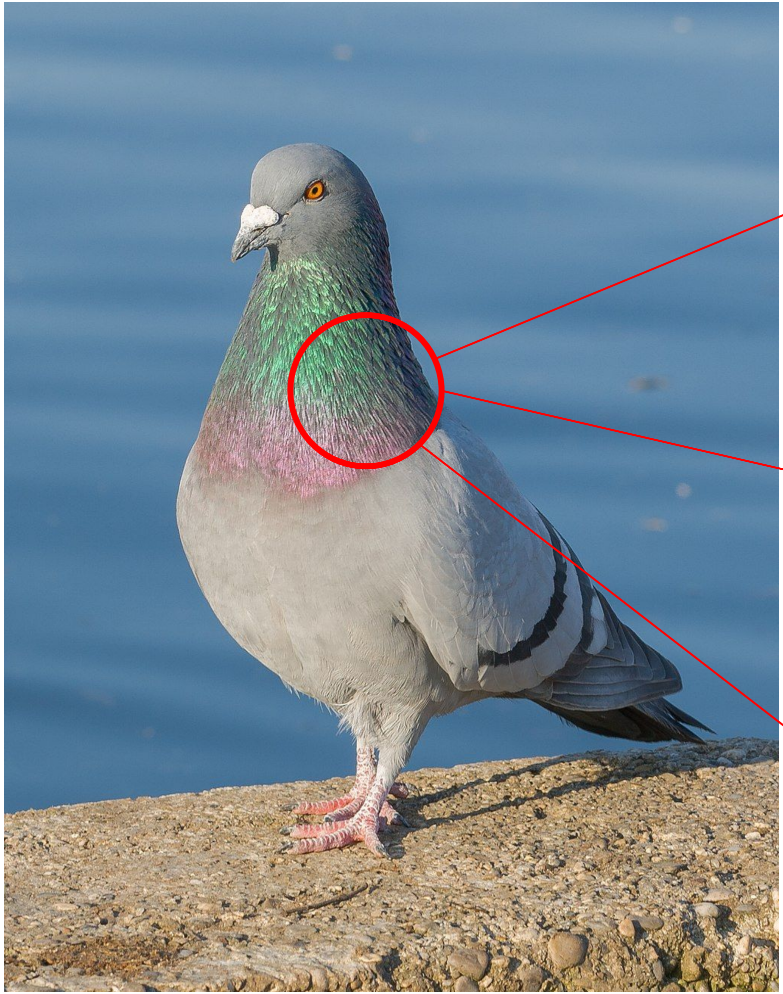
Rendering Iridescent Rock Dove Neck Feathers







Weizhen Huang Sebastian Merzbach Clara Callenberg
Doekele G. Stavenga Matthias B. Hullin

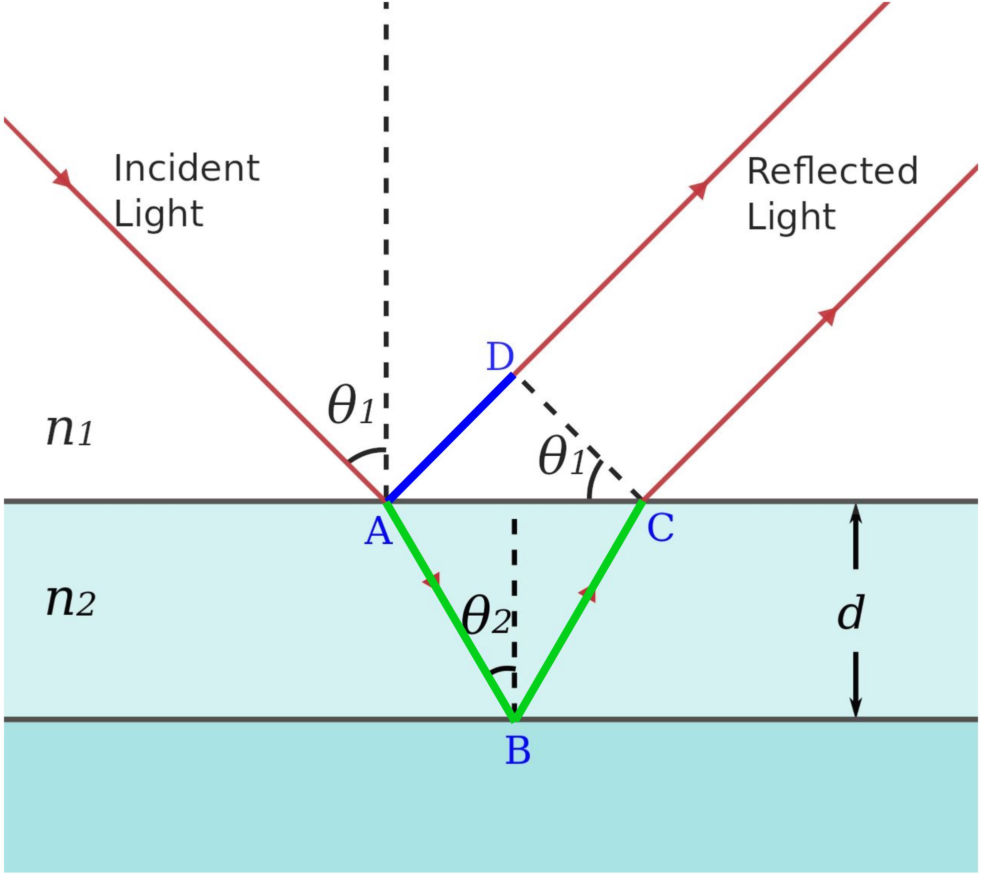


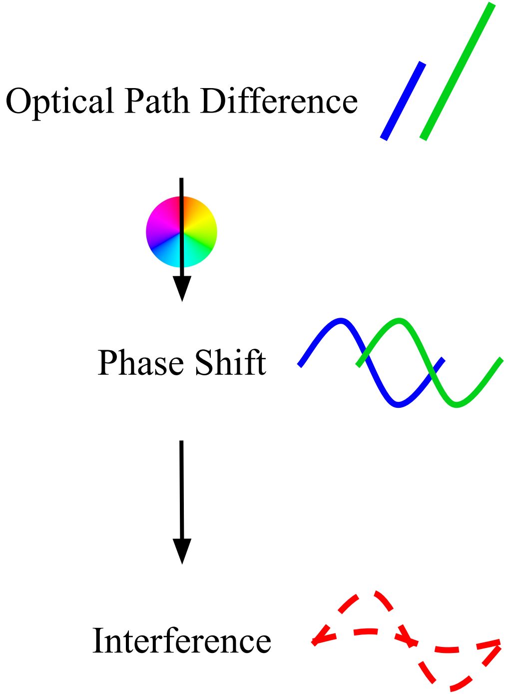
Rock Dove (Columba livia), Nymphenburg Palace, Munich, Germany

Iridescence

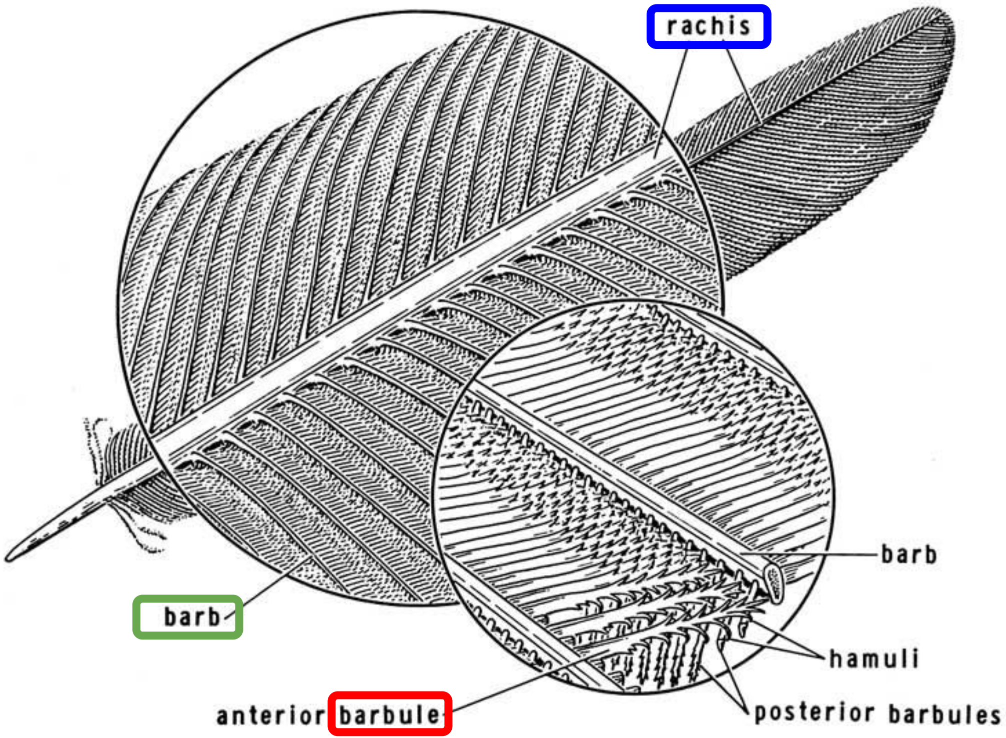
Color changes as the angle of view or the angle of illumination changes

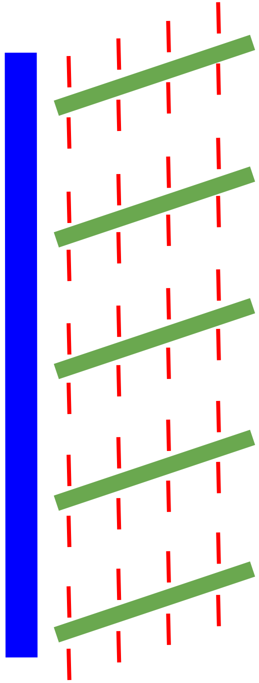
Iridescence from Thin Film Interference





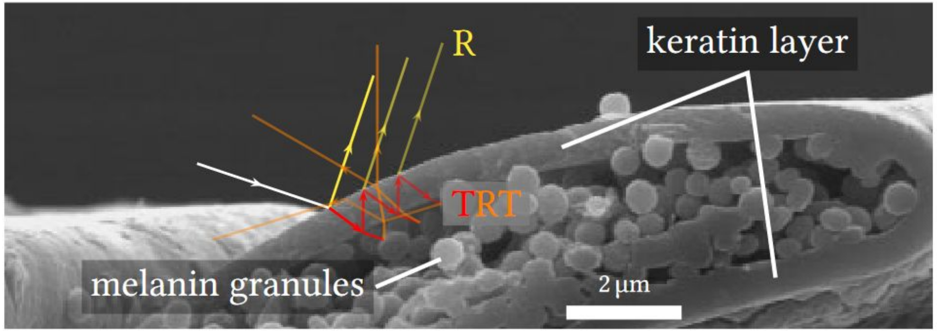
Feathers Structure



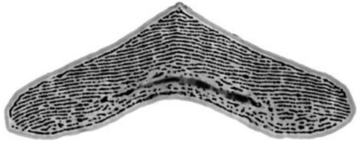


Name	Scale	Feature
Macro	>20 mm	Feather
Milli	0.3 mm	Barb
Micro	40 μm	Barbule
Nano	550 nm	Thin film

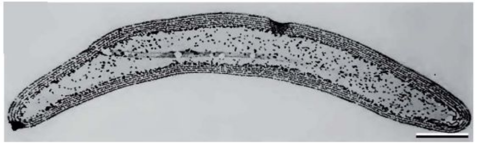
Feathers Structure - Barbules



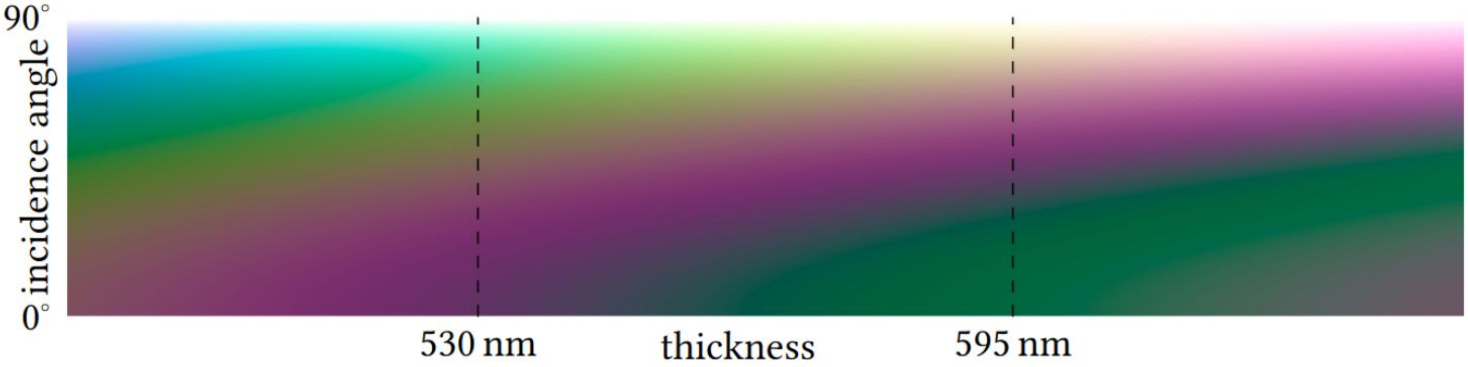
(c) Rock dove (*Columba livia*)



(a) Lawes' parotia (*Parotia lawesii*)



(b) Peacock (*Pavo cristatus*)



Designing the BSDF

Bidirectional **S**cattering **D**istribution **F**unction = BRDF (reflectance) + BTDF (transmittance)

$$L_o(\omega_o, \lambda) = \int L_i(\omega_i, \lambda)\, S(\omega_i, \omega_o, \lambda)\, \langle \omega_i, \vec{n} \rangle\, \mathrm{d}\omega_i$$

Outgoing Radiance

Incoming Radiance

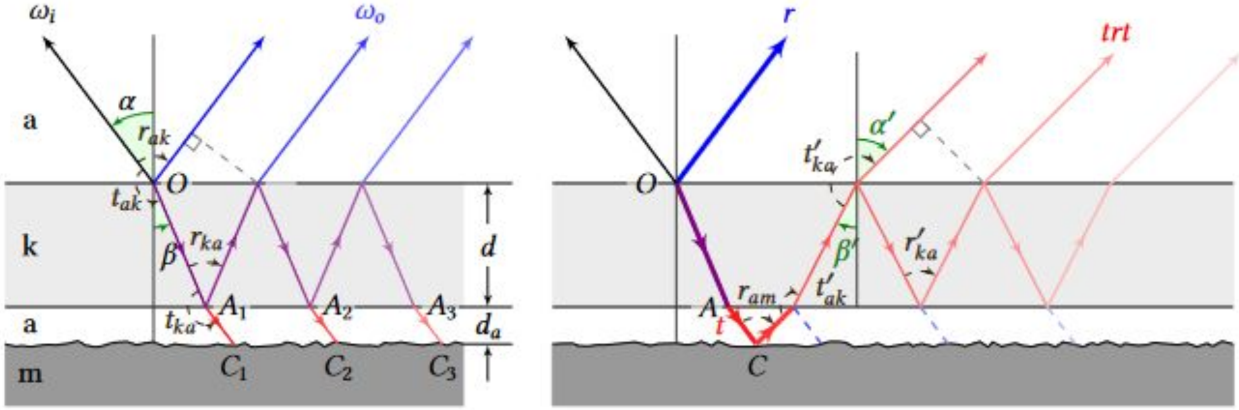
BSDF

Normal vector of barbule plane

Designing the BSDF

$$L_o(\omega_o, \lambda) = \int L_i(\omega_i, \lambda)\, S(\omega_i, \omega_o, \lambda)\, \langle \omega_i, \vec{n} \rangle\, \mathrm{d}\omega_i$$

$$S(\omega_i, \omega_o, \lambda) = S_{\mathrm{R}} + S_{\mathrm{TRT}} + S_{\mathrm{T}}$$



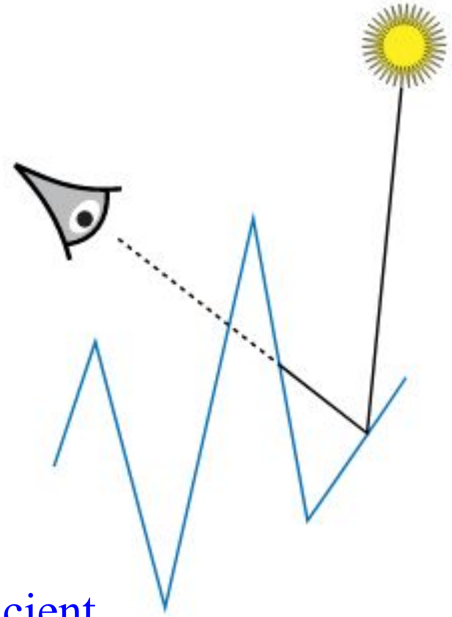
S_R : Microfacets Model

$$f_r(\omega_o, \omega_i) = \frac{D(\omega_h)\, G(\omega_o, \omega_i)\, F_r(\omega_o)}{4 \cos\theta_o \cos\theta_i}$$

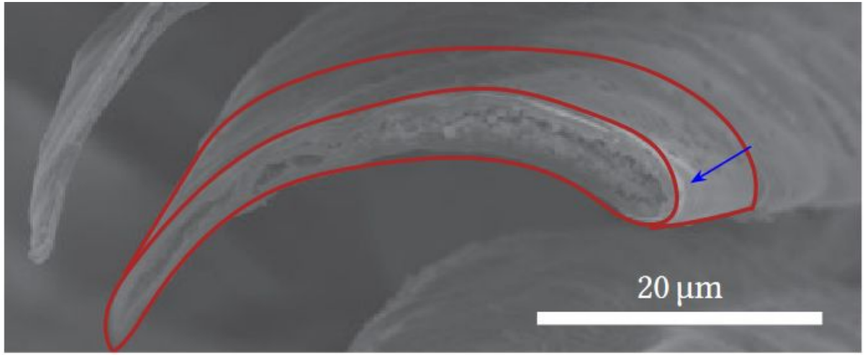
Normal distribution

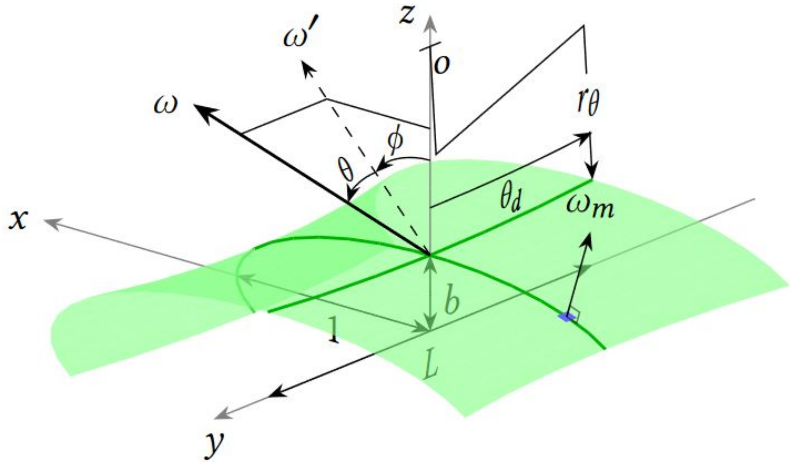
Masking / Shadowing

Fresnel coefficient

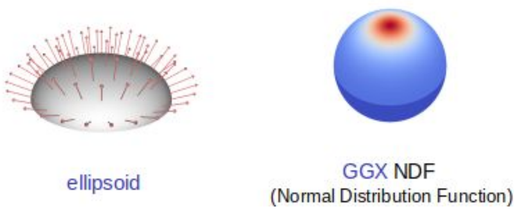


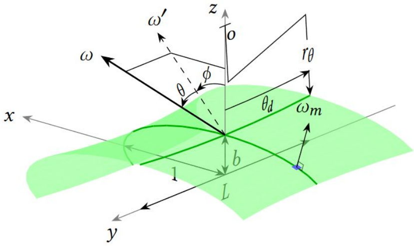
Normal Distribution - Geometry of the barbule

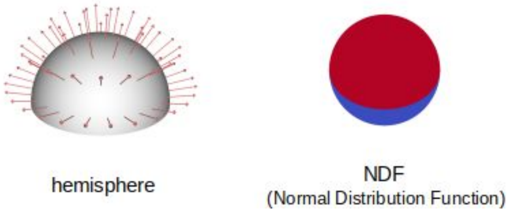


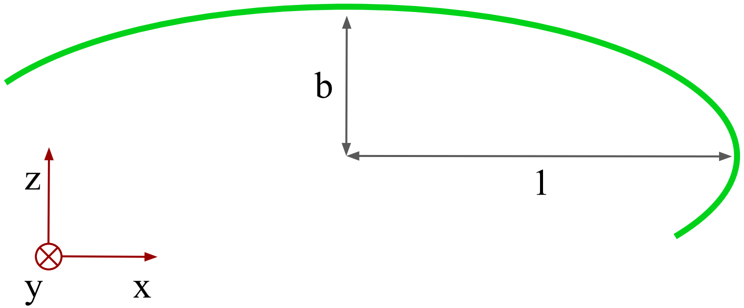


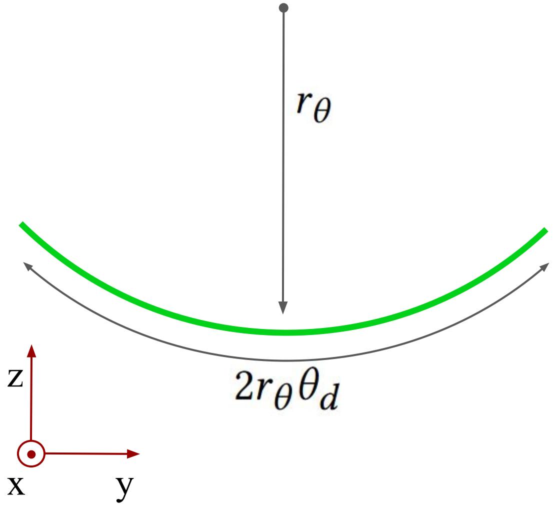
Normal Distribution - Geometry of the barbule











https://perso.univ-lyon1.fr/jean-claude.iehl/Public/educ/M1IMAGE/html/group__reflets.html

Normal Distribution - Geometry of the barbule

$$D_\phi(\phi_m) = \frac{1}{H\kappa(\phi_m)} = \frac{b^2}{H}\left(\sin^2\phi_m + b^2\cos^2\phi_m\right)^{-\frac{3}{2}}$$

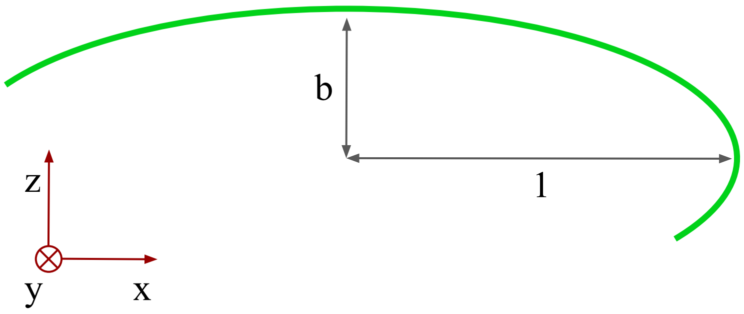
$$D_\theta(\theta_m) = \frac{1}{2\sin\theta_d}$$

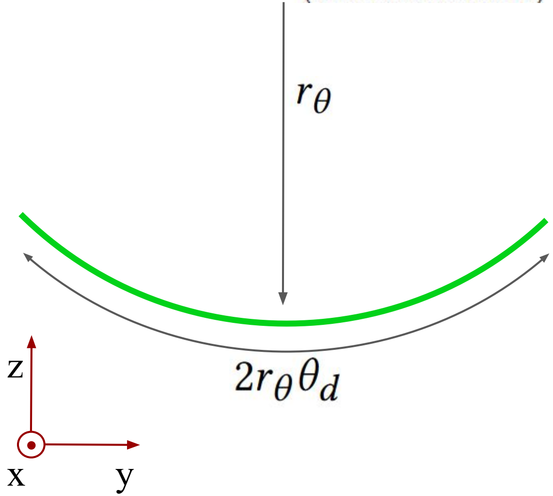
ellipsoid

GGX NDF
(Normal Distribution Function)

hemisphere

NDF
(Normal Distribution Function)

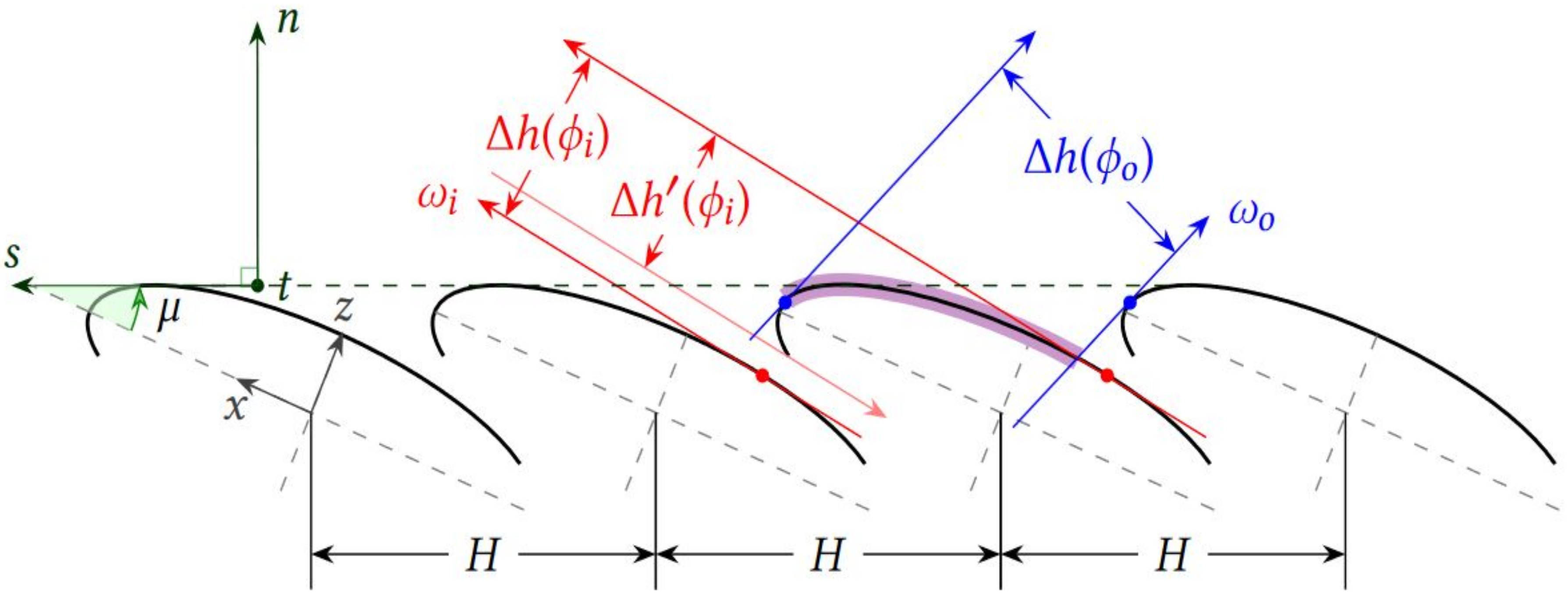




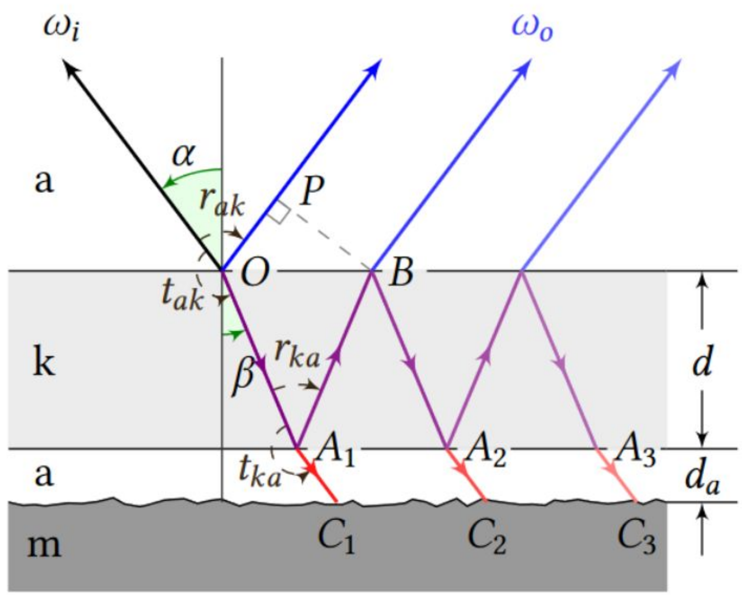
https://perso.univ-lyon1.fr/jean-claude.iehl/Public/educ/M1IMAGE/html/group__reflets.html

Masking / Shadowing

$$G(\omega_i, \omega_m, \omega_o)$$



Fresnel coefficient



Airy formula

$$\mathcal{D} = \eta_k(\overline{OA_1} + \overline{A_1B}) - \eta_a\overline{OP}$$
$$= 2d\eta_k \cos\beta$$

$$r = r_{ak} + \frac{t_{ak} r_{ka} t_{ka} e^{i\Delta\psi}}{1 - r_{ka}^2 e^{i\Delta\psi}}$$

$$I_{\mathrm{R}} = |r|^2$$

R

$$t = \frac{t_{ak} t_{ka}}{1 - r_{ka}^2 e^{i\Delta\psi}}$$

T

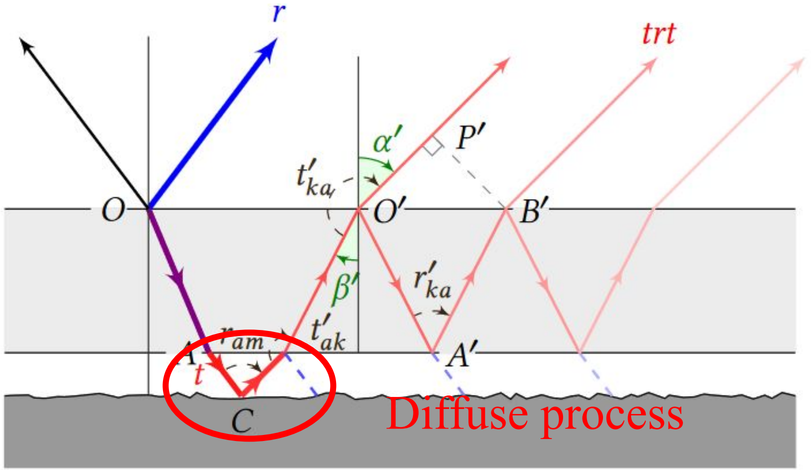
$$I_{\mathrm{TRT}} = \left| \frac{t r_{am} t'_{ak} t'_{ka}}{1 - (r'_{ka})^2 e^{i\Delta\psi'}} \right|^2$$

TRT

S_{TRT} : Diffuse Surface Model

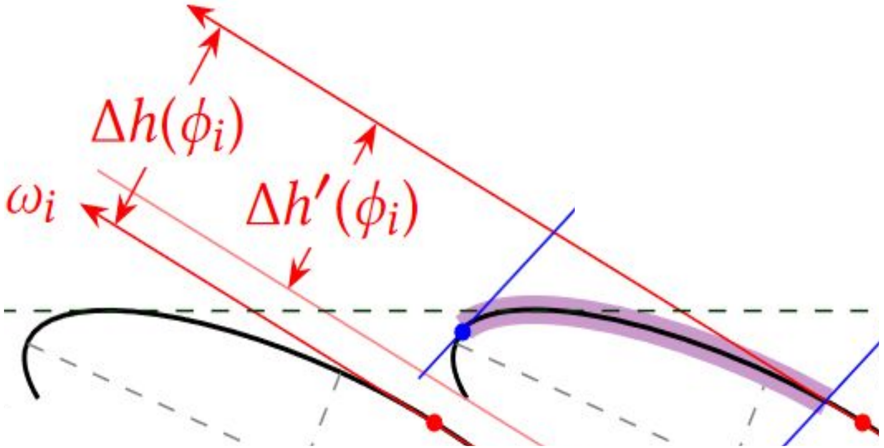
$$S_{\mathrm{TRT}}(\omega_i, \omega_o, \lambda) = \frac{\rho(\omega_i, \omega_o, \lambda)}{\pi},$$

$$\rho(\omega_i, \omega_o, \lambda) = \frac{1}{A_i} \iint I_{\mathrm{TRT}}(\omega_i, \omega_m, \omega_o)\, \mathrm{d}h\, \mathrm{d}l$$



S_{T} : Transmission

$$S_{\mathrm{T}}(\omega_i, -\omega_i, \lambda) = 1 - \frac{\Delta h'(\phi_i)}{\Delta h(\phi_i)}$$

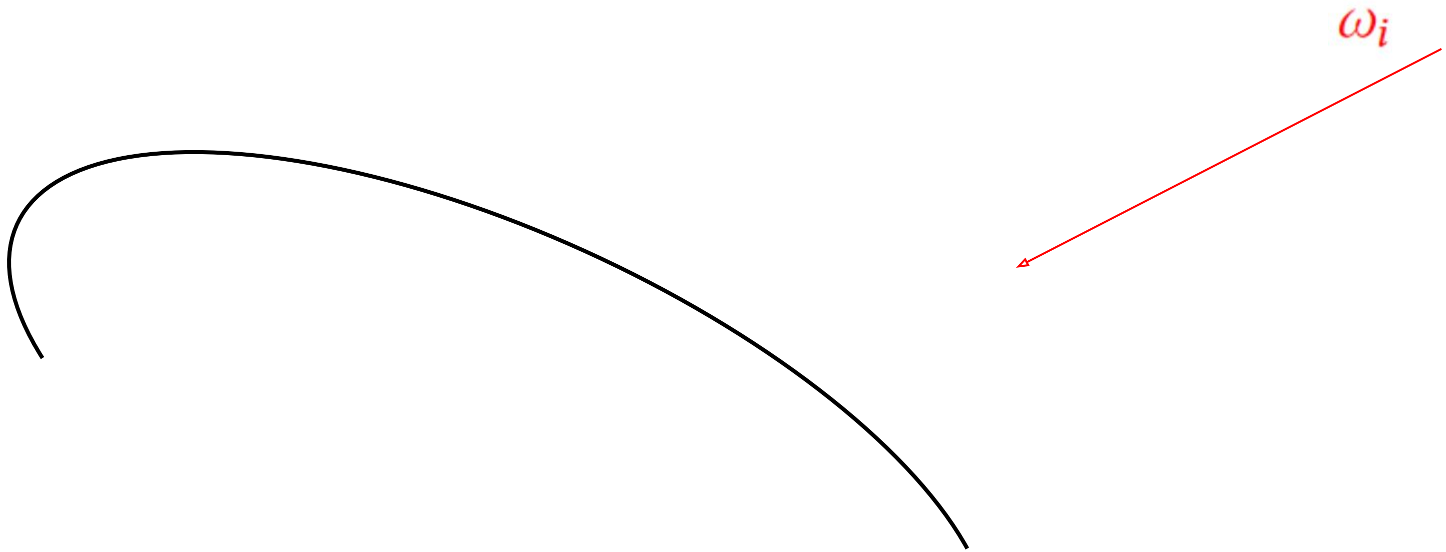


In practice

ALGORITHM 1: Importance Sampling Barbule BSDF

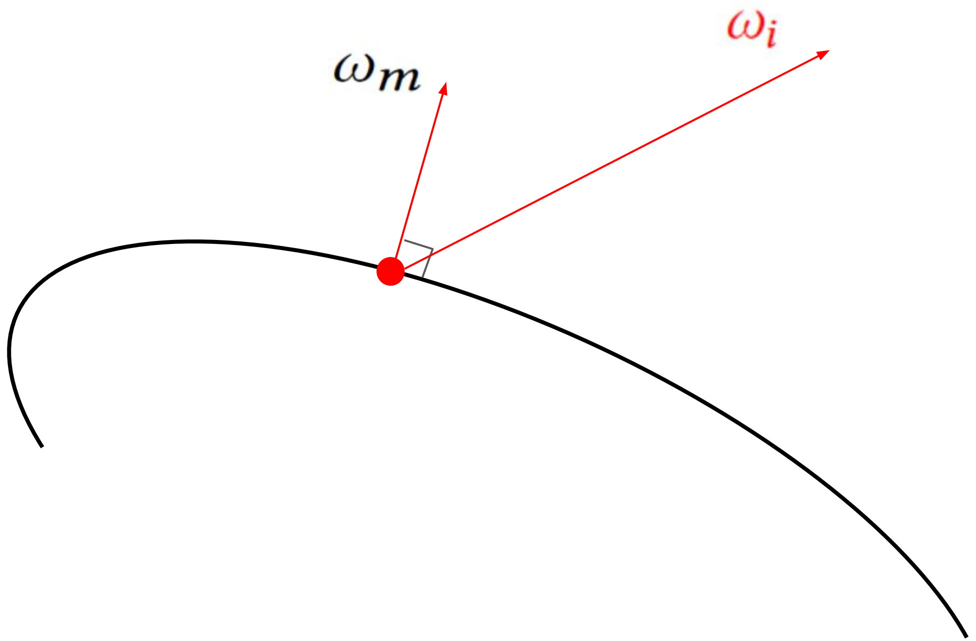
```
Output: pdf, ω_o, sample value
sample valid h and l and compute ω_m(h, l);
calculate I_R(ω_i, ω_m) according to Eq. (2);
sample ω_o^TRT from the cosine-weighted upper hemisphere around
  n⃗;
ω_o^TRT *= sgn⟨ω_m, ω_o^TRT⟩;
calculate I_TRT(ω_i, ω_m, ω_o^TRT) according to Eq. (3);
generate uniform random sample ξ ~ [0, I_R + I_TRT + Δh_i/Δh'_i − 1];
if ξ < I_R then                                  /* choose R lobe */
  | ω_o = reflect(ω_i,ω_m);   pdf = 0.25 I_R D(ω_m)/⟨ω_i, n⃗⟩;
else if ξ < I_R + I_TRT then                     /* choose TRT lobe */
  | ω_o = ω_o^TRT;   pdf = I_TRT |ω_o.z|/π;
else                                             /* choose T lobe. */
  | ω_o = −ω_i;   pdf = Δh_i/Δh'_i − 1;
end
if sample position visible from ω_o then
  | pdf /= I_R + I_TRT + Δh_i/Δh'_i − 1;
  | sample value = (I_R + I_TRT − 1)Δh'_i/Δh_i + 1;
else
  | reject sample;
end
```

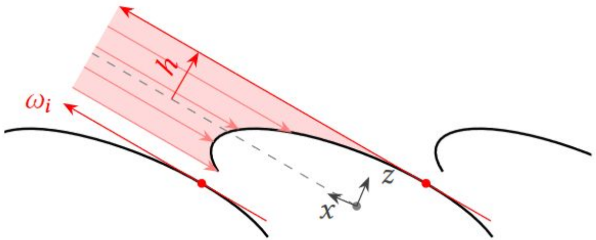
In practice

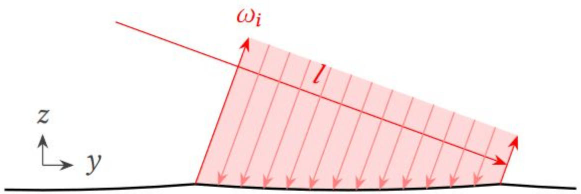


In practice

sample valid h and l and compute $\omega_m(h, l)$;

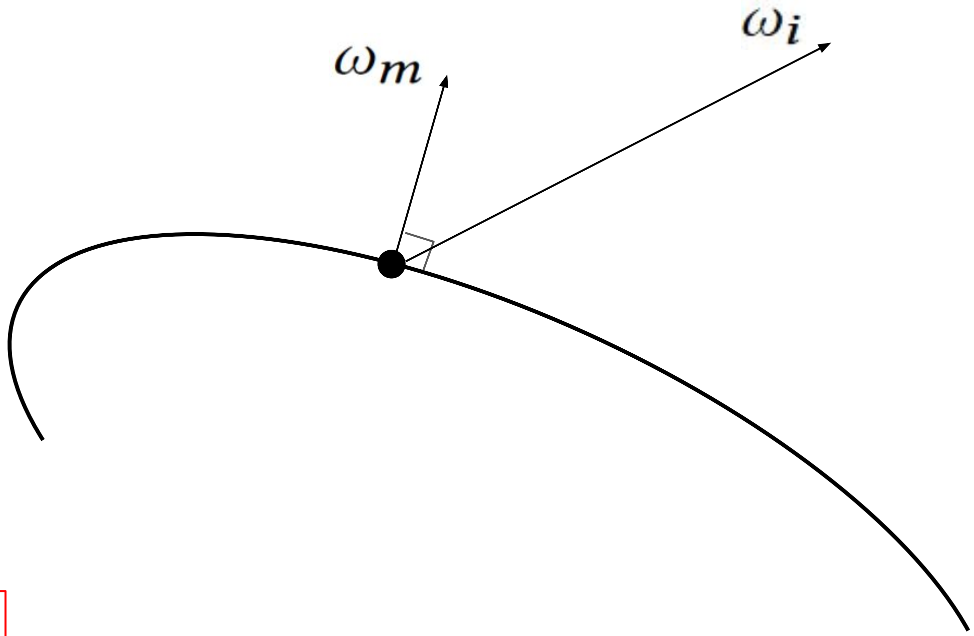




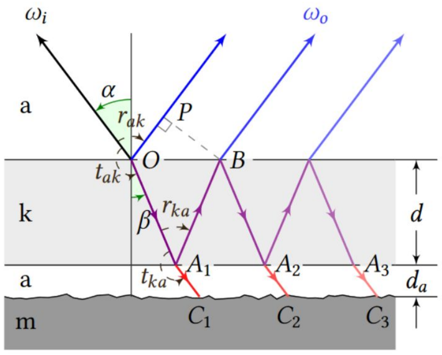


In practice

calculate $I_{\mathrm{R}}(\omega_i, \omega_m)$ according to Eq. (2);



I_{R}

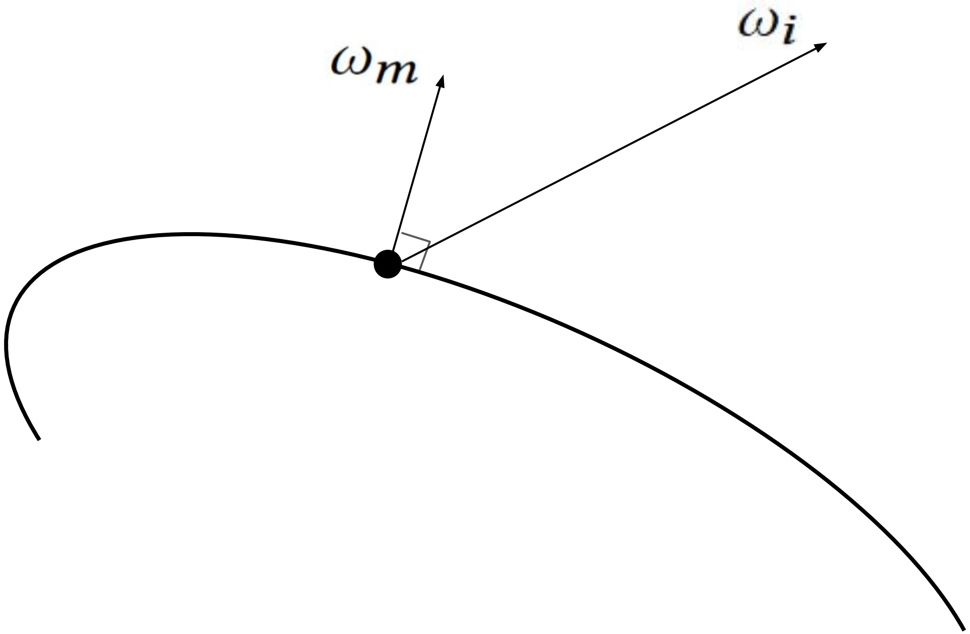


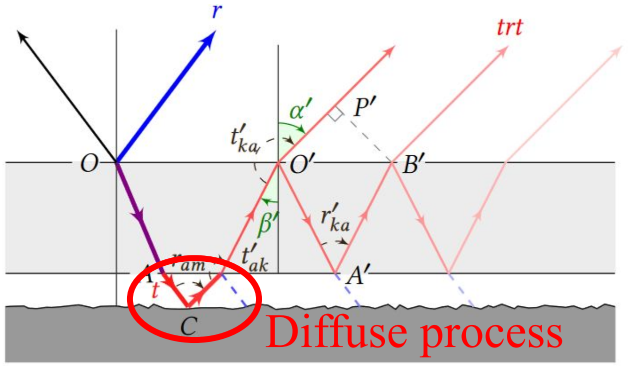
$$r = r_{ak} + \frac{t_{ak} r_{ka} t_{ka} e^{i\Delta\psi}}{1 - r_{ka}^2 e^{i\Delta\psi}}$$

$$I_{\mathrm{R}} = |r|^2$$

In practice

sample ω_o^{TRT} from the cosine-weighted upper hemisphere around $\vec{n}$;
$\omega_o^{\mathrm{TRT}} \mathrel{*}= \mathrm{sgn}\langle \omega_m, \omega_o^{\mathrm{TRT}} \rangle$;
calculate $I_{\mathrm{TRT}}(\omega_i, \omega_m, \omega_o^{\mathrm{TRT}})$ according to Eq. (3);





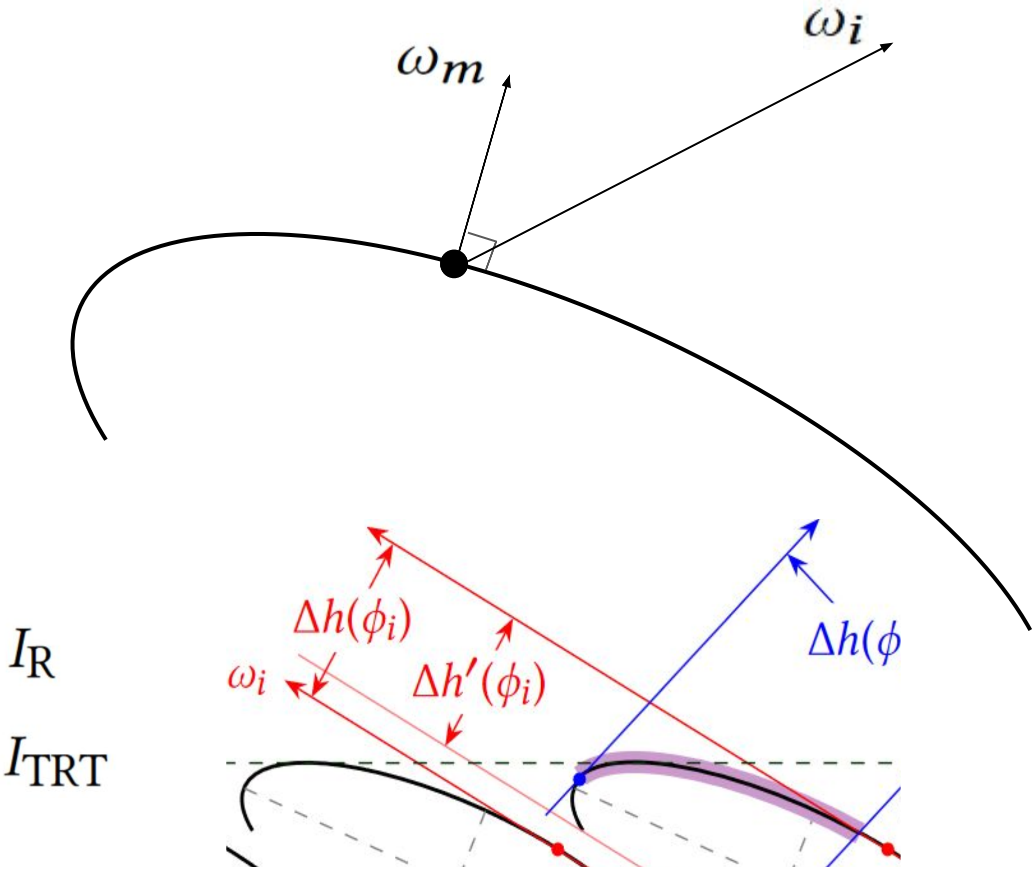
$$I_{\mathrm{TRT}} = \left| \frac{t r_{am} t'_{ak} t'_{ka}}{1 - (r'_{ka})^2 e^{i\Delta\psi'}} \right|^2$$

I_{R}

I_{TRT}

In practice

generate uniform random sample $\xi \sim [0, I_{\mathrm{R}} + I_{\mathrm{TRT}} + \Delta h_i / \Delta h'_i - 1]$;



if $\xi < I_{\mathrm{R}}$ **then**

```
    /* choose R lobe */
```

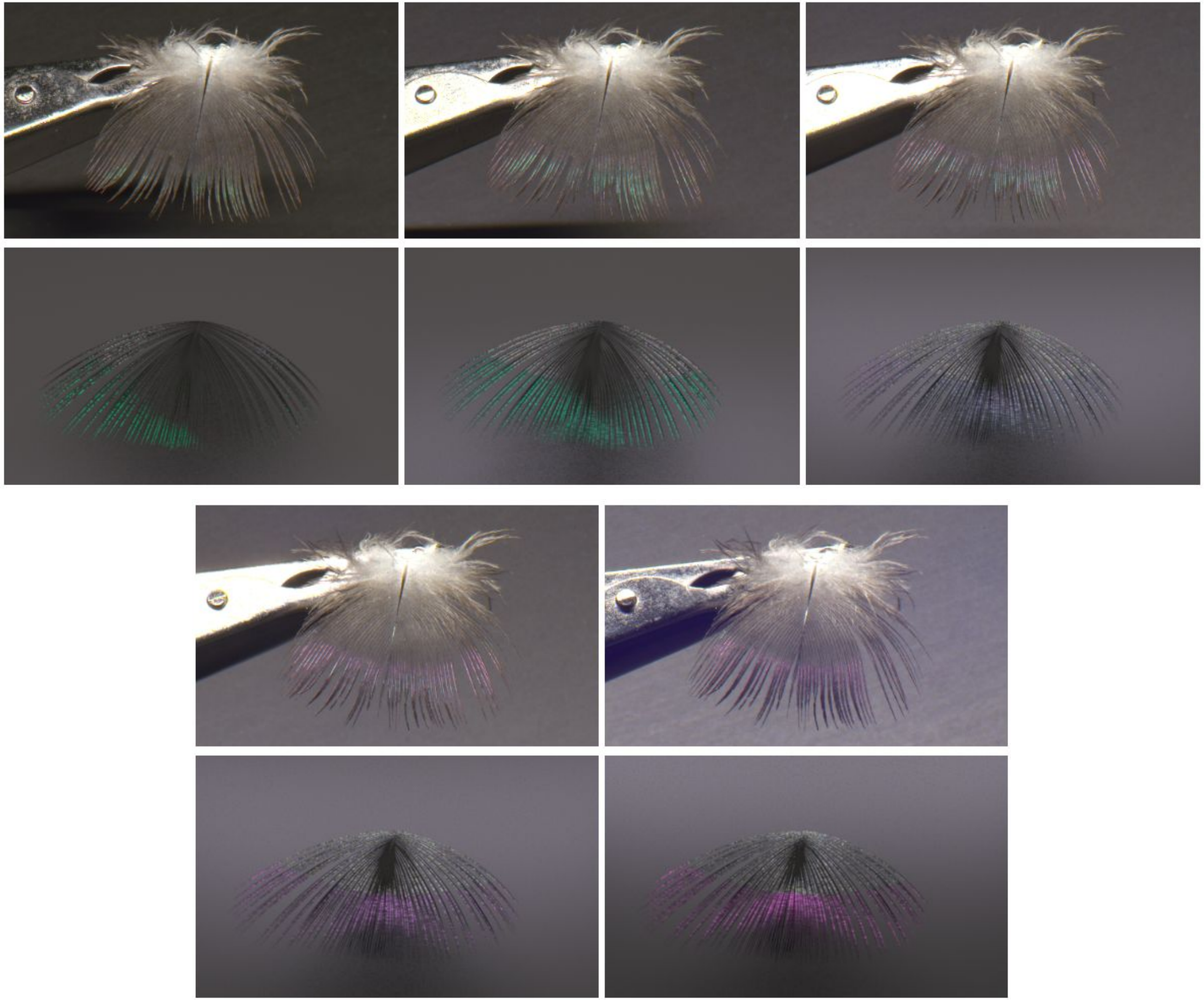
else if $\xi < I_{\mathrm{R}} + I_{\mathrm{TRT}}$ **then**

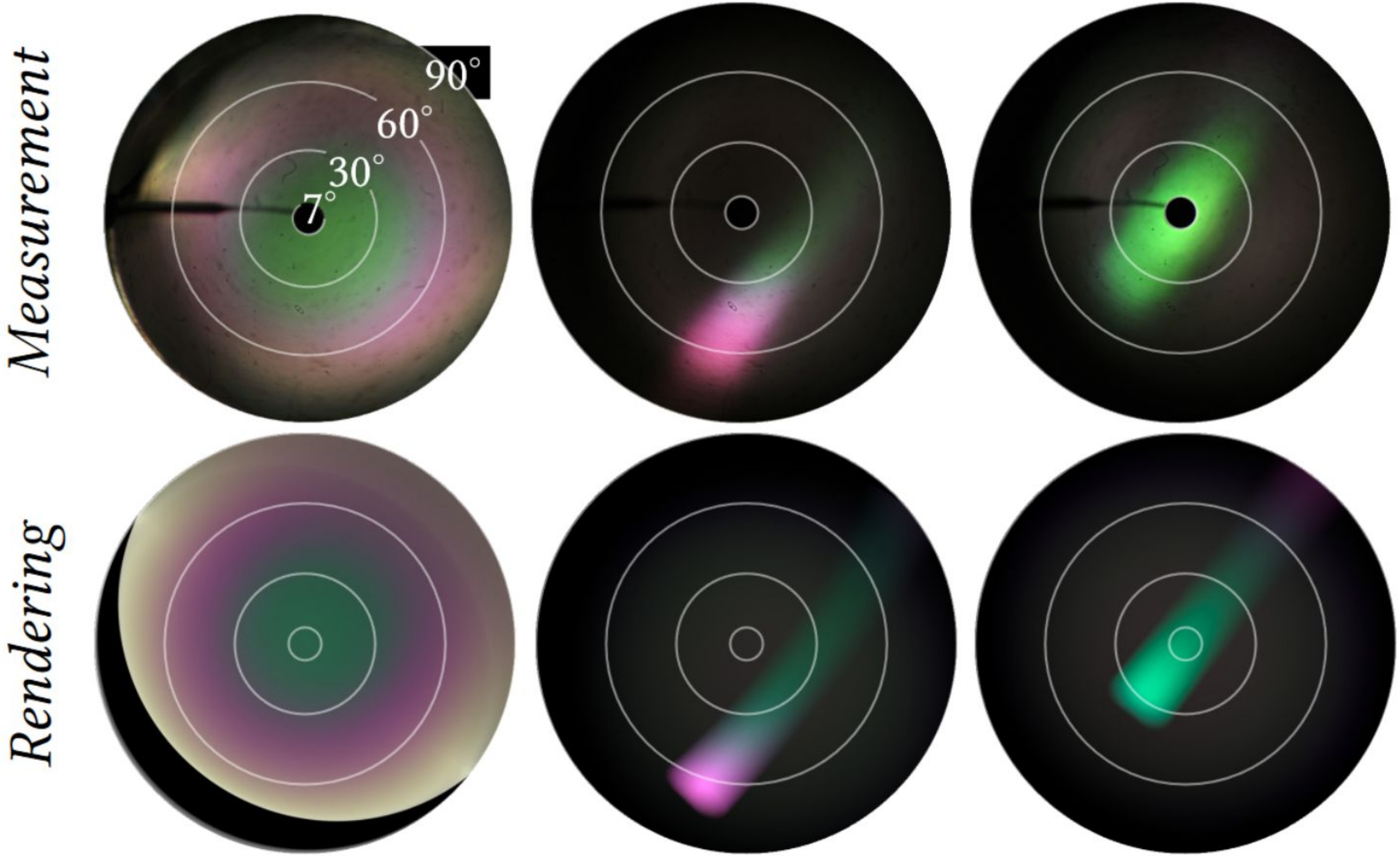
```
    /* choose TRT lobe */
```

else

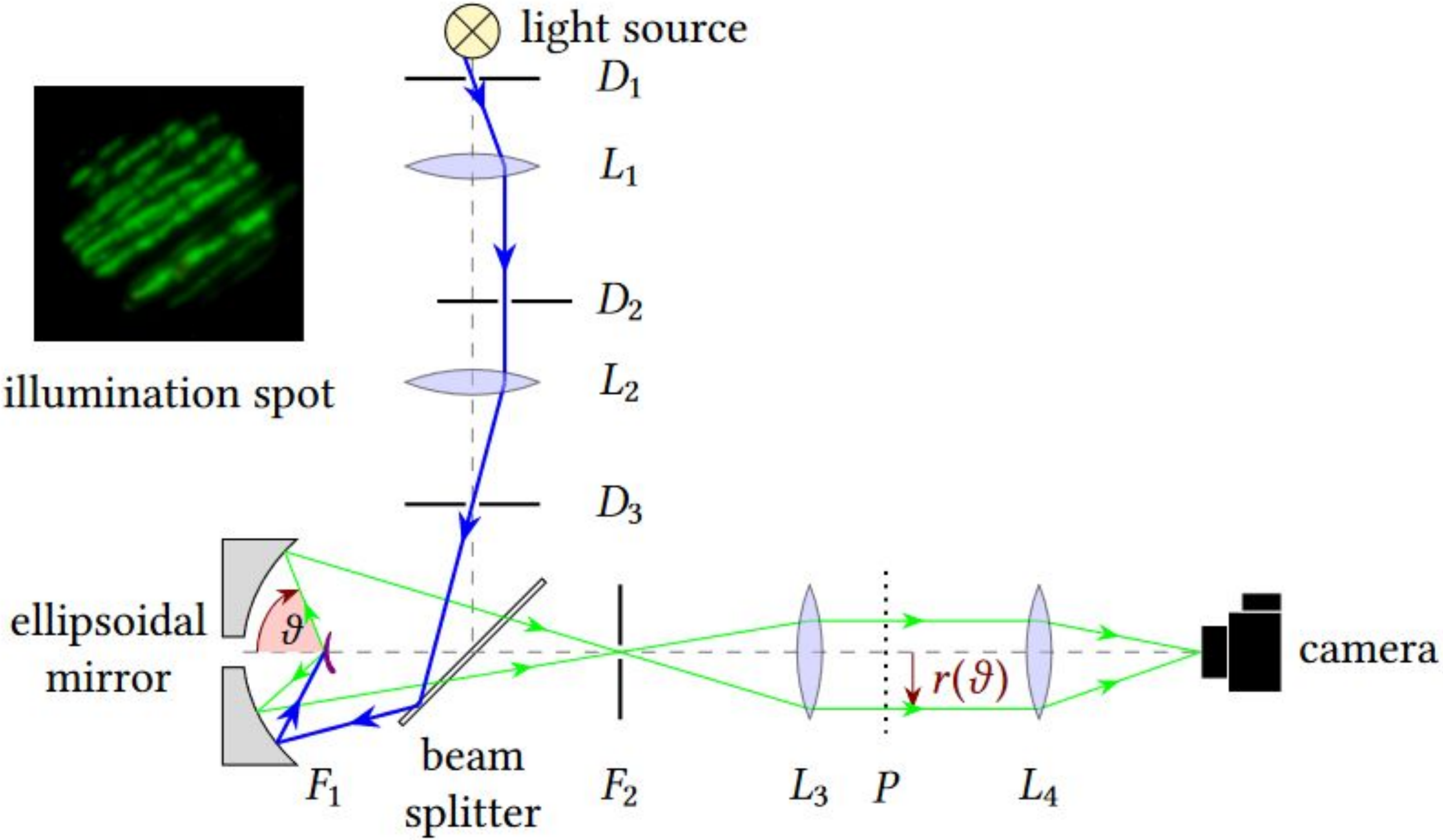
```
    /* choose T lobe. */
```

end



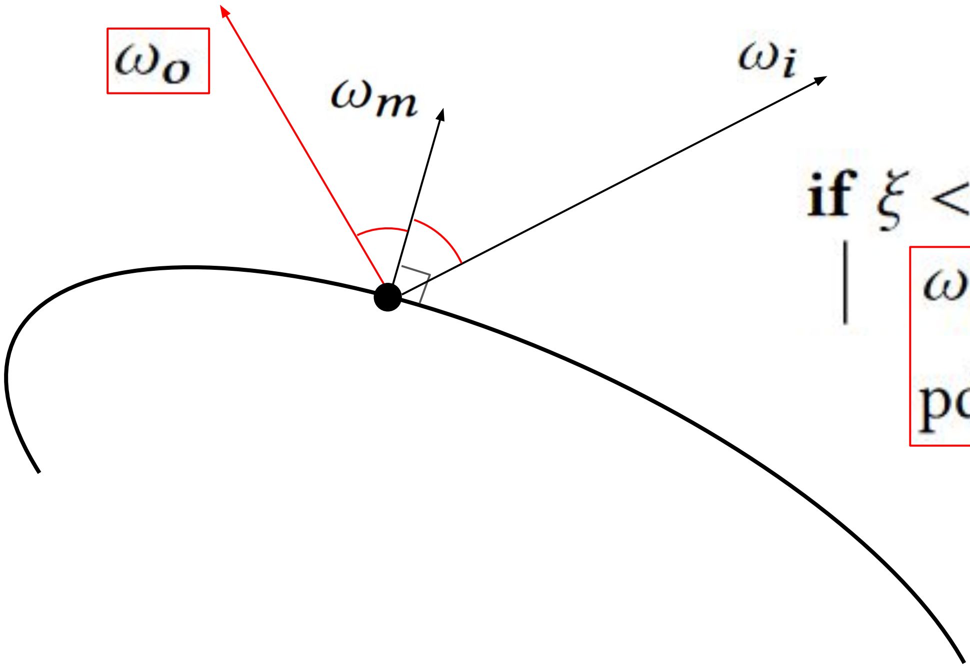


(b) Omnidirectional (c) Direction 1 (d) Direction 2



light source
D_1
L_1
D_2
L_2
D_3
illumination spot
ellipsoidal mirror
ϑ
F_1
beam splitter
F_2
L_3
P
$r(\vartheta)$
L_4
camera

In practice




```
/* choose R lobe */
```

if $\xi < I_R$ **then**

$\omega_o = \text{reflect}(\omega_i, \omega_m);$

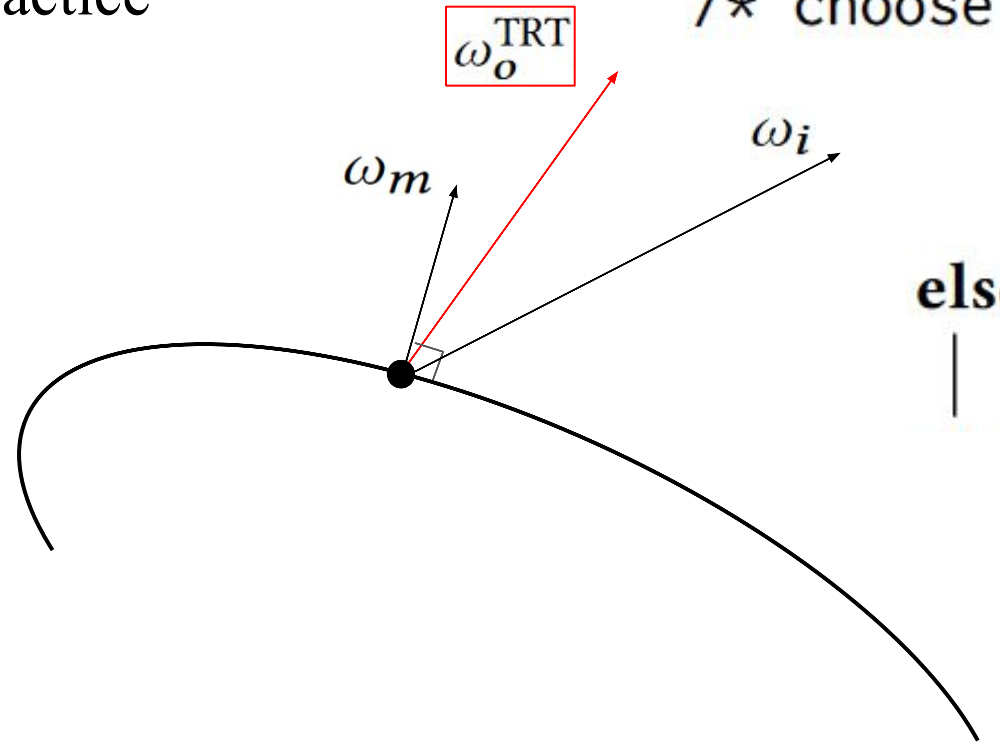
$\text{pdf} = 0.25 I_R D(\omega_m) / \langle \omega_i, \vec{n} \rangle;$

apply microfacet brdf

I_R

I_{TRT}

In practice




```
/* choose TRT lobe */
```

else if $\xi < I_{\text{R}} + I_{\text{TRT}}$ **then**

$\omega_o = \omega_o^{\text{TRT}}$;

$\text{pdf} = I_{\text{TRT}} |\omega_o.z| / \pi$;

I_{R}

I_{TRT}

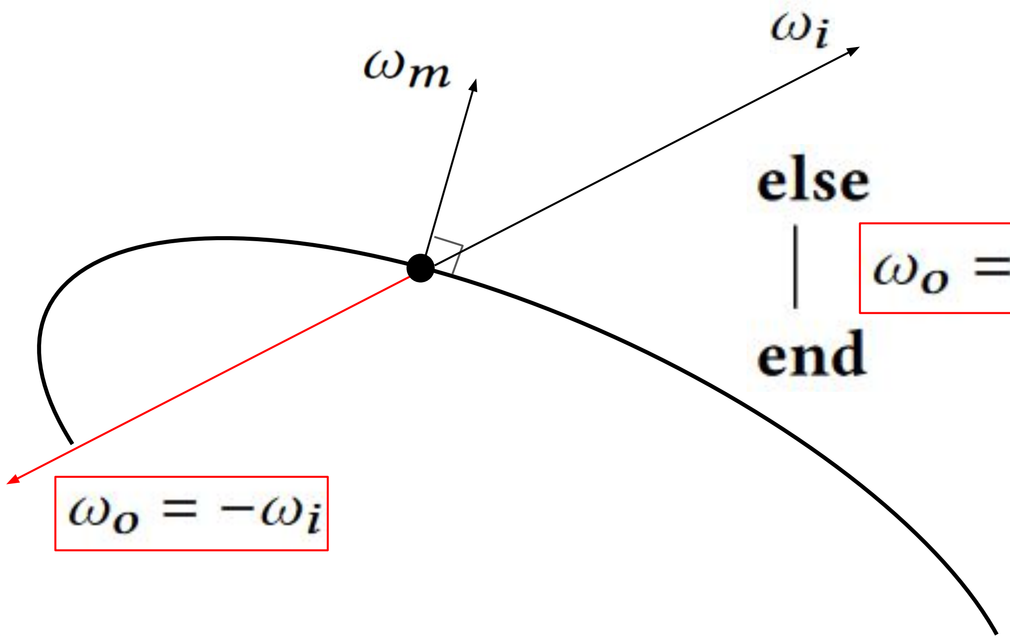
In practice

```
/* choose T lobe. */
```

else

$\omega_o = -\omega_i; \quad \text{pdf} = \Delta h_i / \Delta h'_i - 1;$

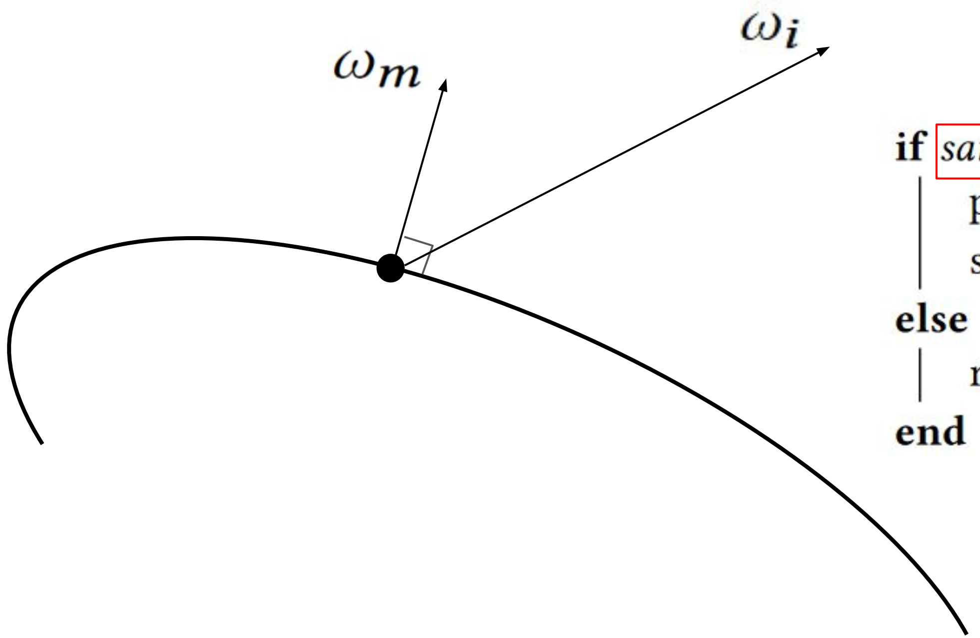
end



I_{R}

I_{TRT}

In practice



masking / shadowing

if *sample position visible from* ω_o **then**

  pdf $/= I_R + I_{TRT} + \Delta h_i / \Delta h'_i - 1$;

  sample value $= (I_R + I_{TRT} - 1)\Delta h'_i / \Delta h_i + 1$;

else

  reject sample;

end

I_R

I_{TRT}