Applications of Light Polarization in Vision

Lecture #18

Thanks to Yoav Schechner et al, Nayar et al, Larry Wolff, Ikeuchi et al

Separating Reflected and Transmitted Scenes

Reconstructing Shape of Transparent Objects

Removing Haze and Underwater Scattering Effects

Removing Specularities

Separation of Diffuse and Specular Reflections

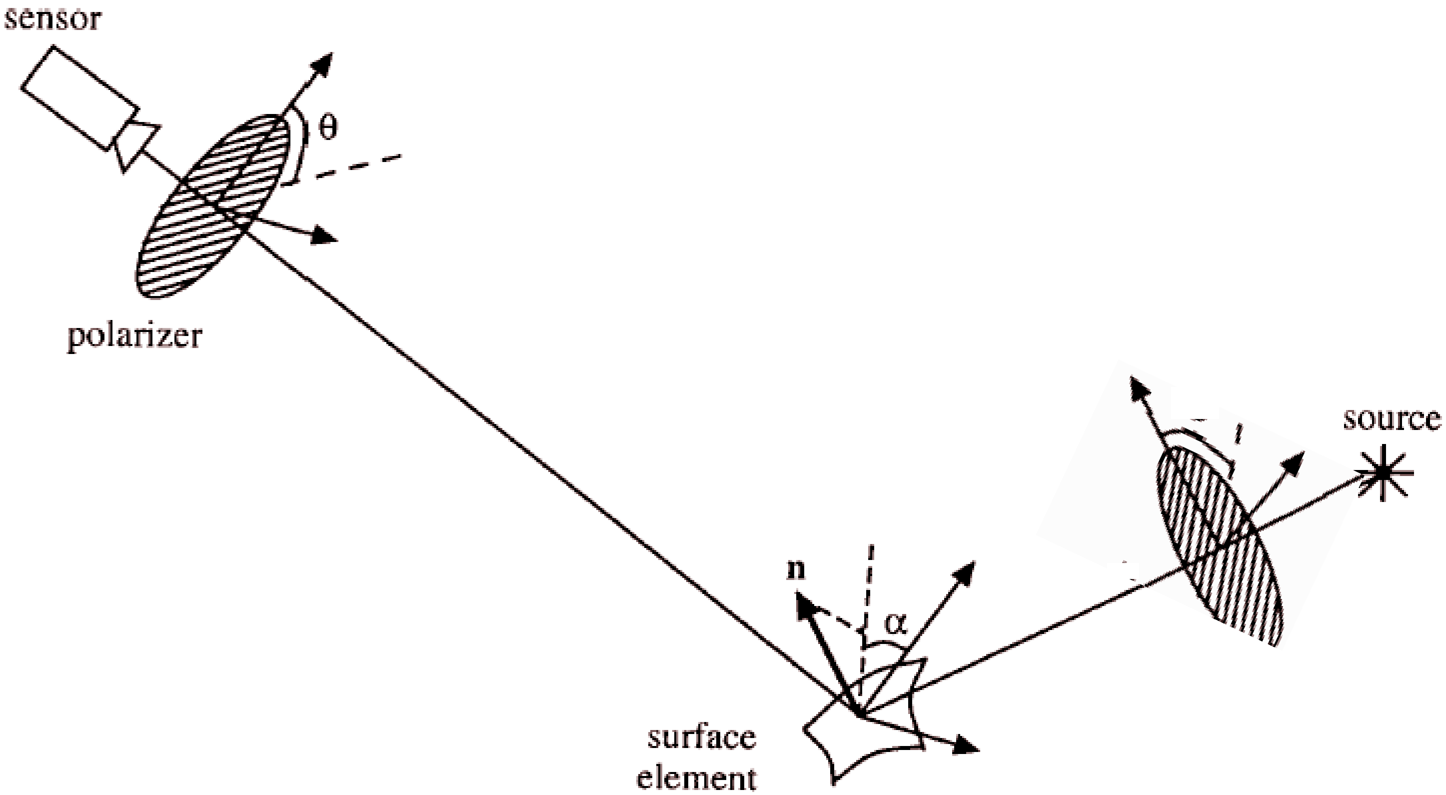
Diffuse surfaces : No (or minimal) Polarization

All light depolarized due to many random scattering events inside object.

Specular Surfaces: Strong Polarization (even though partially polarized)

Smooth/Rough Surfaces: The degree of polarization decreases with roughness.

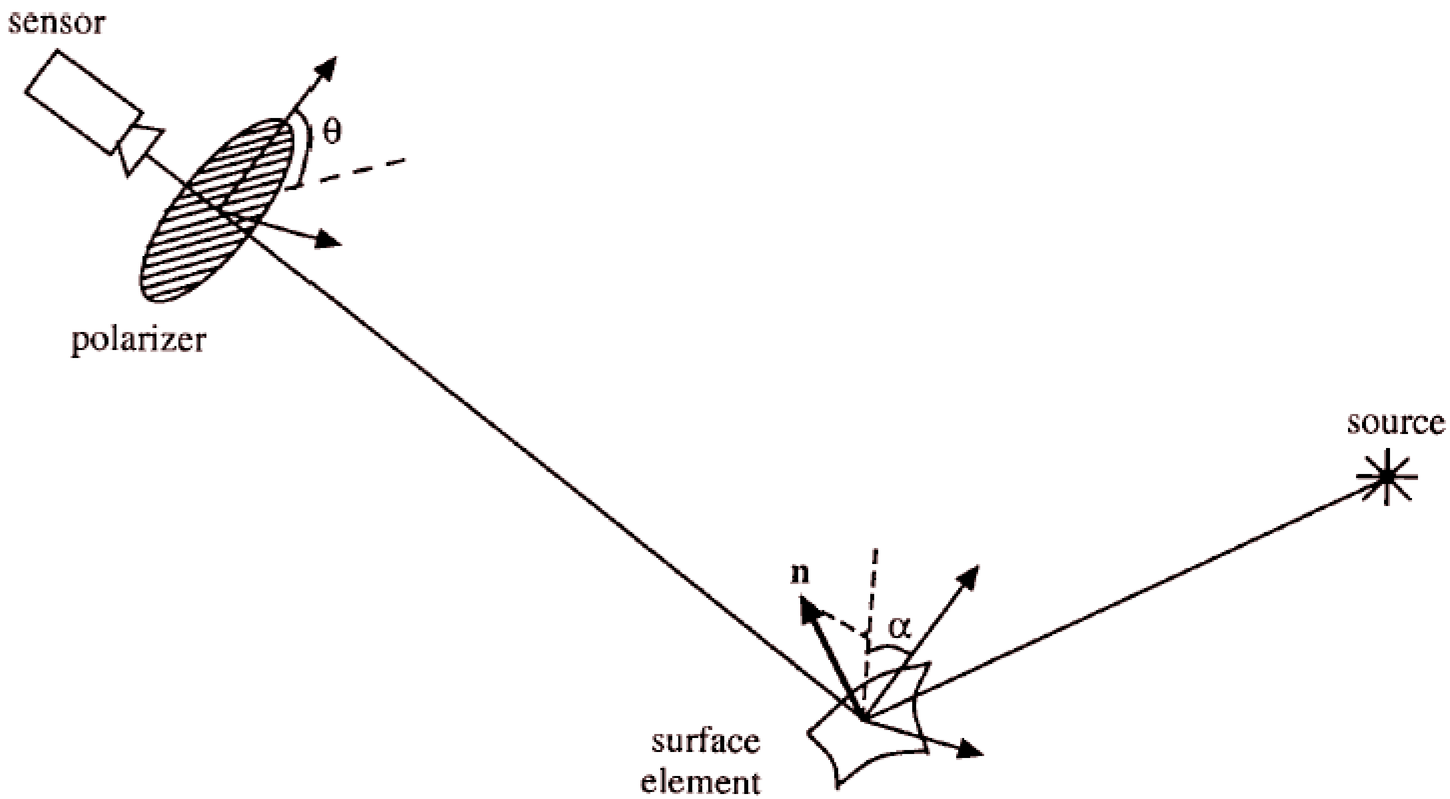
Active Illumination



- Completely remove specular reflections using polarized light when the filters are 90 degrees apart.

- Commonly used in industrial settings.

Passive Illumination



- Most illumination from sources (sun, sky, lamps) is unpolarized.
- Merely using a polarizer will not remove specular reflections completely.

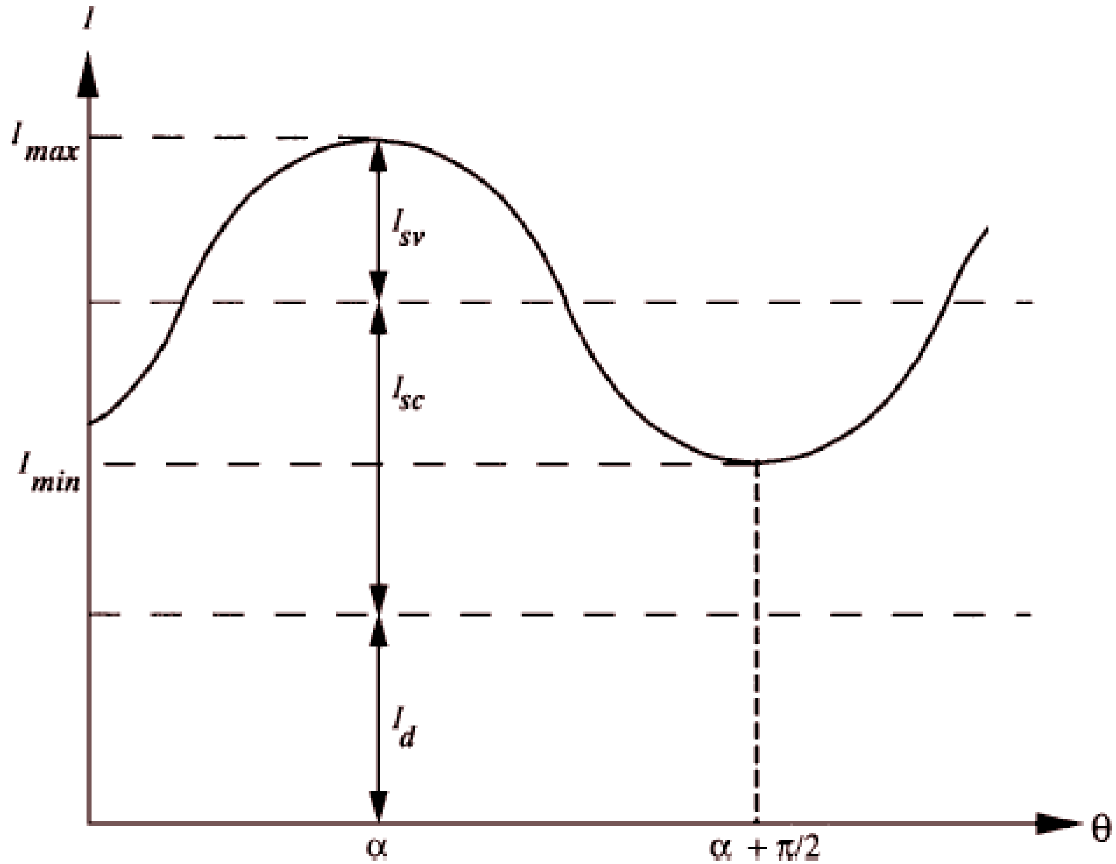
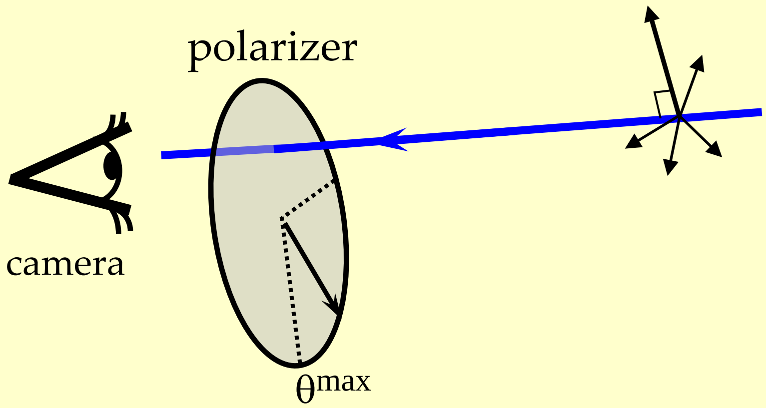


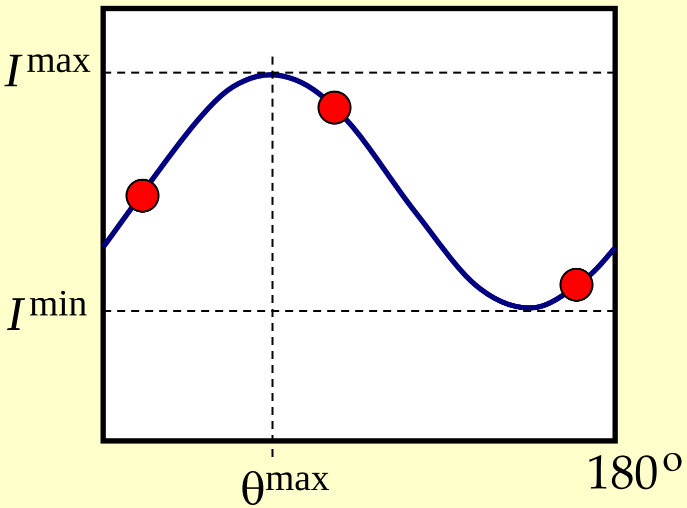
Figure 4. Image brightness plotted as a function of polarization filter angle.

$$I = I_d + I_{\mathrm{sc}} + I_{\mathrm{sv}} \cos 2(\theta - \alpha)$$

I_min is not equal to I_d (diffuse component)

Polarization Measurements





Polarization vector determination

3 general measurements suffice

Determining the Polarization Cosine Curve

$$I = I_d + I_{sc} + I_{sv} \cos 2(\theta - \alpha)$$

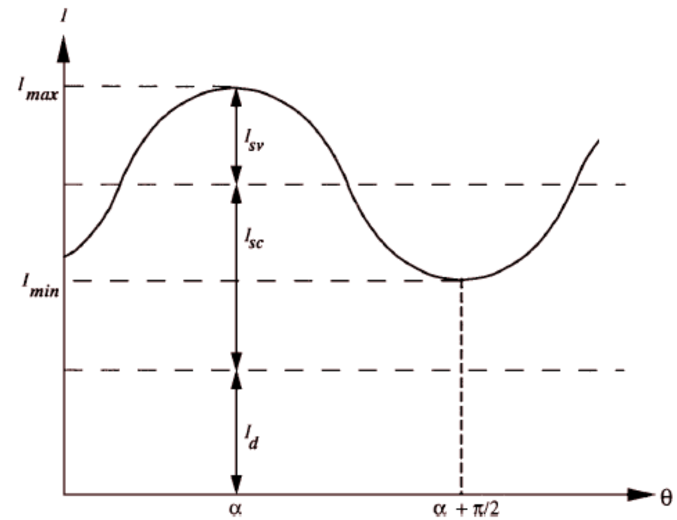


Figure 4. Image brightness plotted as a function of polarization filter angle.

For any given filter angle θ_i we have:

$$I_i = I_c + I_{sv} \cos 2(\theta_i - \alpha)$$

Using Vector Notation:

$$\mathbf{f}_i = (1, \cos 2\theta_i, \sin 2\theta_i)$$

$$\mathbf{v} = (I_c, I_{sv} \cos 2\alpha, I_{sv} \sin 2\alpha)$$

$$I_i = \mathbf{f}_i \cdot \mathbf{v}$$

Three measurements suffice to determine the cosine curve.

$$I_{\min} = I_c - I_{sv}$$

$$I_{\max} = I_c + I_{sv}$$

Degree of Polarization

$$\rho = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

- Varies between 0 and 1.
- If zero, then there is no polarization → Only diffuse component present.
- If one, only specular component present.
- If degree of polarization does not change as polarizer is rotated, then there is no guarantee that specular component is completely removed (I_sc may still be present).

Fresnel Ratio

- I_sc and I_sv depend on refractive index and angle of incidence.

- I_sc and I_sv are related to fresnel coefficients:

$$\frac{I_{sc} + I_{sv}}{I_{sc} - I_{sv}} = \frac{F_{\perp}(\eta, \psi)}{F_{\parallel}(\eta, \psi)} = q$$

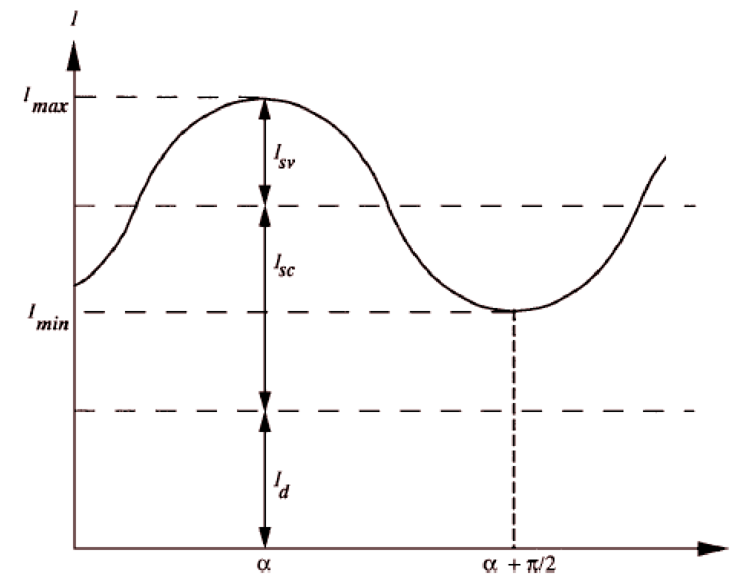
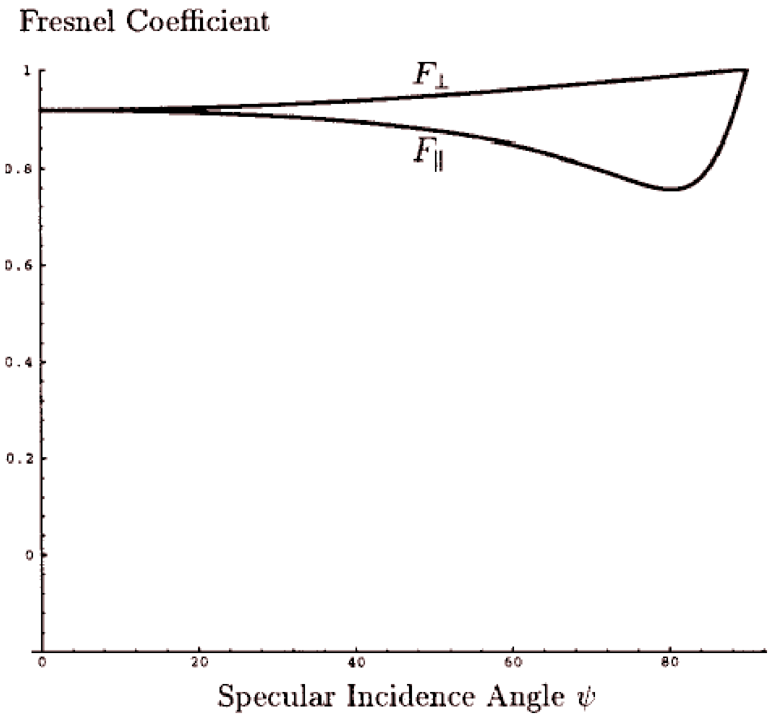


Figure 4. Image brightness plotted as a function of polarization filter angle.

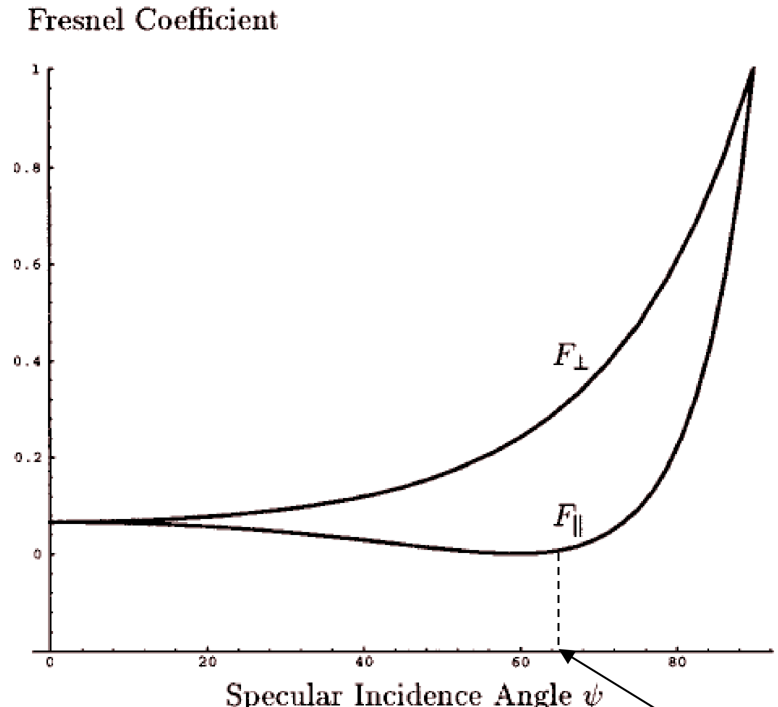
$F_{\perp}(\eta, \psi)$ is fresnel coefficient perpendicular to plane of incidence

$F_{\parallel}(\eta, \psi)$ is fresnel coefficient parallel to plane of incidence

Fresnel Ratio



Metals



Dielectrics

Brewster angle

- Hard to separate diffuse and specular parts for metals.
- Easier for dielectrics (good for non-normal incidences).

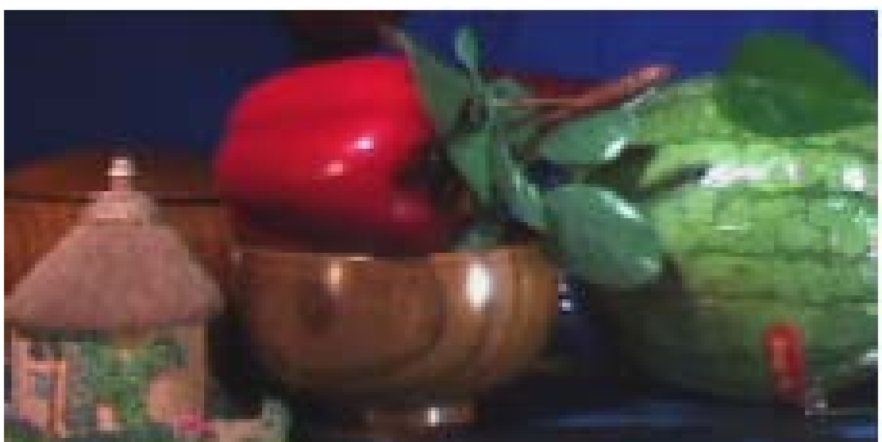
Dichromatic Model for Removing Specularities Completely

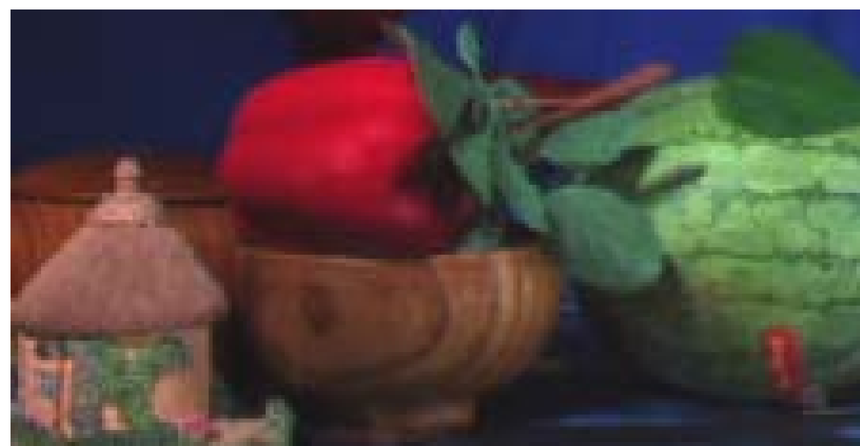
- Specularities are only reduced in intensity using polarization.

- They are removed completely only for the Brewster angle of incidence.

- Nayar et al. use additional color constraints in dichromatic model to remove reflections completely.
-

Assume a local patch where the highlight and its surrounding area have the same diffuse component.

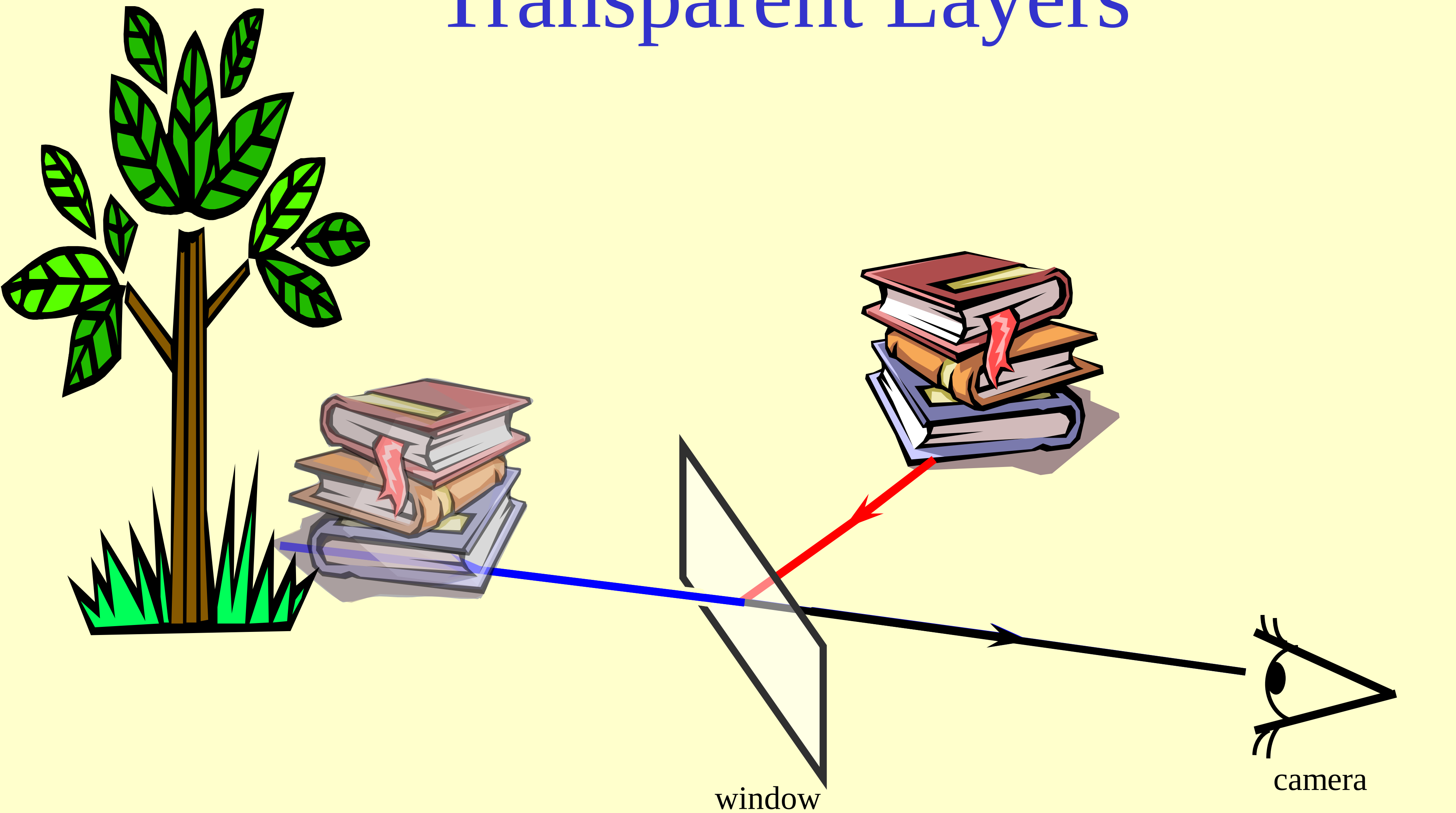




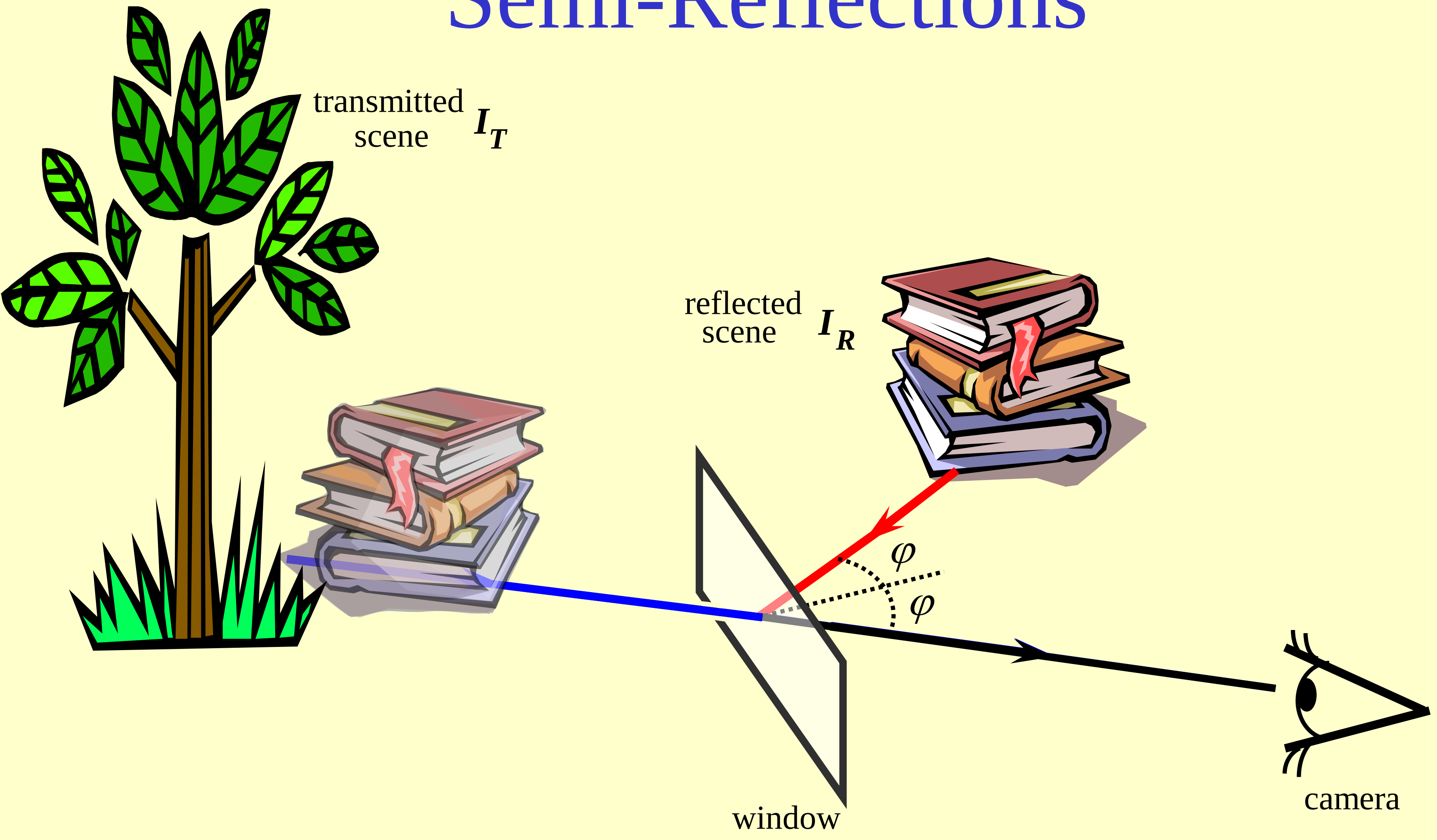
Semi-Reflections

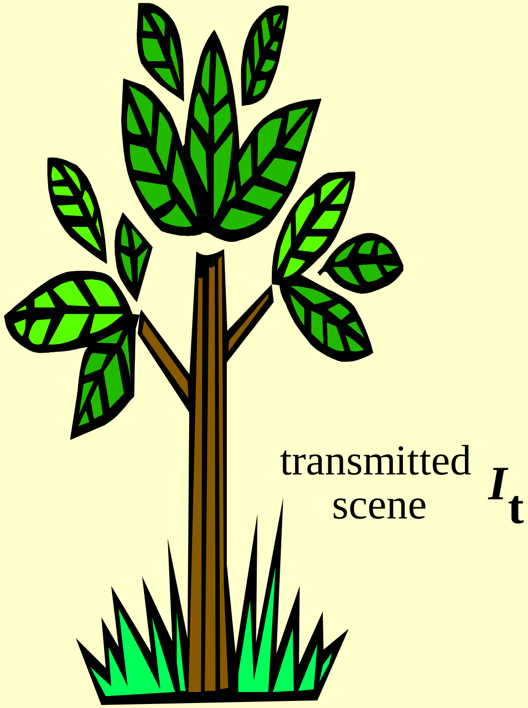
- Both Reflected and Transmitted light are polarized.
- But they are polarized differently.
- They depend on the orientation of the transparent layer.
- Reflections are removed completely only at Brewster Angle of Incidence.

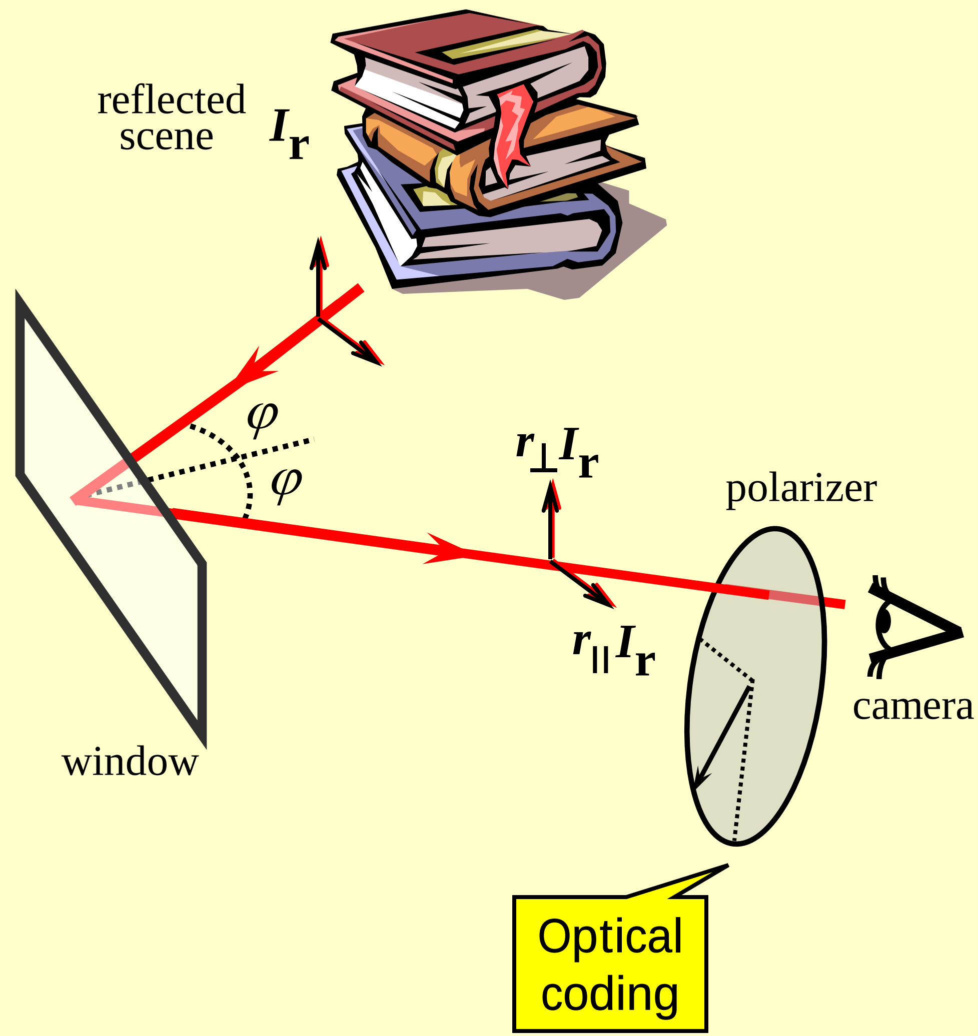
Transparent Layers

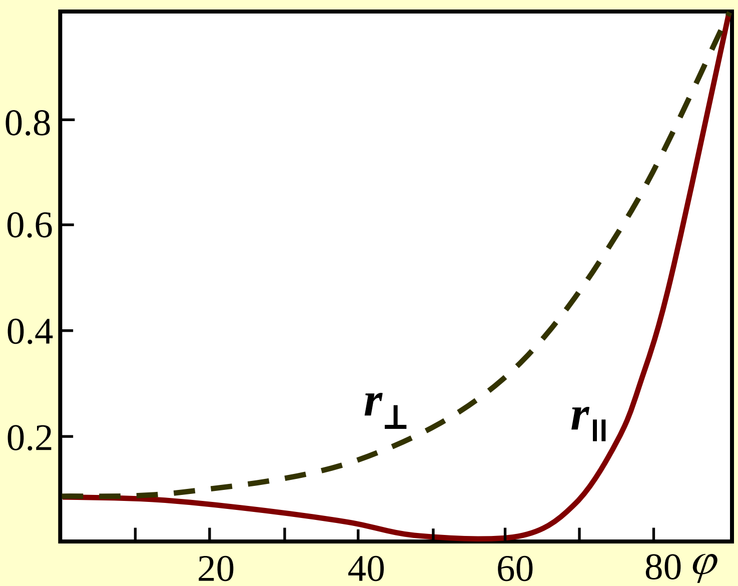


Semi-Reflections



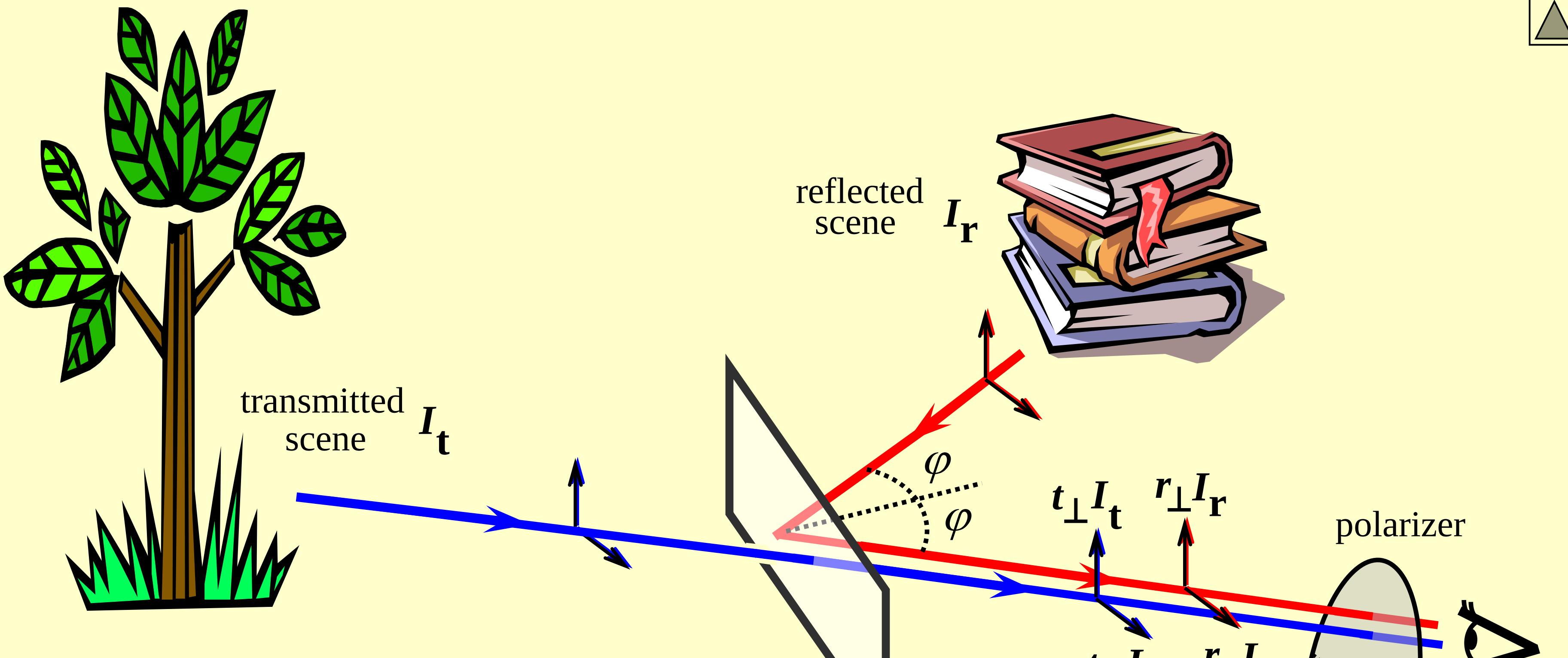


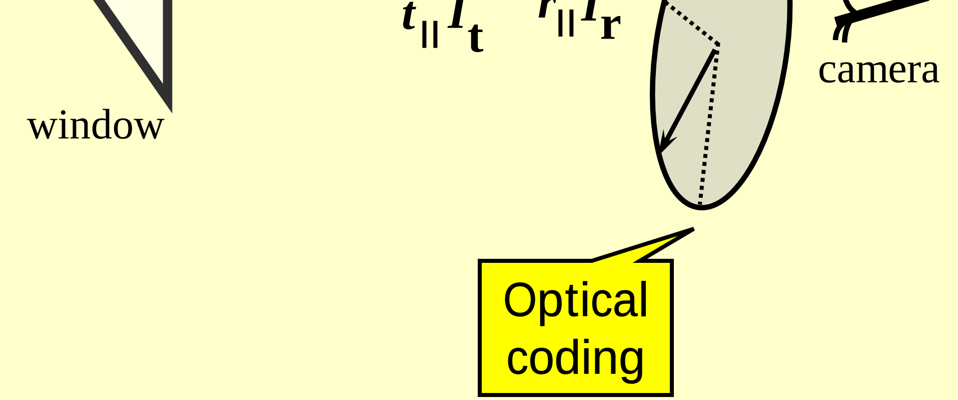


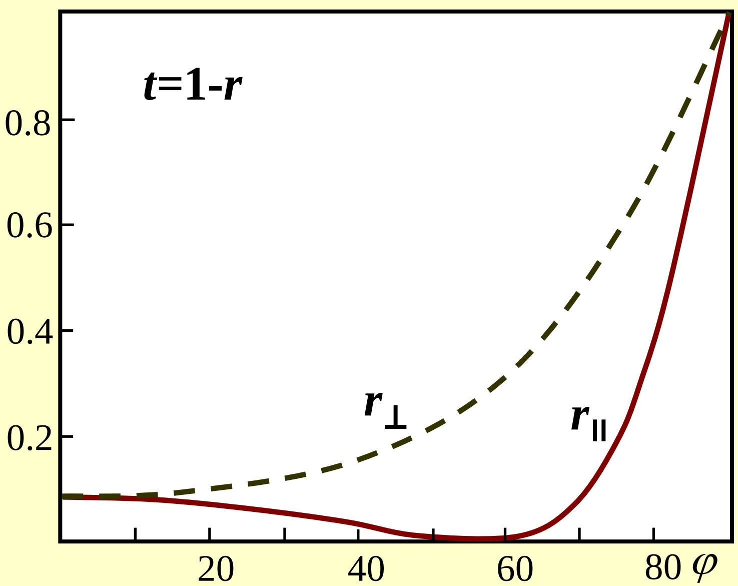


$$R_{||} = \frac{\tan^2(\varphi - \varphi')}{\tan^2(\varphi + \varphi')} \quad , \quad R_\perp = \frac{\sin^2(\varphi - \varphi')}{\sin^2(\varphi + \varphi')}$$

Yoav Schechner, Joseph Shamir, Nahum Kiryati ‘99



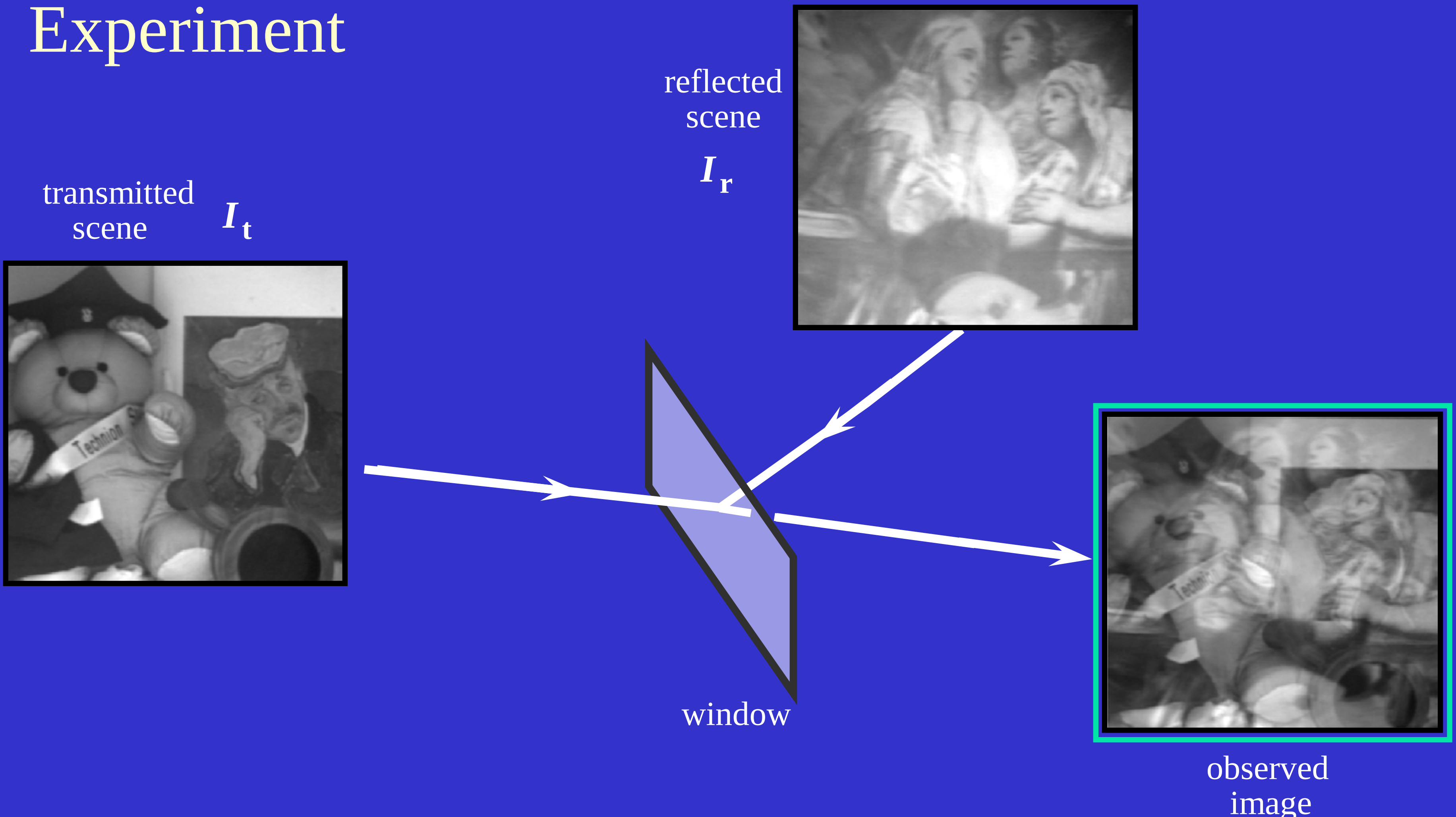




$$R_{||} = \frac{\tan^2(\varphi-\varphi')}{\tan^2(\varphi+\varphi')} \quad , \quad R_{\perp} = \frac{\sin^2(\varphi-\varphi')}{\sin^2(\varphi+\varphi')}$$

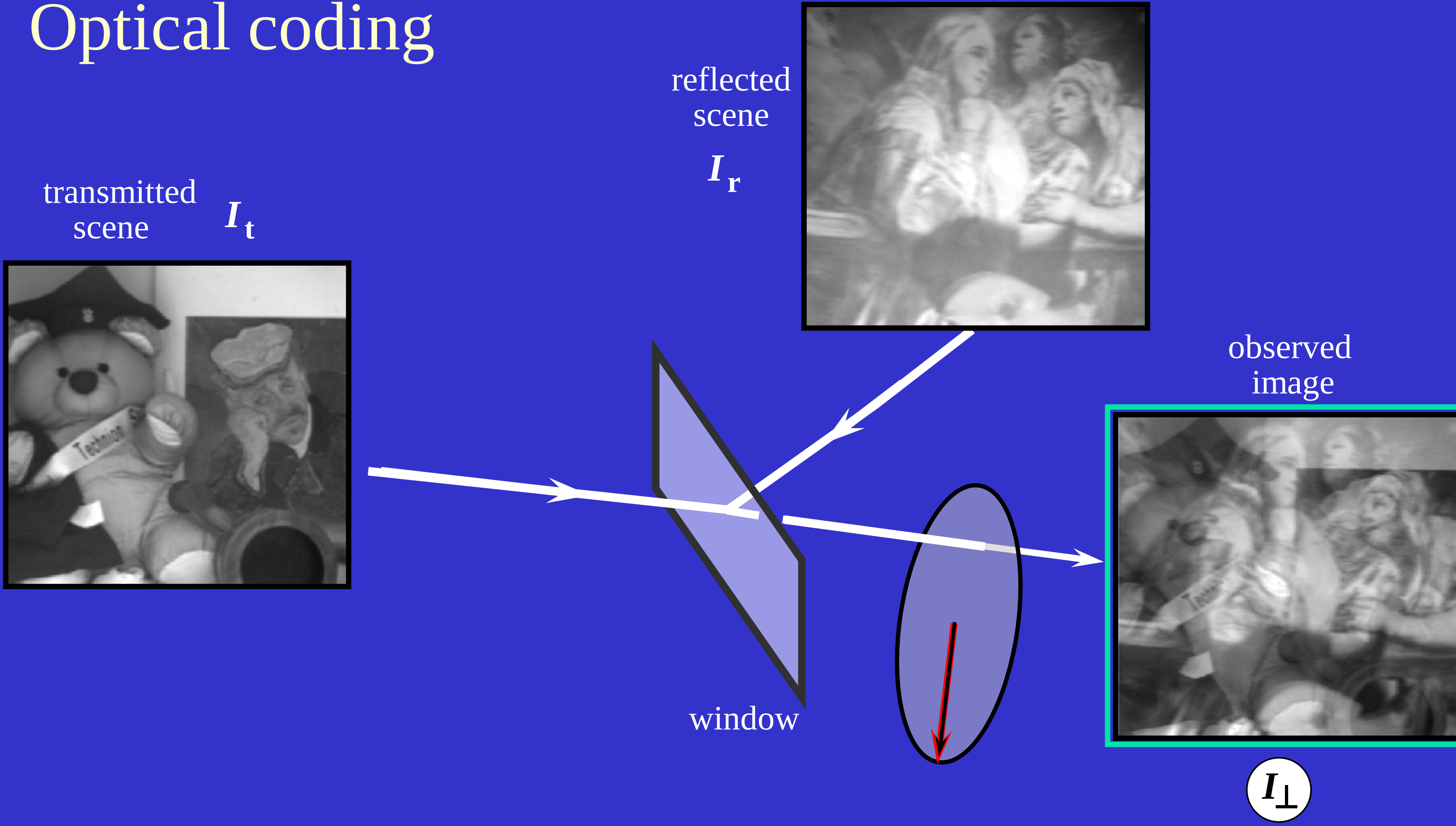
Yoav Schechner, Joseph Shamir, Nahum Kiryati ‘99

Experiment



Yoav Schechner, Joseph Shamir, Nahum Kiryati ‘99

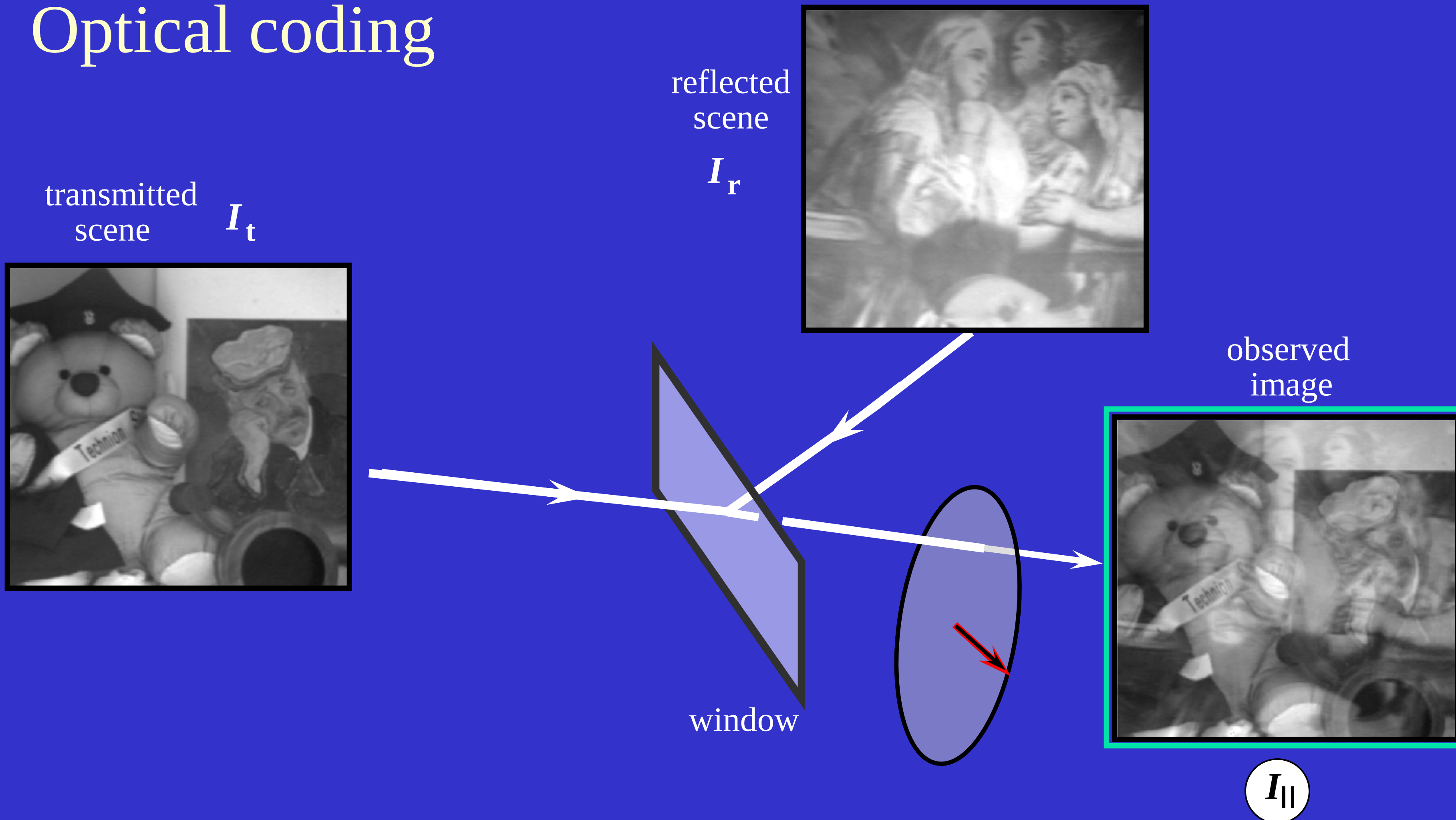
Optical coding



$$I_\perp = [\,r_\perp I_r + t_\perp I_t\,]/2$$

Yoav Schechner, Joseph Shamir, Nahum Kiryati '99

Optical coding



$$I_{||} = [\, r_{||} I_r + t_{||} I_t \,]/2$$

Yoav Schechner, Joseph Shamir, Nahum Kiryati ‘99

Digital decoding

2 Linear equations $I_{\parallel} = [\, r_{\parallel} I_{\mathrm{r}} + t_{\parallel} I_{\mathrm{t}} \,]/2$ $\quad I_{\perp} = [\, r_{\perp} I_{\mathrm{r}} + t_{\perp} I_{\mathrm{t}} \,]/2$

Solve for 2 unknowns: $\widehat{I}_R \, , \, \widehat{I}_T$ Window at 27 ^{o}

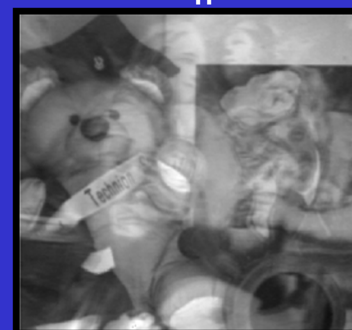
$I_{\perp}$

$\dfrac{2 - 2\, r_{\parallel}}{r_{\perp} - r_{\parallel}}$

$-$

$I_{\parallel}$

$\dfrac{2 - 2\, r_{\perp}}{r_{\perp} - r_{\parallel}}$



Reflected $\widehat{I}_R$

$I_{\parallel}$

$\dfrac{2 r_{\perp}}{r_{\perp} - r_{\parallel}}$

$-$

$I_{\perp}$

$\dfrac{2 r_{\parallel}}{r_{\perp} - r_{\parallel}}$

Transmitted $\widehat{I}_T$

Yoav Schechner, Joseph Shamir, Nahum Kiryati ‘99

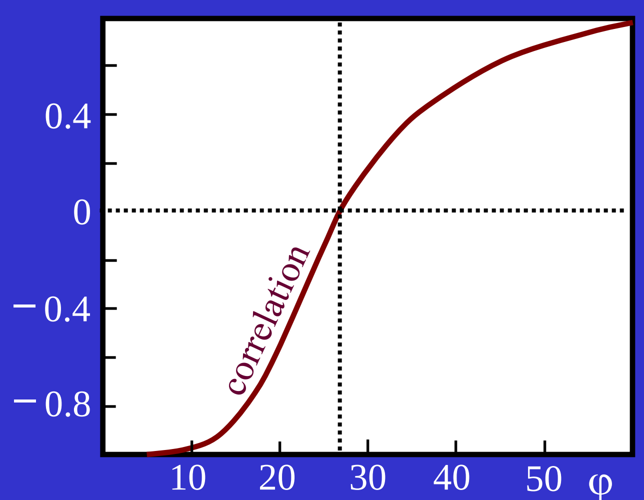
17° 27° 37°

Transmitted $\widehat{I}_T$

Reflected $\widehat{I}_R$

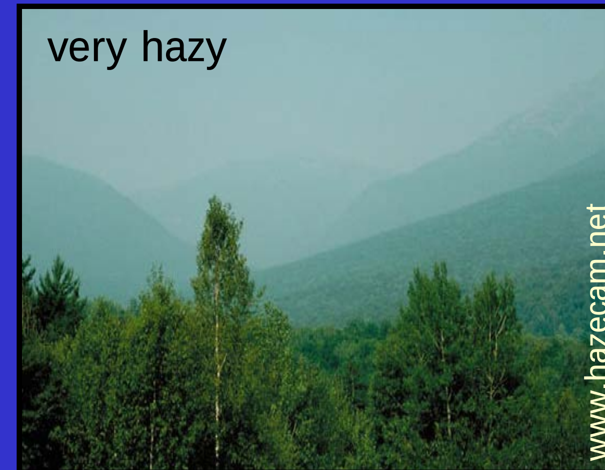
negative crosstalk

positive crosstalk



The inclination of an invisible surface

Imaging through Haze



Recover:

- Object + haze layers
- Scene structure
- Info about the aerosols

Previous work

Pure image processing

Grewe & Brooks ’98, Kopeika ’98

Oakley & Satherley ’98

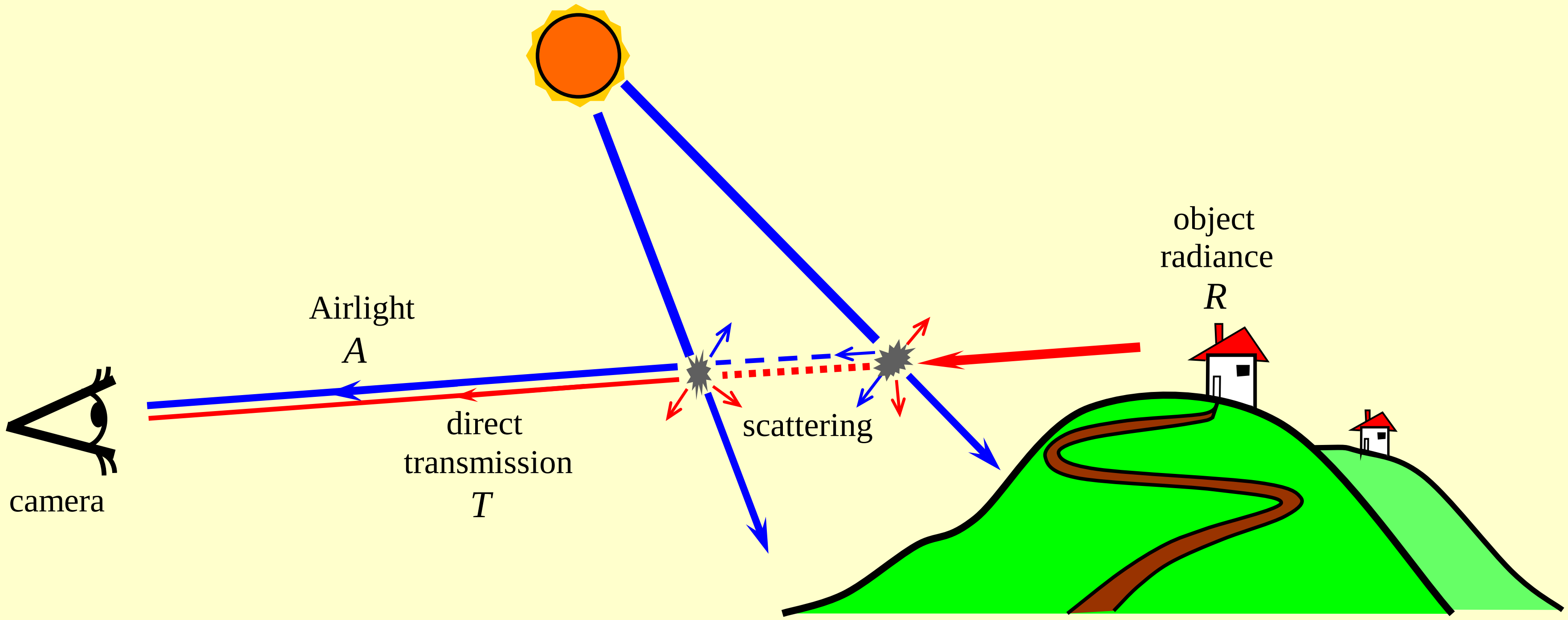
Physics based

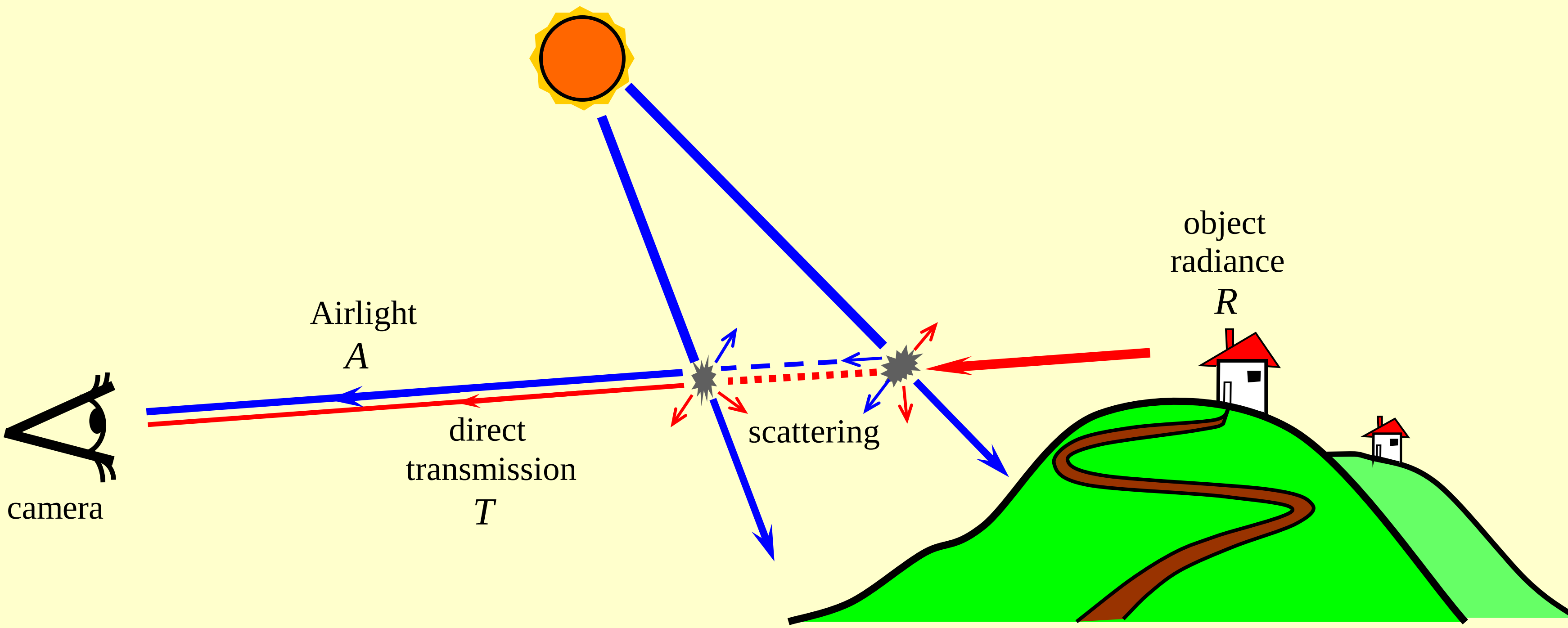
Nayar & Narasimhan ’99

Polarization filtering

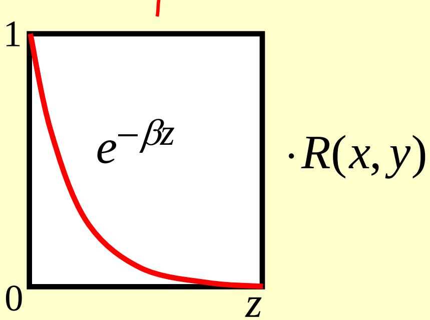
Shurcliff & Ballard ’64

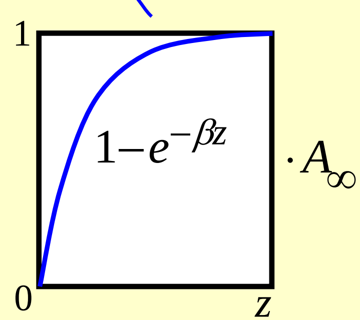
Imaging through Haze





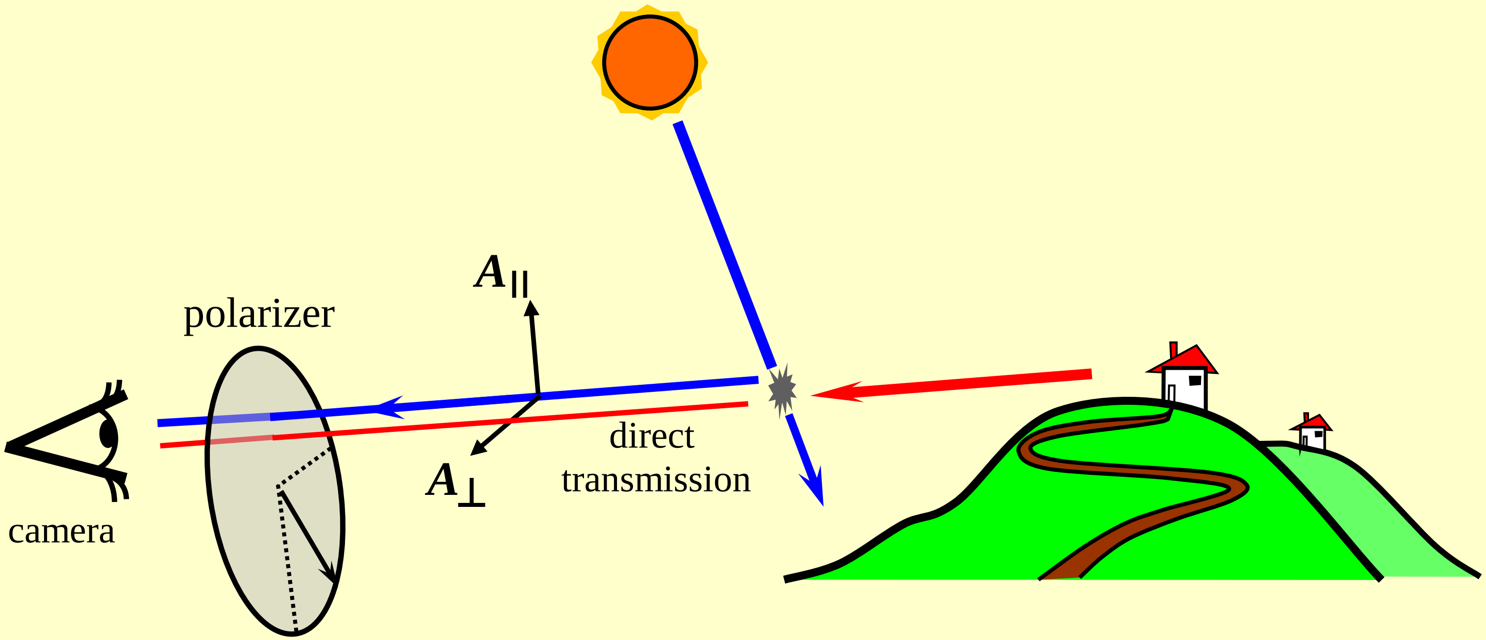
$$I^{\text{total}}(x,y) = T(x,y) + A(x,y)$$





- z is a function of (x,y)
- **Color**
- Multiplicative & additive models
  - similar dependence

Polarization and Haze



- *Plane of rays* determines airlight components $A_{\perp} \geq A_{||}$

Airlight degree of polarization

$$p \equiv \frac{A_{\perp} - A_{||}}{A_{\perp} + A_{||}}$$

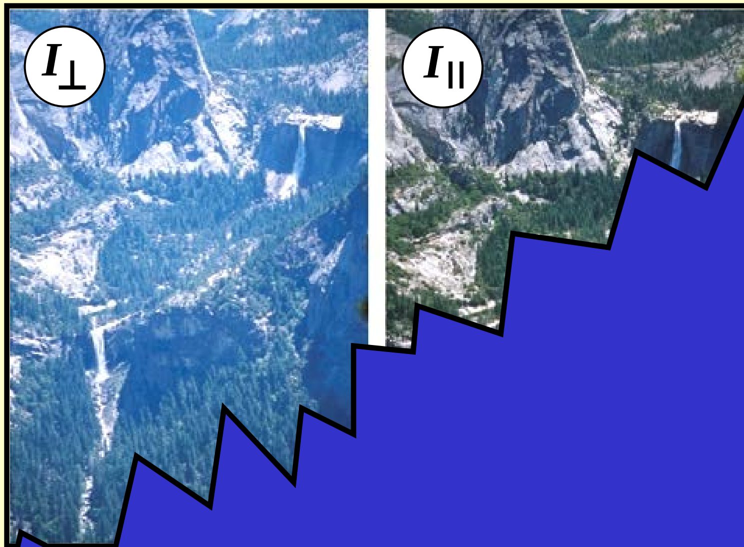
$A_{||} = 0$ polarized $p=1$

$A_{||} = A_{\perp}$ unpolarized $p=0$

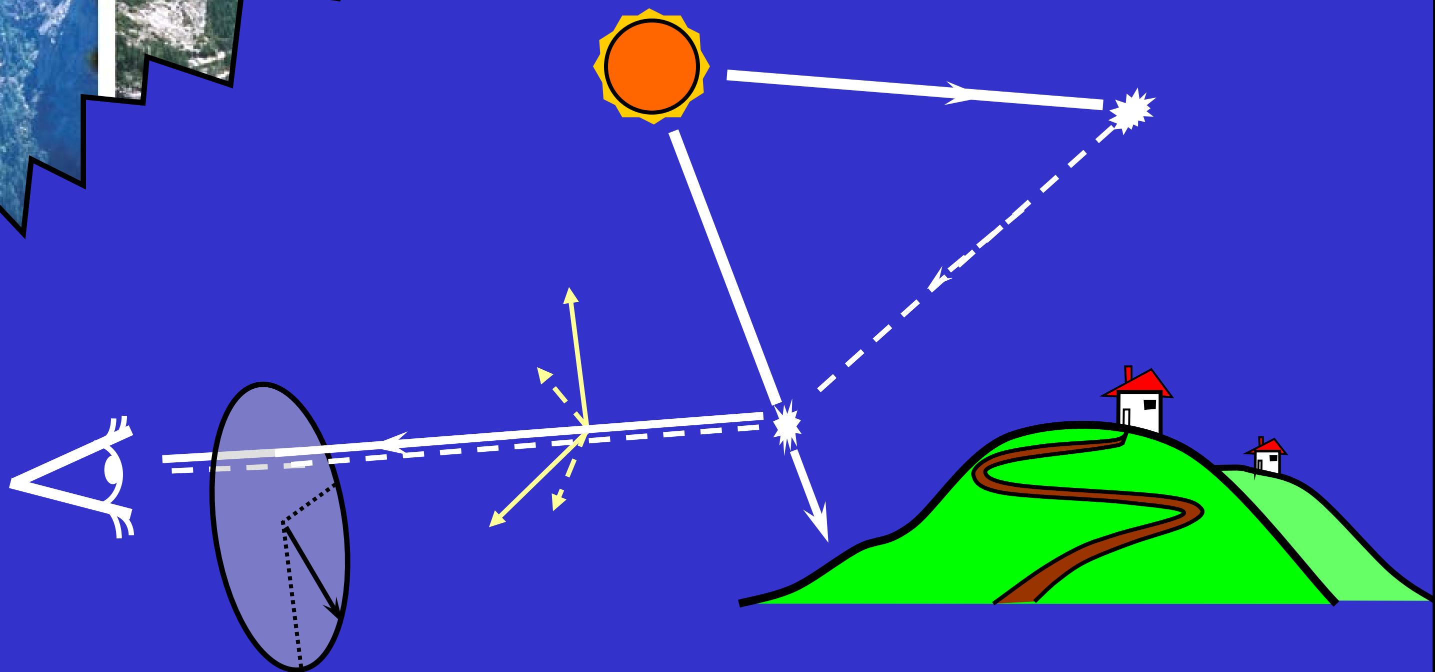
- Along the *line of sight,* polarization state is distance invariant

Assume: The object is unpolarized ➡ $T/2$ @ all orientations

Trivial case



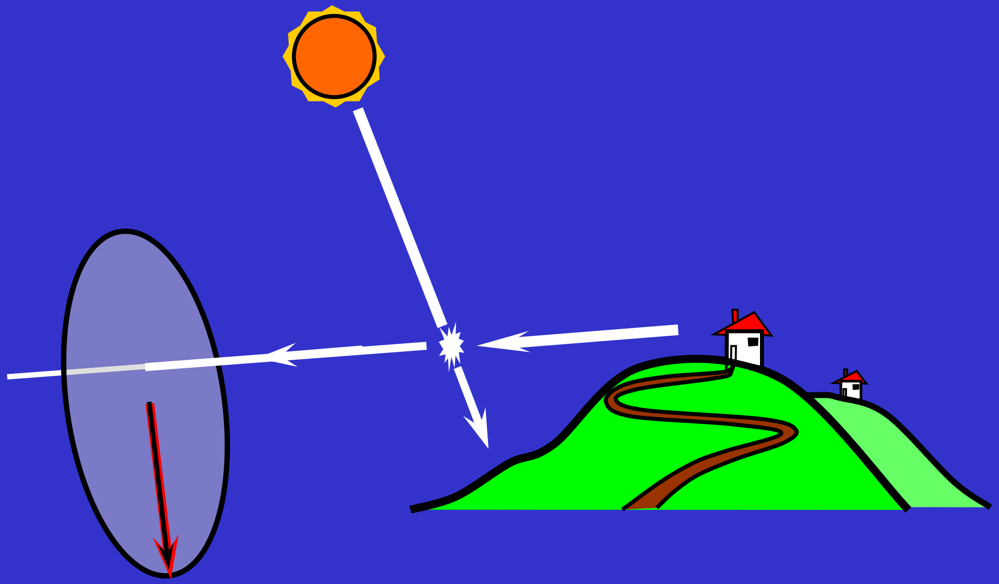
Life is tough...



... still, there is a dominant polarization

Experiment

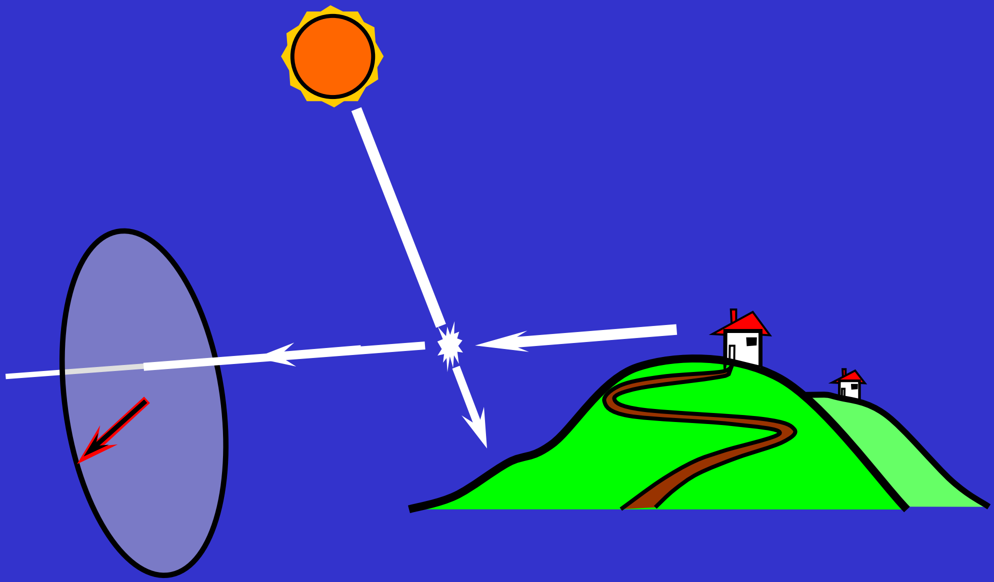
Best polarized image



$$I_{||} = T/2 + A_{||}$$

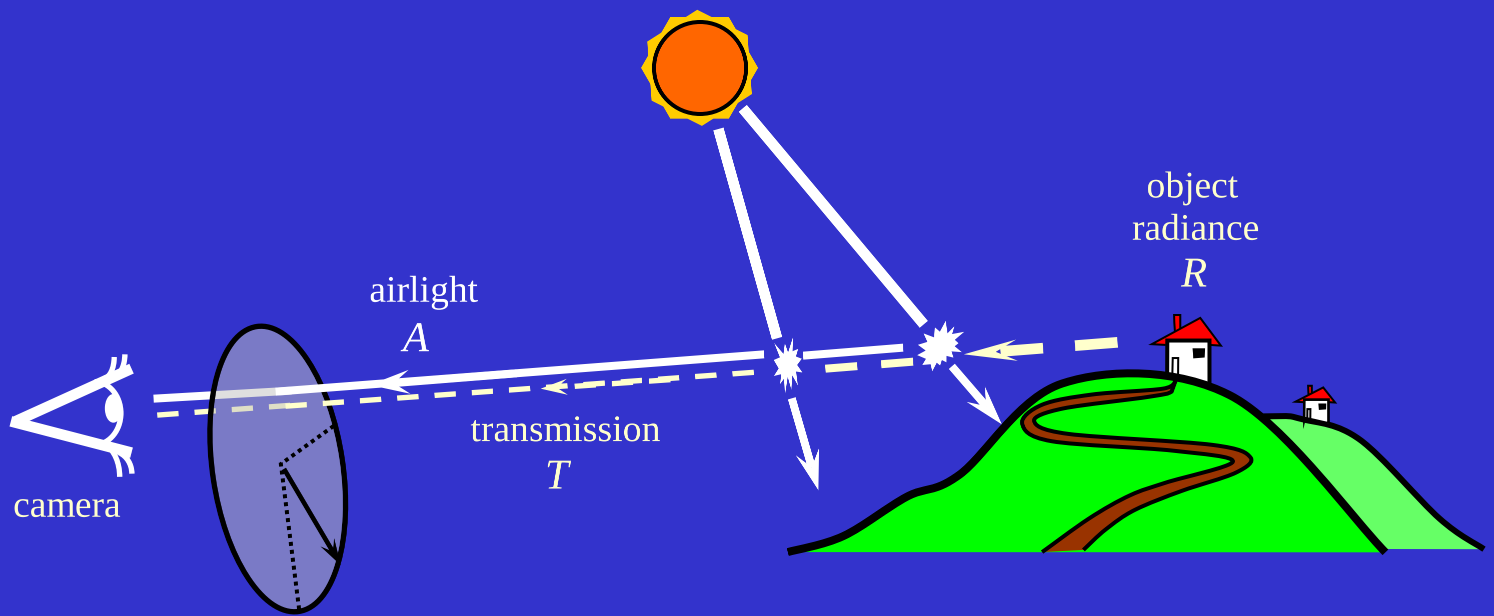
Experiment

Worst polarized image



$I_{\perp} = T/2 + A_{\perp}$

Model



2 input images:

$$I_{||} = T/2 + A_{||}$$

$$I_{\perp} = T/2 + A_{\perp}$$

transmission $T = R e^{-\beta z}$

airlight $A = A_{\infty}\left(1\text{-}e^{-\beta z}\right)$

polarization degree $p \equiv \dfrac{A_{\perp} - A_{||}}{A_{\perp} + A_{||}}$

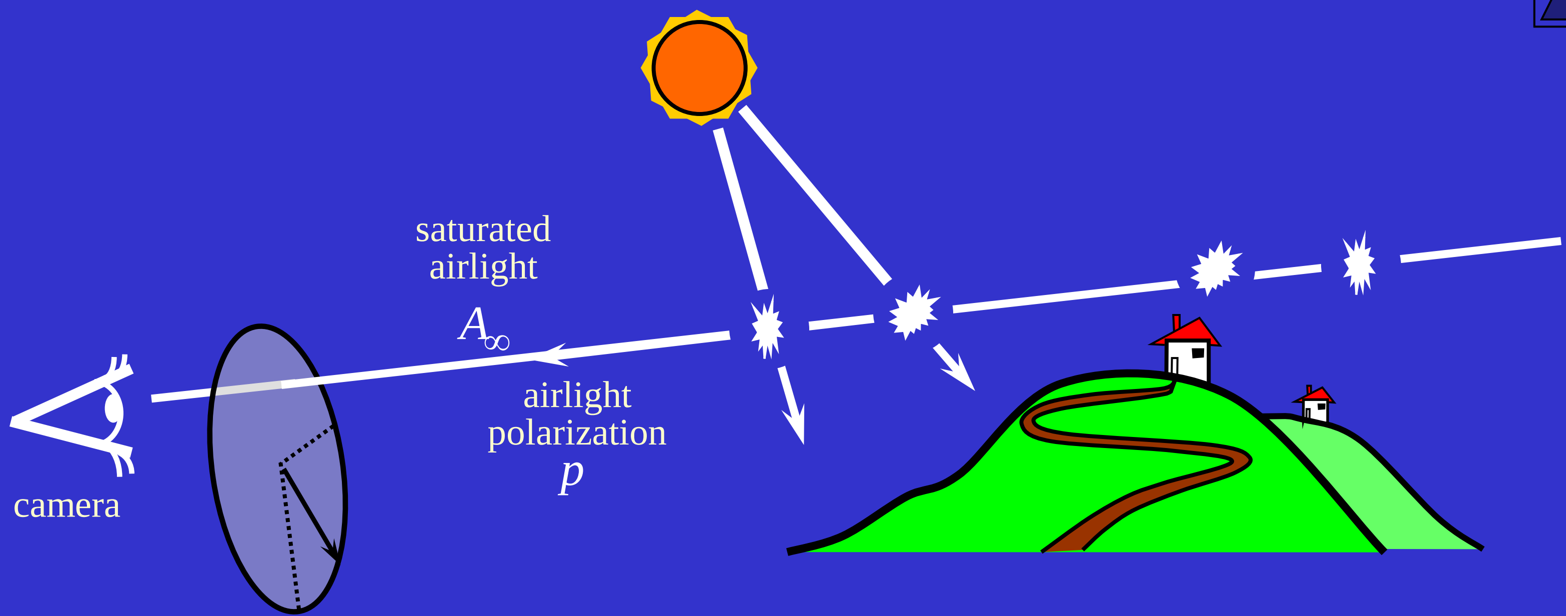
Recovery

depth $e^{-\beta z} = 1 - \dfrac{(I_{\perp} - I_{||})/p}{A_{\infty}}$

radiance $R = \dfrac{(I_{\perp} + I_{||}) - (I_{\perp} - I_{||})/p}{e^{-\beta z}}$

for known p, A_{∞}

Model



2 input images:

$$I_{\parallel} = T/2 + A_{\parallel}$$

$$I_{\perp} = T/2 + A_{\perp}$$

transmission $T = R e^{-\beta z}$

airlight $A = A_\infty \left(1 - e^{-\beta z}\right)$

polarization degree $p \equiv \dfrac{A_\perp - A_\parallel}{A_\perp + A_\parallel}$

Recovery

depth $e^{-\beta z} = 1 - \dfrac{(I_\perp - I_\parallel)/p}{A_\infty}$

radiance $R = \dfrac{(I_\perp + I_\parallel) - (I_\perp - I_\parallel)/p}{e^{-\beta z}}$

for known p, A_∞

Dehazing Experiment

$I_{||}$

Best polarized image

Dehazing Experiment

R

Dehazed image

Range map

depth $e^{-\beta z} = 1 - \frac{(I_{\perp} - I_{||})}{pA_{\infty}}$

log → $\beta z(x,y)$

component images $I_{\perp}(x,y)$, $I_{||}(x,y)$

Airlight
saturation A_{∞}
polarization p

Dehazing Experiment

$I_{||}$

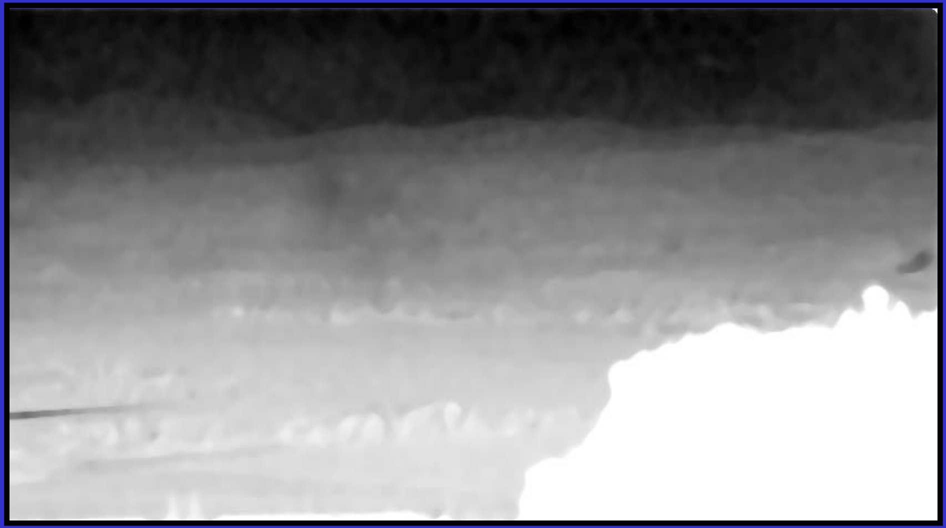
Best polarized image

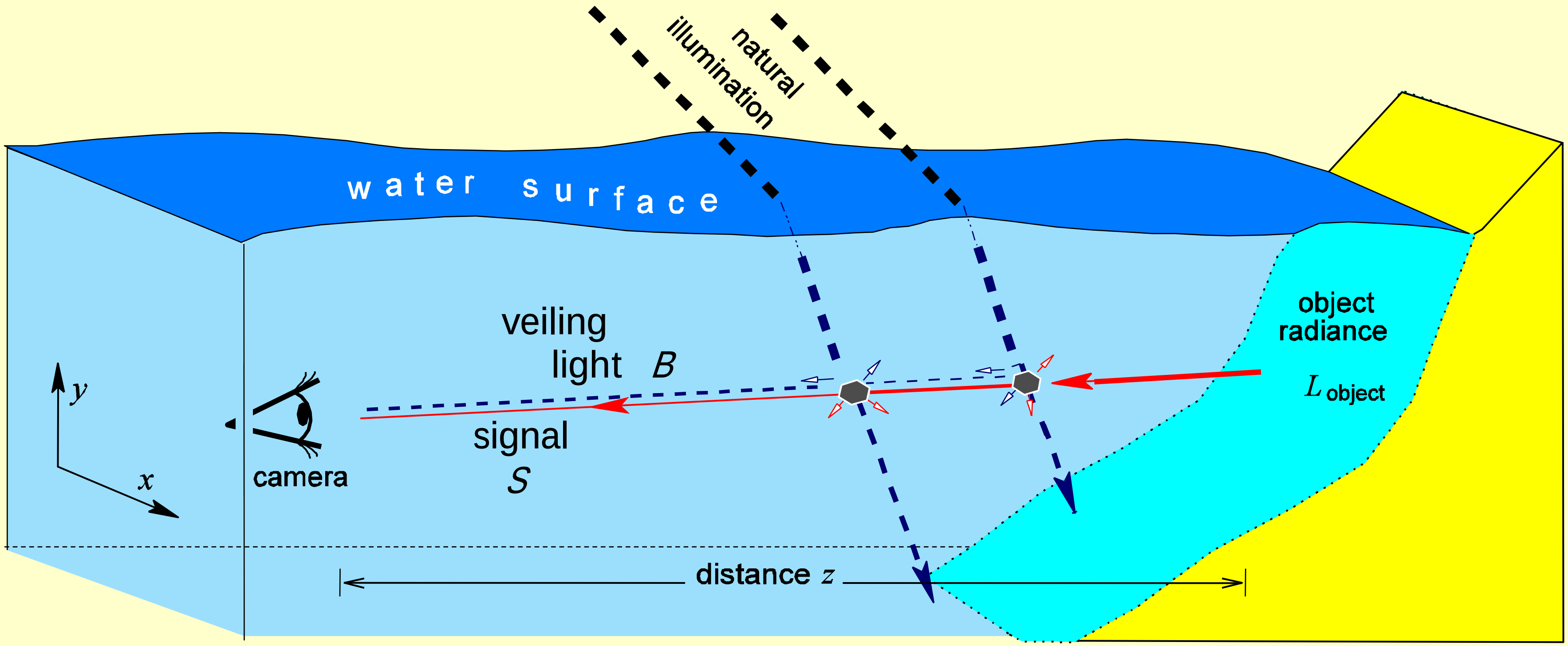
Dehazing Experiment

R

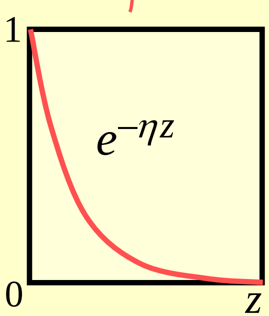
Dehazed image

Range map

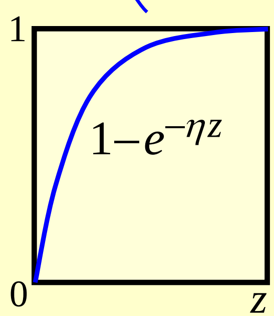




$$I^{\text{total}}(x,y) = S(x,y) + B(x,y)$$



$$\cdot L_{\text{object}}^{\text{effective}}(x,y) +$$



$$\cdot B_{\infty}$$

- z is a function of (x,y)
- **Color**
- $L_{\text{object}}^{\text{effective}}$ - object with blur

Hypothesis, 4 Decades Old

Lythgoe & Hemmings, 1967 (*Nature*) :

> "Many invertebrates are able to distinguish the plane of polarized light. Does this enable them to **see further** underwater?"

Lythgoe, 1972 (*Handbook Sensory Physiol*) :

> "…there is a strong possibility that it [polarization] could be useful for improving the visibility of **distant objects**, especially under water."

Hypothesis, 4 Decades Old

Lythgoe & Hemmings, 1967 (*Nature*) :

“Many invertebrates are able to distinguish the plane of polarized light. Does this enable them to **see further** underwater?”

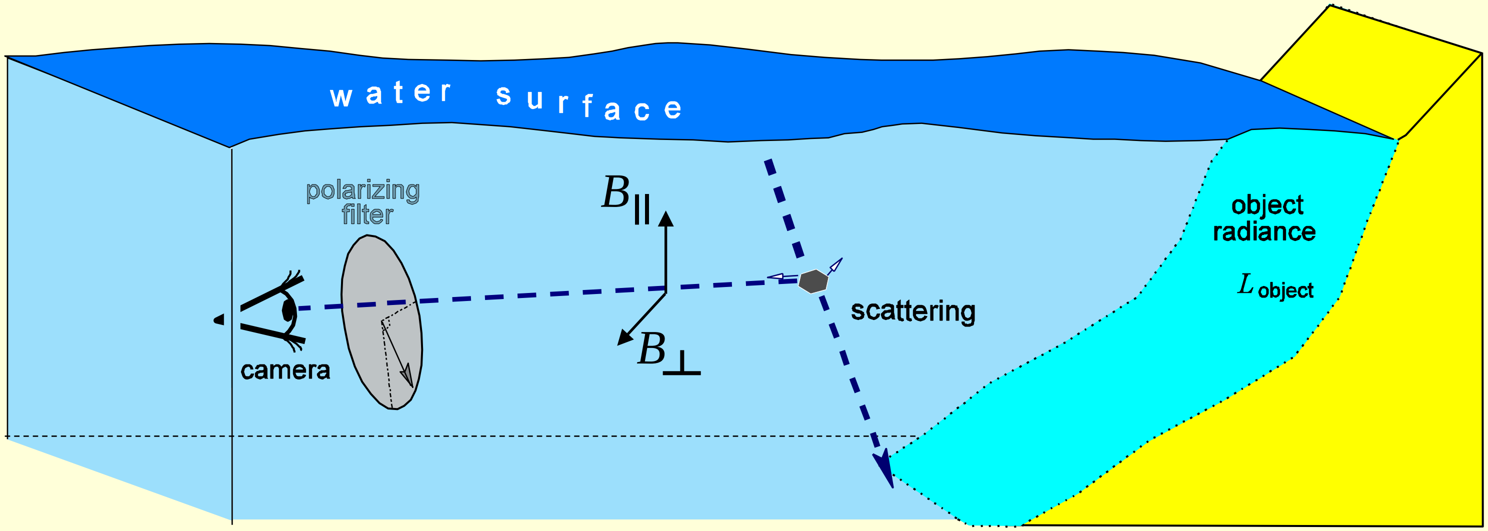
“…when the [polarizing] screen was oriented to exclude the maximum spacelight … fishes stood out in greater contrast against their background.”

“… simple polarizing screen will be less versatile than the system found in Octopus, where there is the intra-ocular ability to distinguish light polarized in one plane from that polarized in another.”

Lythgoe, 1972 (*Handbook Sensory Physiol*) :

“…there is a strong possibility that it [polarization] could be useful for improving the visibility of **distant objects**, especially under water.”

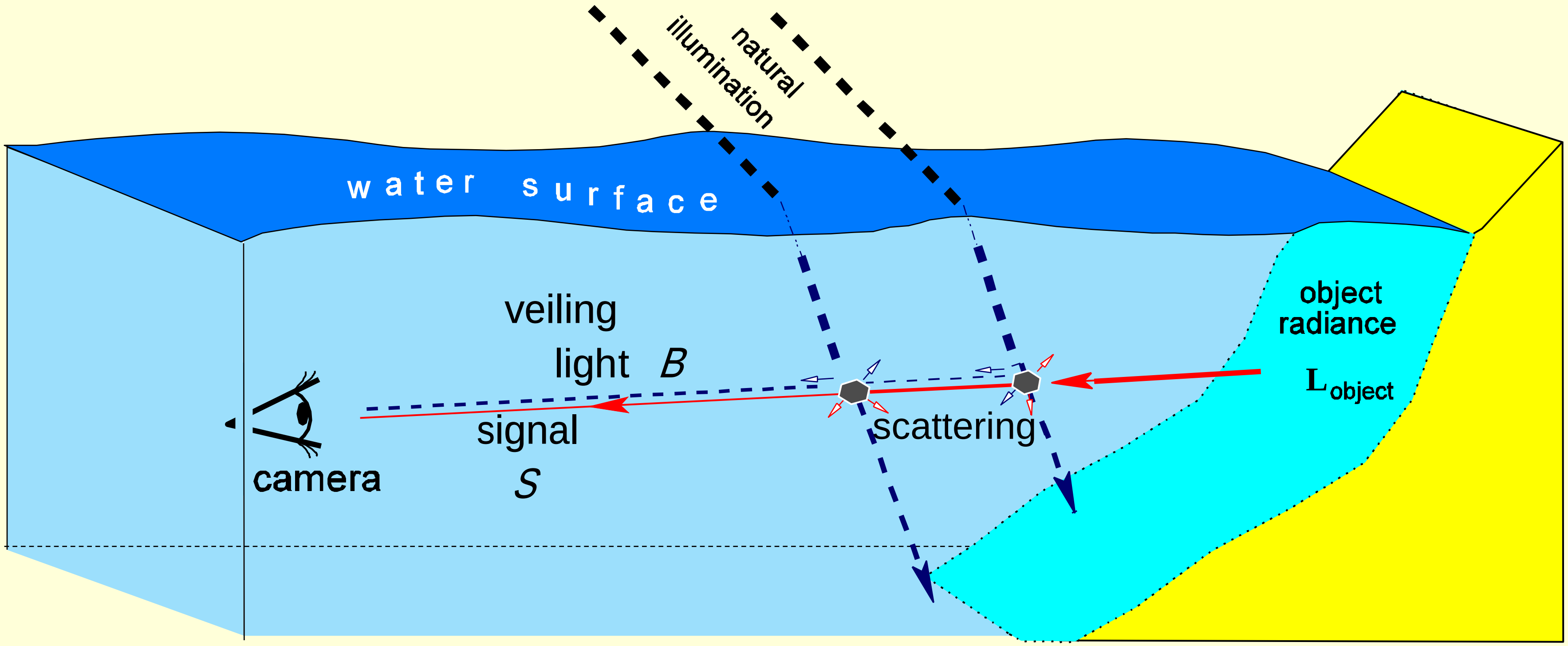
Polarization of Veiling Light



- Veiling light is partially polarized

$$B_{\perp} > B_{||}$$

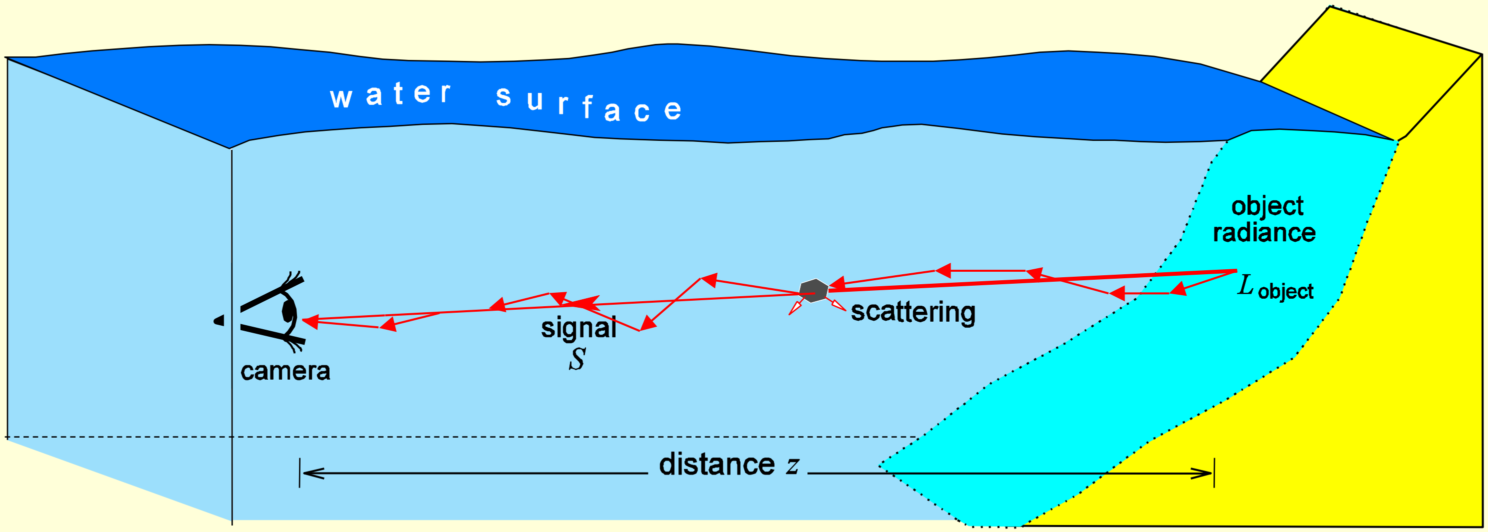
Image Components



Veiling light = Spacelight = Path radiance = Backscatter

Schechner, Karpel, *underwater vision*

Signal Polarization



- Rough surfaces : naturally depolarize
- Specular reflection : weaker than in air
- Multiple scattering
- Signal decreases with distance / veiling-light increases

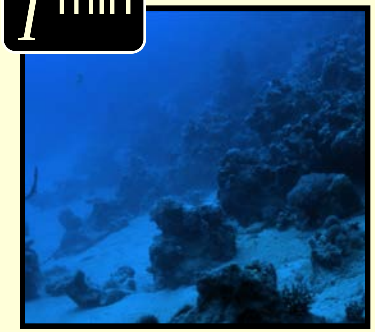
At large distance:
signal polarization has a negligible effect

(Supported by Shashar, Sabbah & Cronin 2004)

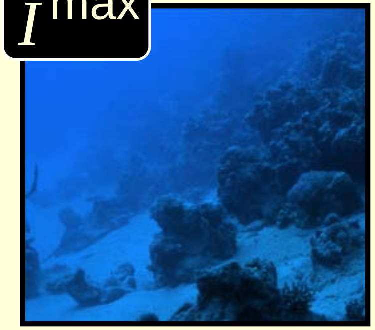
Polarization Photography

Past Polarization-Based Methods

I^{min}



I^{max}

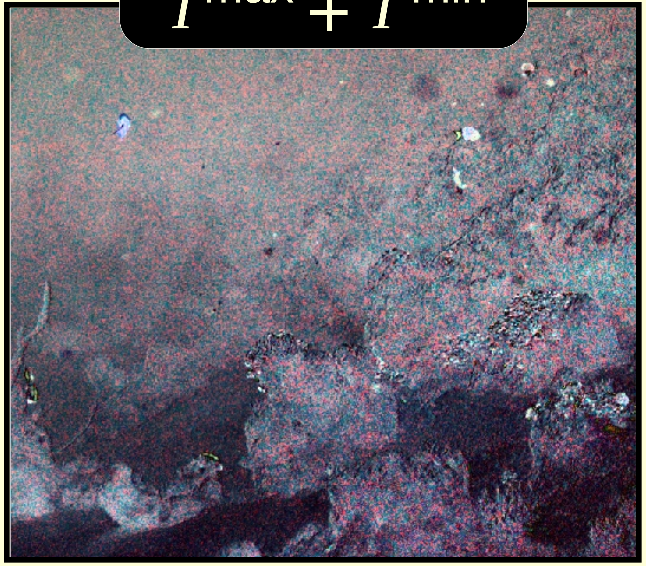


Raw images

$I^{max} - I^{min}$

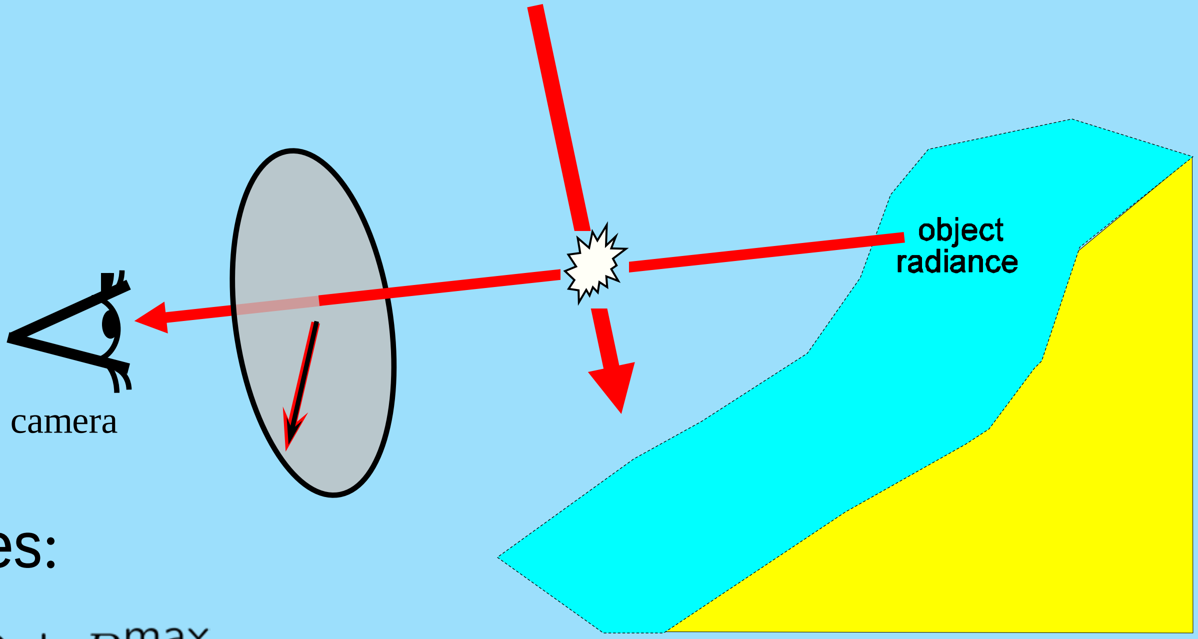
Polarization-difference imaging

$$\frac{I^{max} - I^{min}}{I^{max} + I^{min}}$$



Degree of polarization

Model



2 input images:

$$I^{\text{max}} = S/2 + B^{\text{max}}$$
$$I^{\text{min}} = S/2 + B^{\text{min}}$$

---

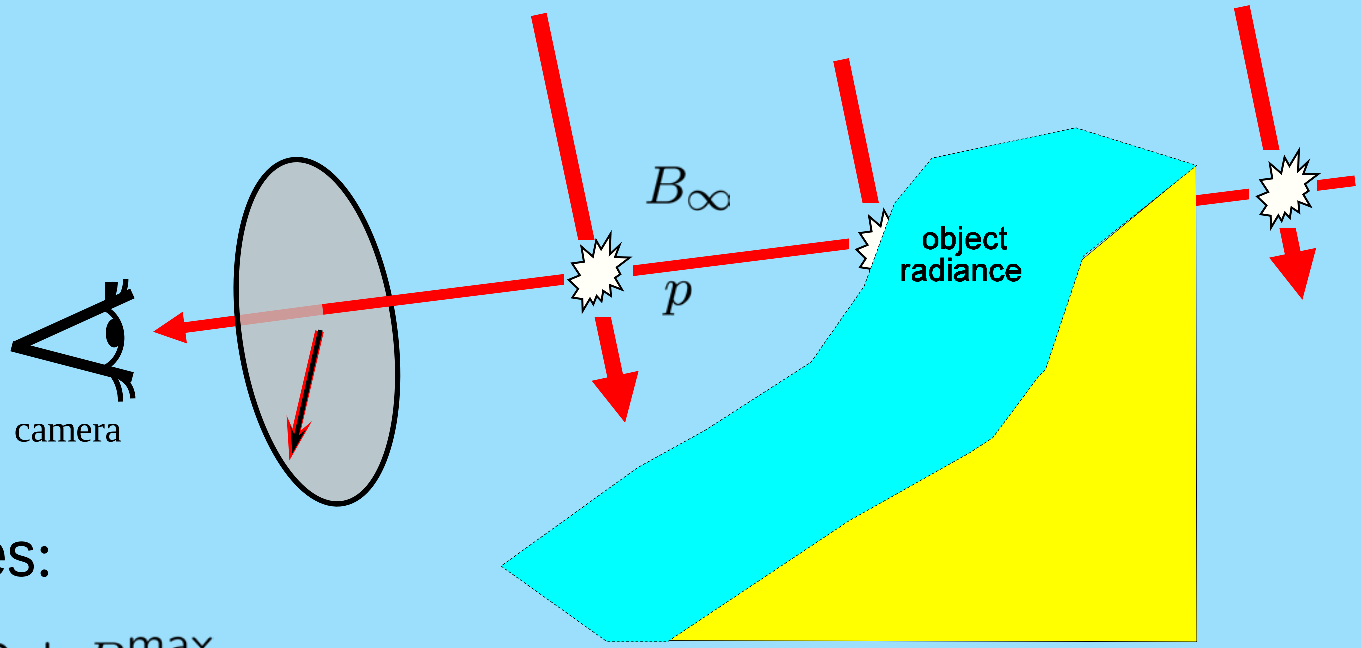
backscatter $B = B_\infty \left(1 - e^{-\eta z}\right)$

signal $S = e^{-\eta z}\ L_{\text{object}}$

polarization $p \equiv \frac{B_{\text{max}} - B_{\text{min}}}{B}$

Recovery

$$L_{\text{object}} = \frac{I^{\text{max}} + I^{\text{min}} + (I^{\text{max}} - I^{\text{min}})/p}{1 - \frac{(I^{\text{max}} - I^{\text{min}})/p}{B_\infty}}$$



2 input images:

$$I^{\text{max}} = S/2 + B^{\text{max}}$$
$$I^{\text{min}} = S/2 + B^{\text{min}}$$

---

backscatter $B = B_\infty \left(1 - e^{-\eta z}\right)$

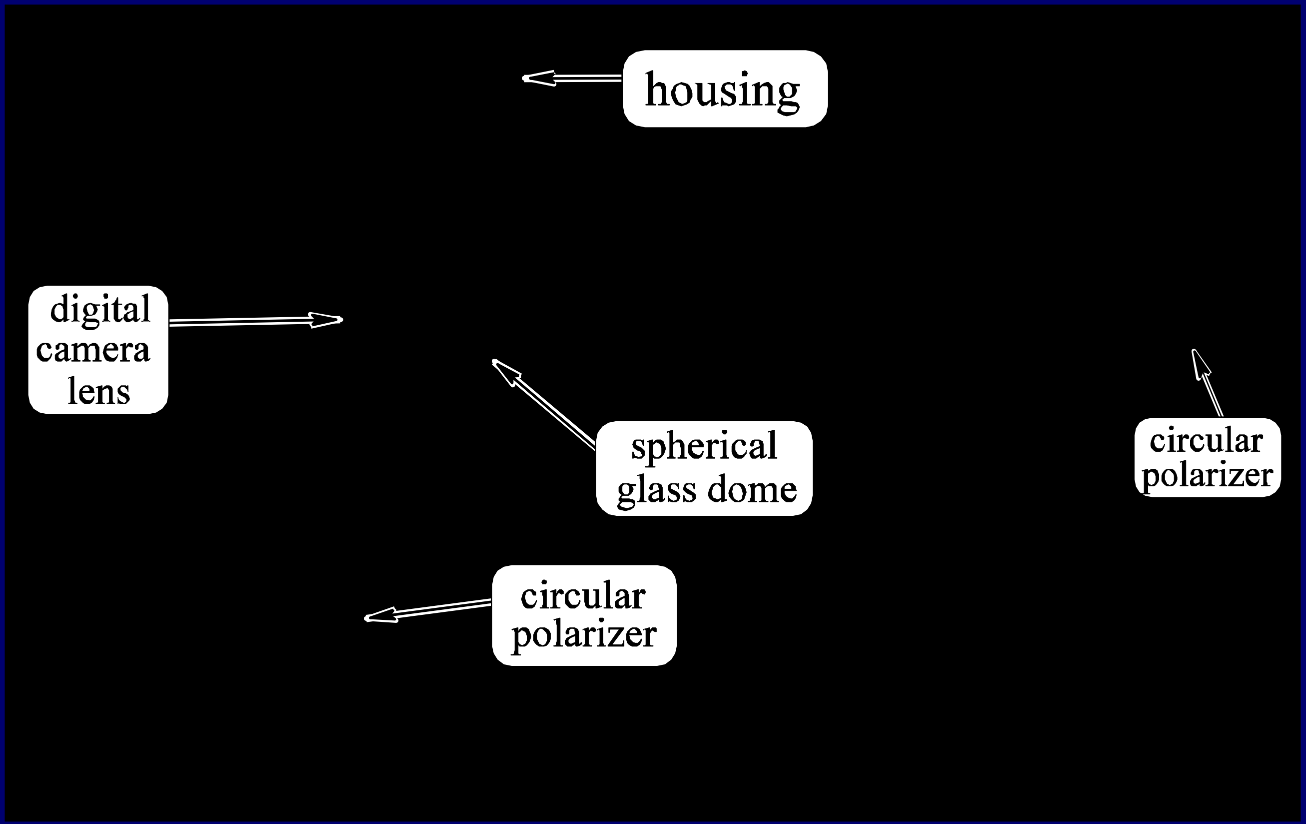
signal $S = e^{-\eta z}\ L_{\text{object}}$

polarization $p \equiv \frac{B_{\text{max}} - B_{\text{min}}}{B}$

Recovery

$$L_{\text{object}} = \frac{I^{\text{max}} + I^{\text{min}} + (I^{\text{max}} - I^{\text{min}})/p}{1 - \frac{(I^{\text{max}} - I^{\text{min}})/p}{B_\infty}}$$

Aqua-polaricam

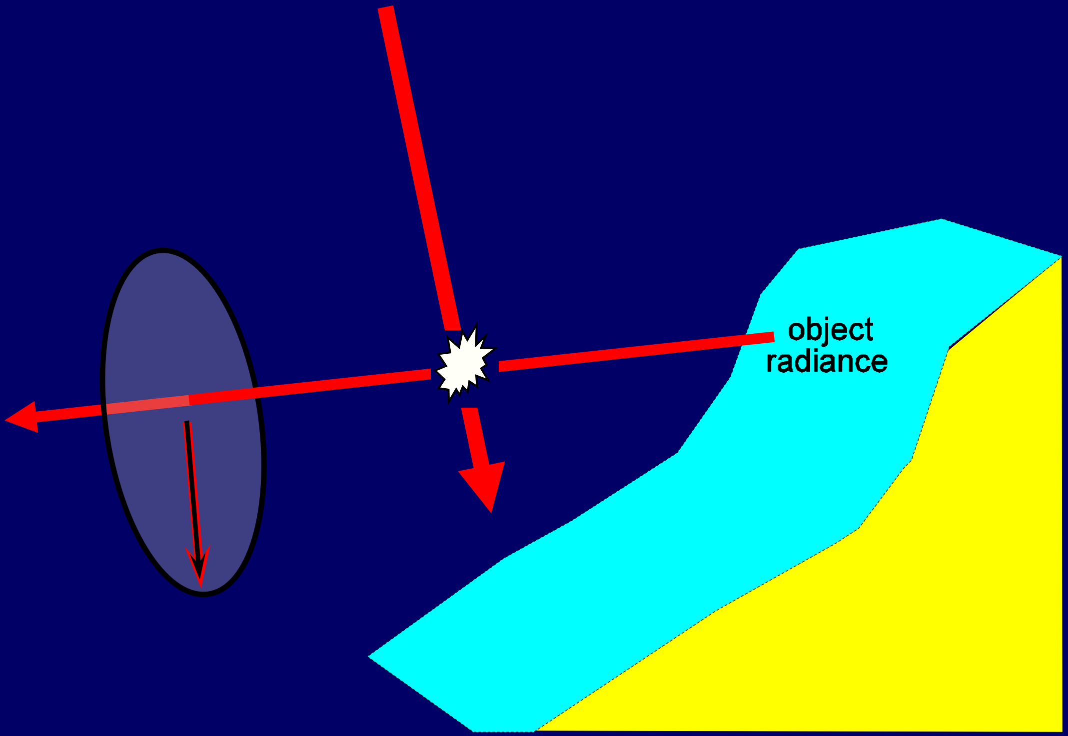


Experiments

Experiment

Eilat, 26m underwater

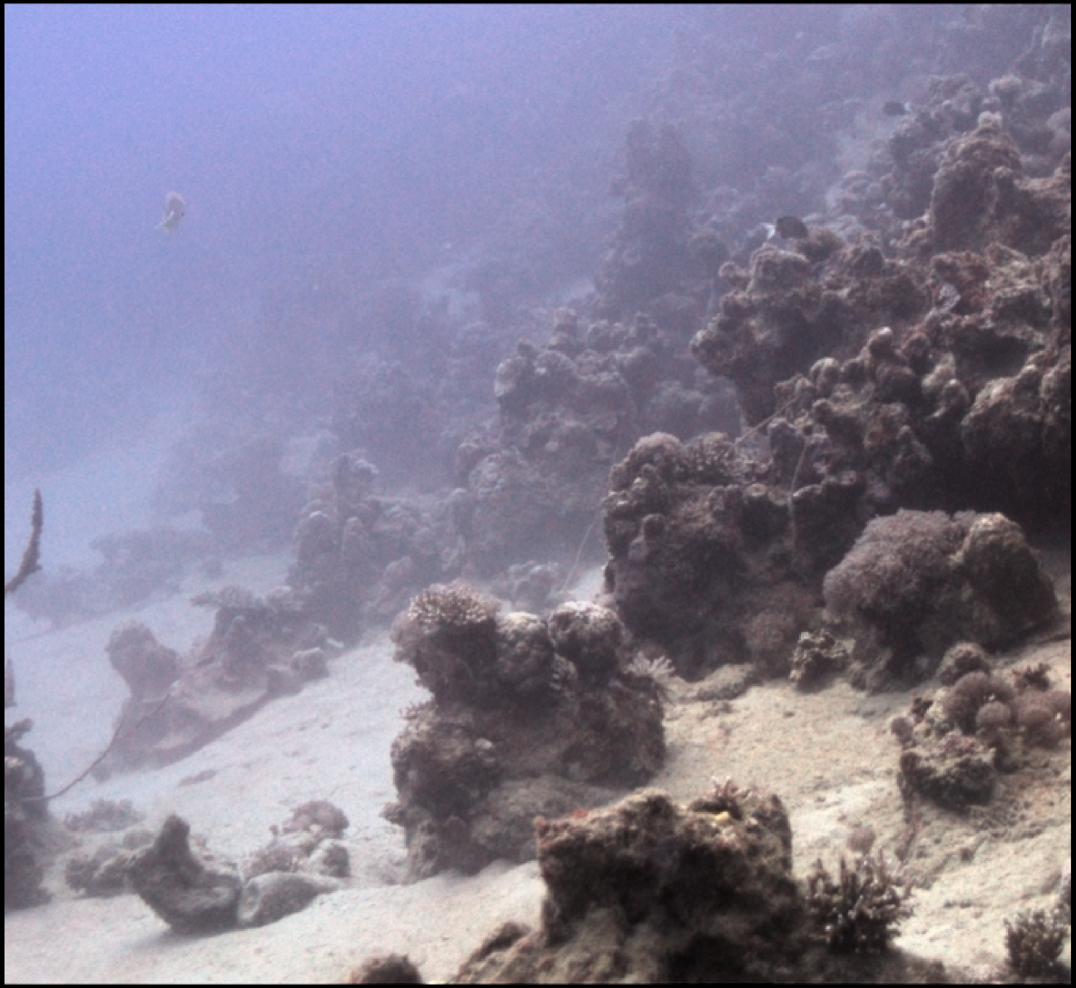
Best polarization image



$$I^{\text{min}} = S/2 + B^{\text{min}}$$

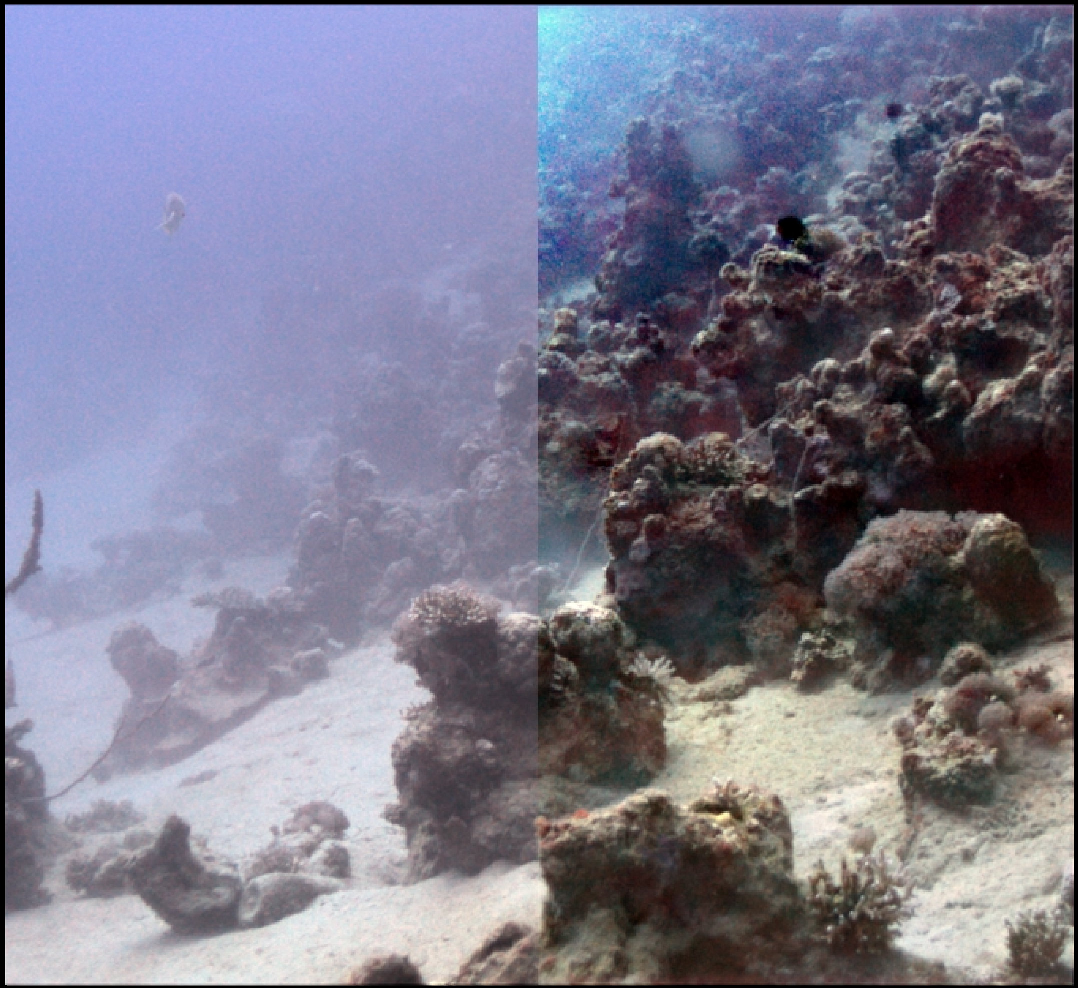
Y. Schechner & N. Karpel, *underwater imaging*

Naive White Balancing



26m underwater

Y. Schechner & N. Karpel, *underwater imaging*



26m underwater

Y. Schechner & N. Karpel, *underwater imaging*

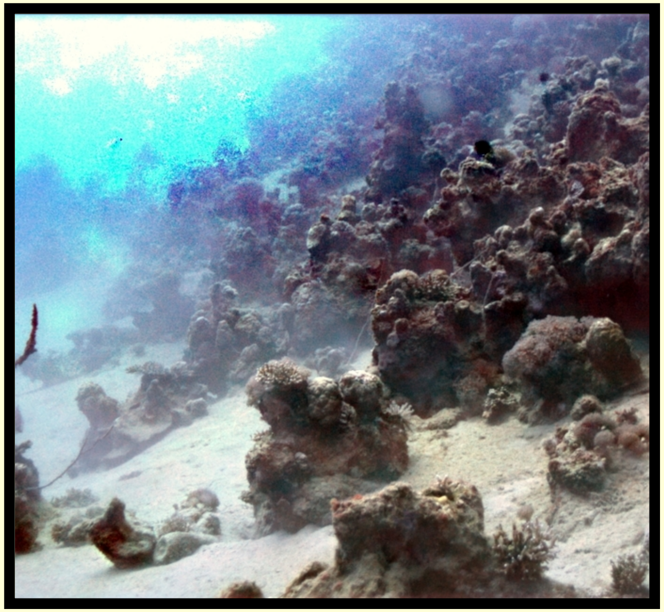
Range Map

Attenuation

$$e^{-\eta z} = 1 - \frac{(I^{\text{max}} - I^{\text{min}})/p}{B_\infty}$$

Image components $I^{\text{max}}, I^{\text{min}}$

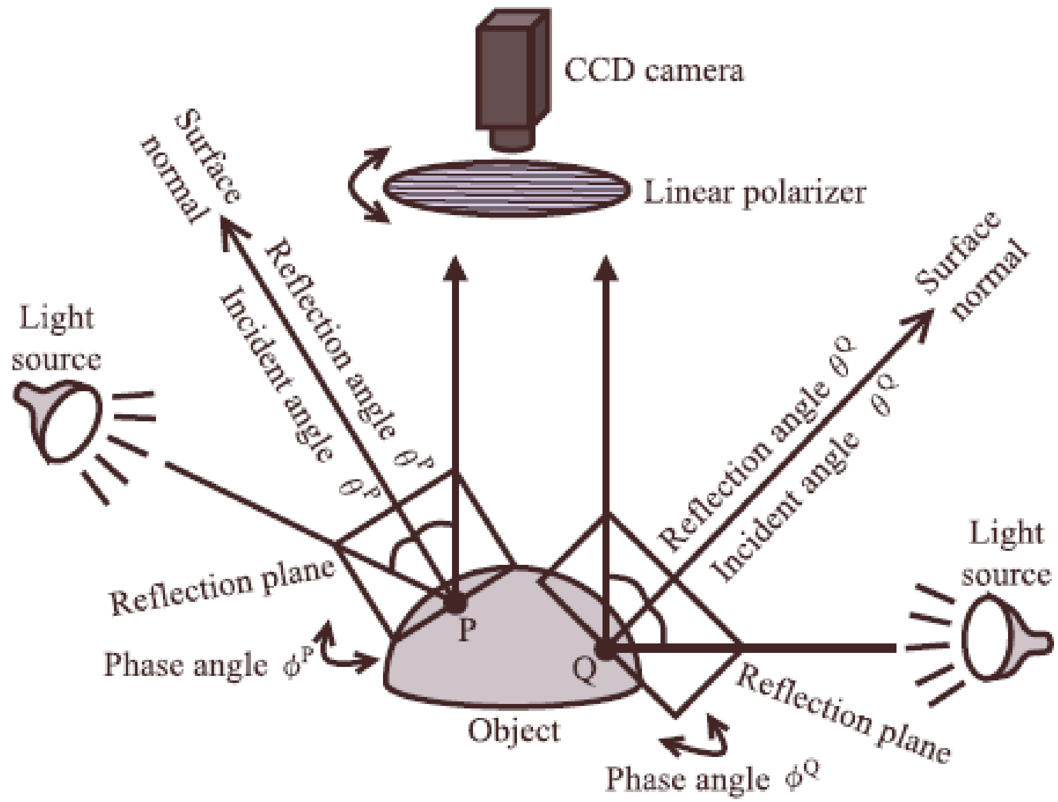
backscatter B_∞, p



Y. Schechner & N. Karpel, *underwater imaging*

Shape Reconstruction of Transparent Objects

Miyazaki et al

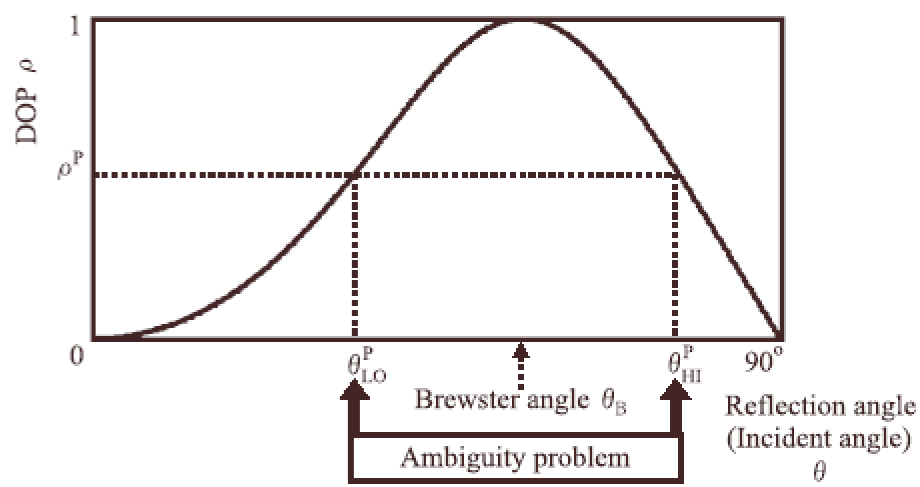


- Incident light is completely unpolarized.
- Index of refraction is given.
- Exploit relation between degree of polarization and angle of incidence (Surface normal).

Relationship between DOP and Angle of Incidence

$$\rho = \frac{2\sin^2\theta\cos\theta\sqrt{n^2-\sin^2\theta}}{n^2-\sin^2\theta-n^2\sin^2\theta+2\sin^4\theta}$$

Two-way ambiguity in recovered angle of incidence:



Manually disambiguate, use multiple views
or use prior knowledge (convex, concave, etc).

Recovered Shape




NEXT WEEK

Volumetric Scattering and its Applications to Computer Vision and Computer Graphics

Lectures #18, #19, #20