Introduction to Polarization for Rendering and Vision

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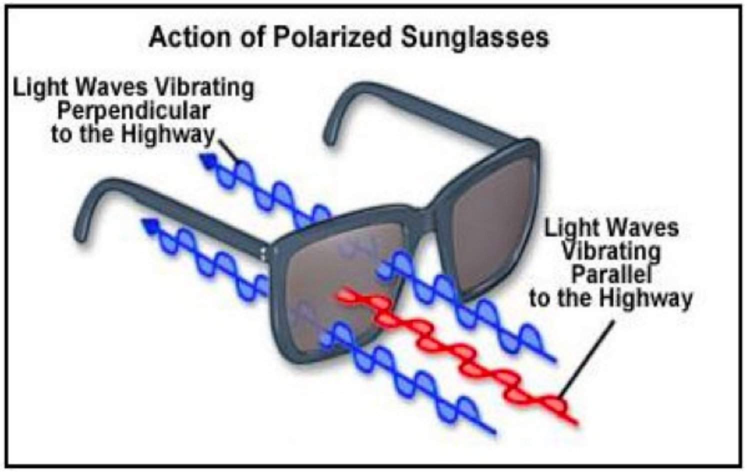
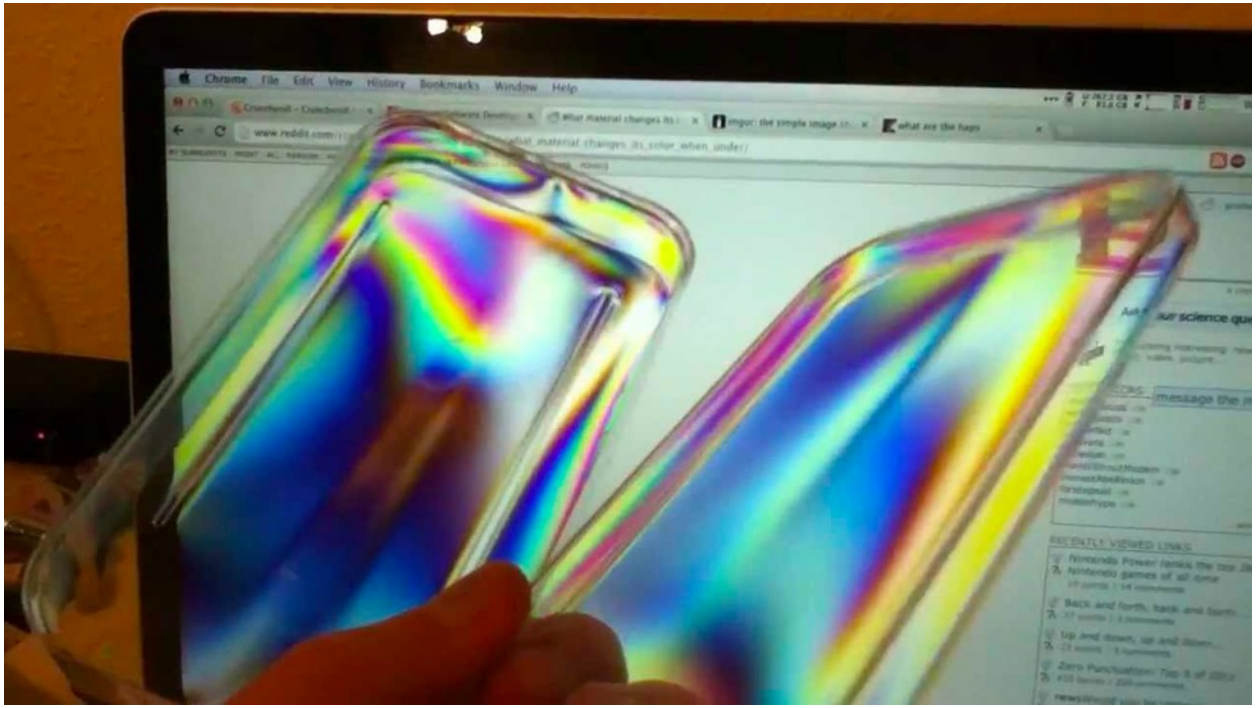
PART 1: Course Overview Rendering

- **Overview of real-world polarization effects**
- Polarization in nature
- RayTracer Normal vs. Polarized
- Overview on Jones Calculus
- Overview on Mueller Calculus
- Build up of the RayTracer

Polarized Sunglasses



Birefringence Effects



Sky is differently polarized depending on time of day

Polarization in Art

Course Overview

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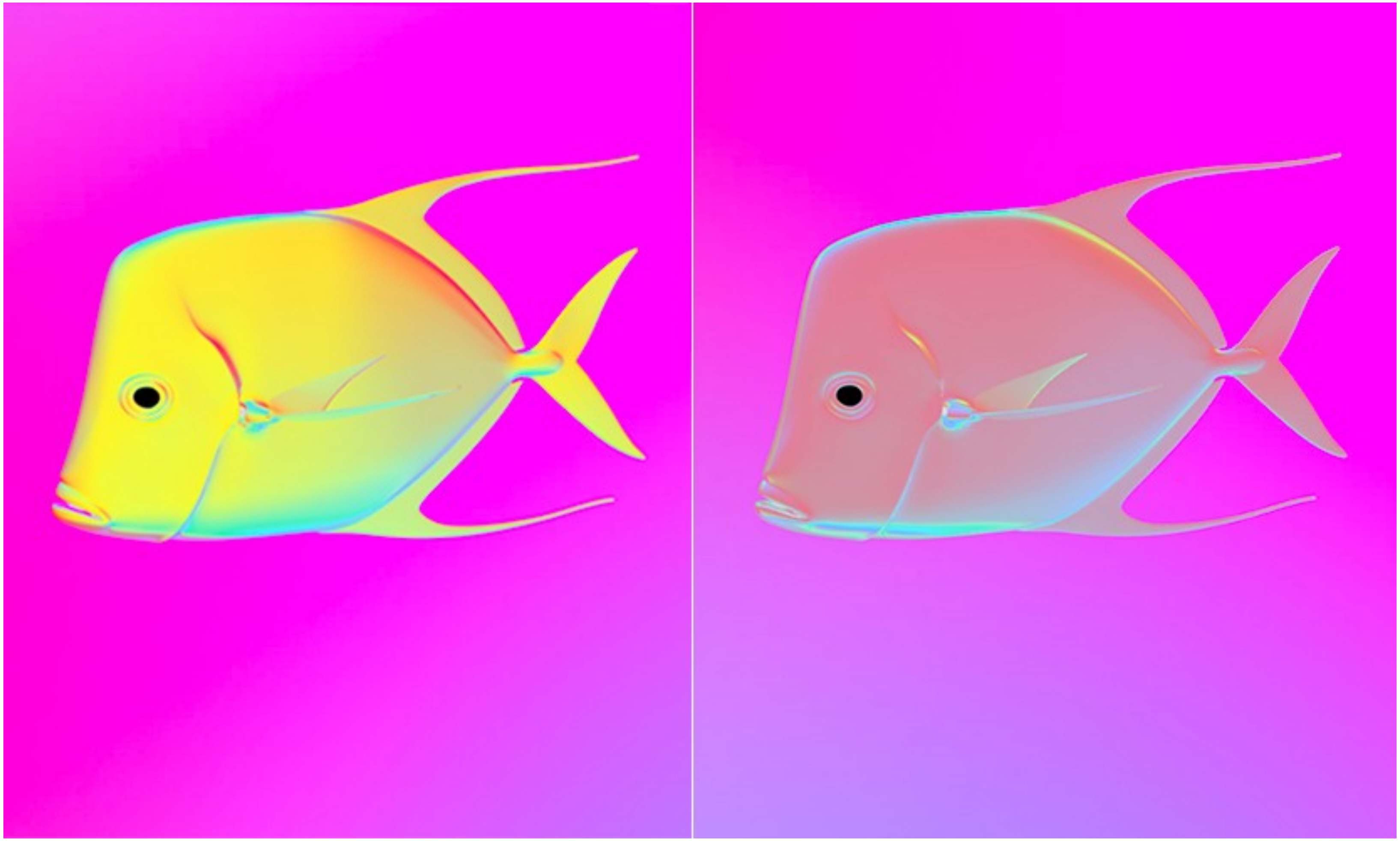
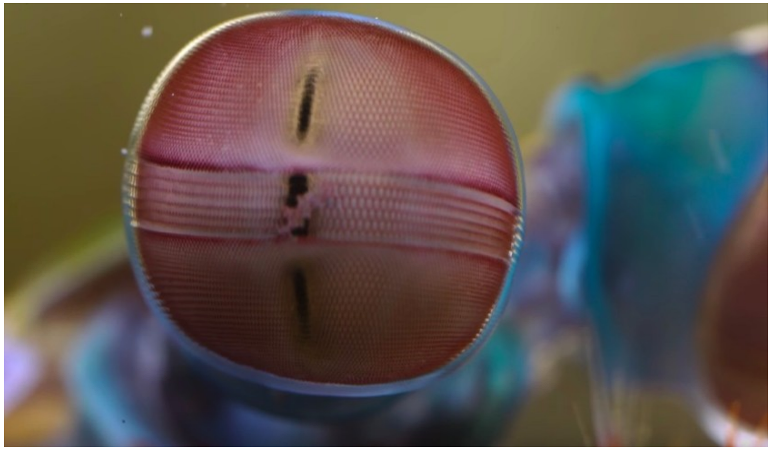
Fish skin polarization

Simulated Polarization

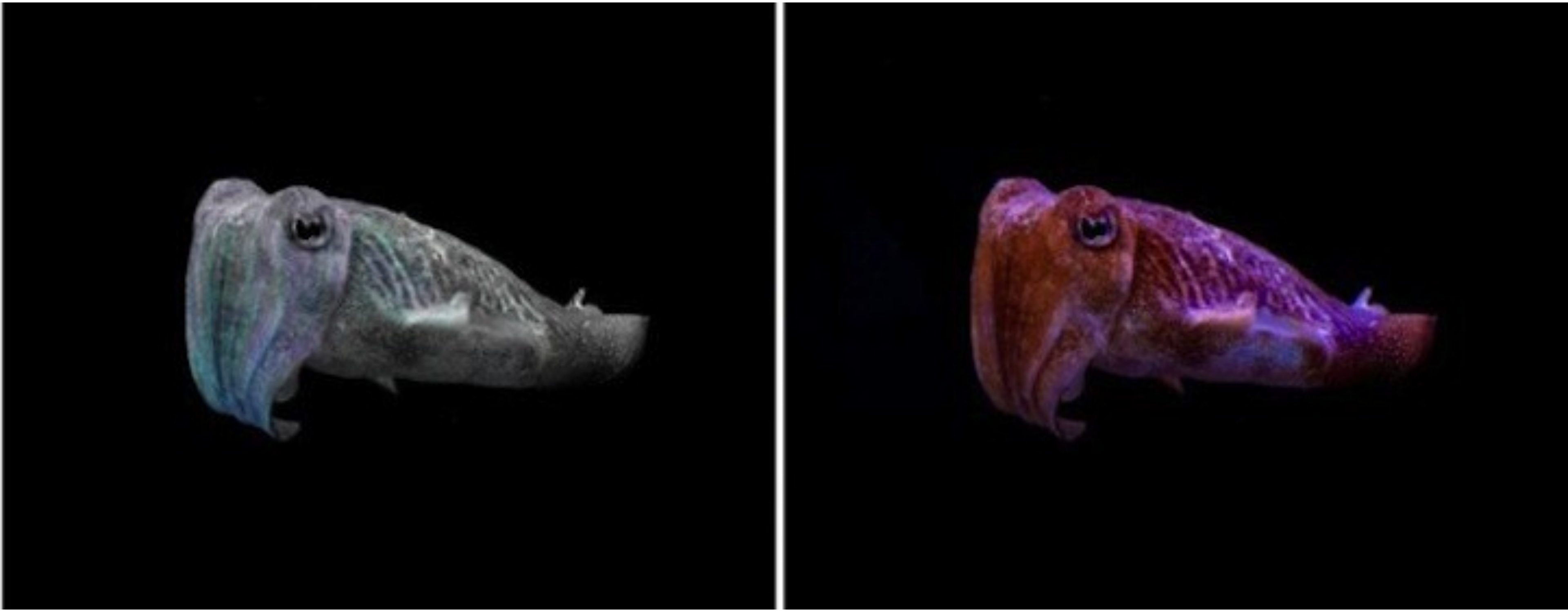


Mantis Shrimp

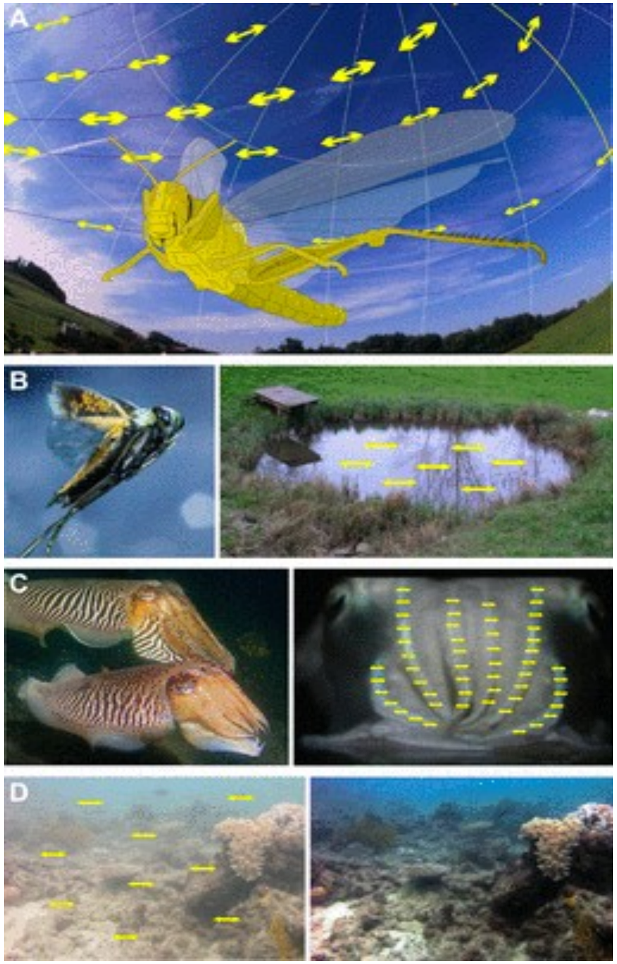


Seeing and being seen – the butterfly

Polarized Skin for communication – the Cuttlefish



Polarization for Navigation



Can invertebrates see the e-vector of polarization as a separate modality of light?
Thomas Labhart
Journal of Experimental Biology 2016 219: 3844-3856; doi: 10.1242/jeb.139899

Course Overview

- Overview of real-world polarization effects
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- **Ray Tracer Normal vs. Polarized**
- Overview on Calculus and Formulae
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Ray Tracer Normal vs. Polarized

Your Turn!

- Live demo for standard Raytracer
- Live demo for polarization aware Raytracer

Course Overview

- Overview of real-world polarization effects
- Polarization in nature
- RayTracer Normal vs. Polarized
- **Overview on Calculus and Formulae**
- Build up of the RayTracer
- Use Case Scenario: Polarized Light for improving Stereo Vision

Stokes Vector Representation of incident polarized light

$$S_0 = I_0 + I_{90}$$

$$S_1 = I_0 - I_{90}$$

$$S_2 = I_{45} - I_{135}$$

S_3 = Chirality, not measured

$I_0, I_{45}, I_{90}, I_{135}$

From a polarization aware camera such as PolarCam/ Bumblebee with Polarizer

Stokes Vector Representation of incident polarized light

(Spherical coordinate representation)

S_0 = I

S_1 = Ip cos 2¢ cos 2x

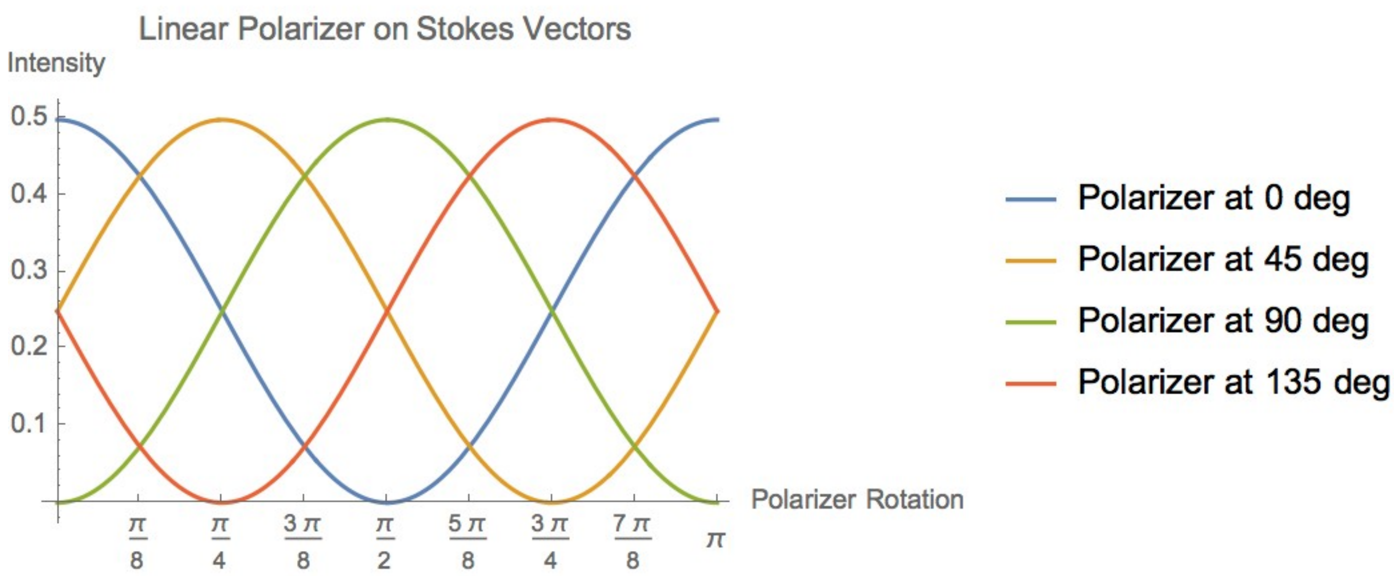
S_2 = Ip sin 2¢ cos 2x

S_3 = Ip sin 2x

I the Intensity,p the DOLP, ¢ the AOP, x the ellipticity - not measured

Source:The Poincare Sphere https://spie.org/publications/fg05_p10-11_poincare_sphere

Linear Polarizer vs. Intensity



Mueller Matrix representation of light-transport through glass

- Light transport for transmissive and reflective glass

$$M_{\text{reflect}} \cdot S_{\text{reflect}} + M_{\text{transmit out}} \cdot M_{\text{transmit in}} \cdot S_{\text{transmit}}$$

- Unknown incident light S_{reflect}, S_{transmit}, potentially already polarized

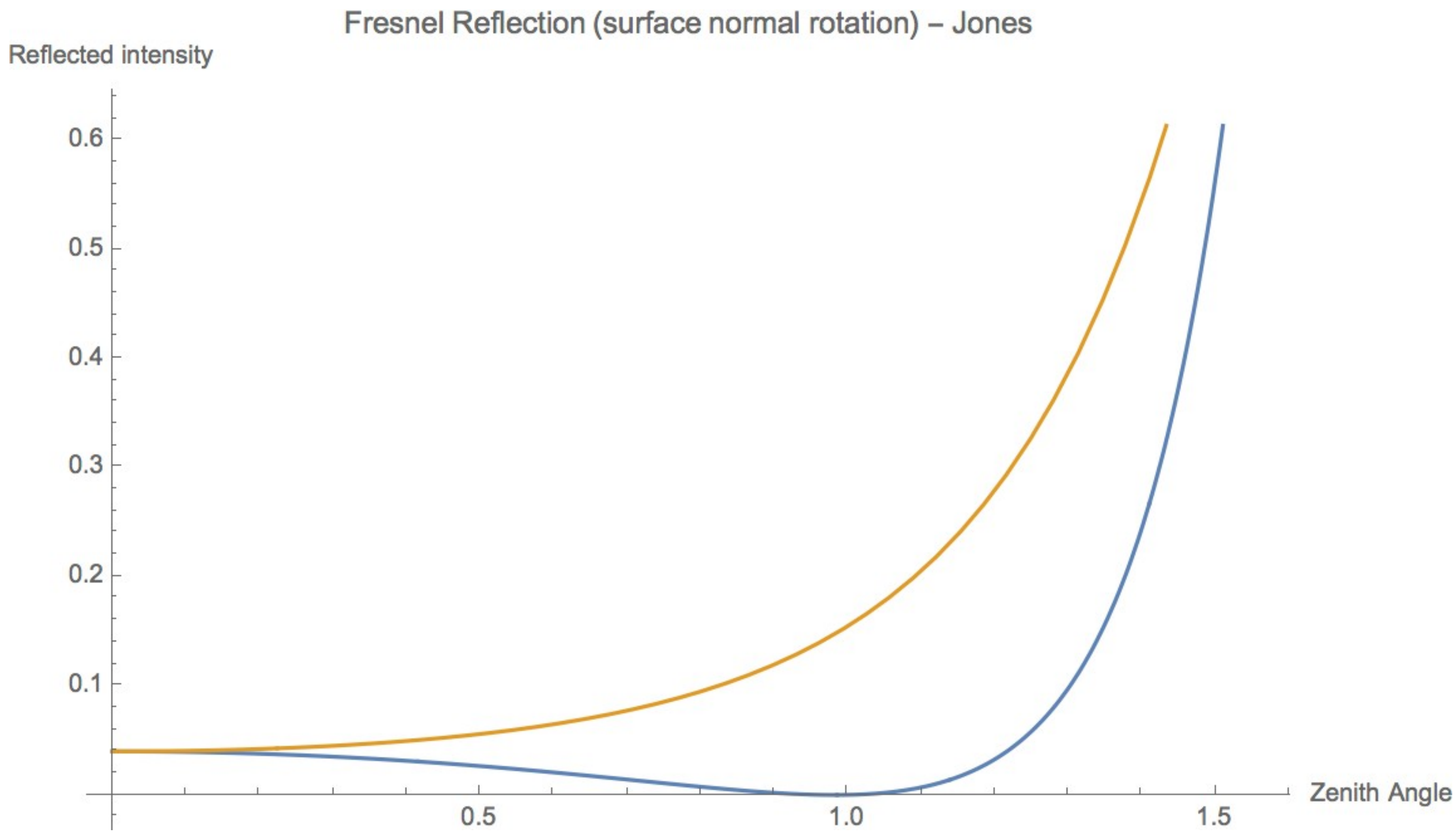
$$M_{\text{reflect}} =$$

$$\frac{1}{2}\begin{pmatrix} \cos^2(\theta-)+\cos^2(\theta+) & \cos^2(\theta-)-\cos^2(\theta+) & 0 & 0 \\ \cos^2(\theta-)-\cos^2(\theta+) & \cos^2(\theta-)+\cos^2(\theta+) & 0 & 0 \\ 0 & 0 & -2\cos(\theta-)\cos(\theta+) & 0 \\ 0 & 0 & 0 & -2\cos(\theta-)\cos(\theta+) \end{pmatrix}\left(\frac{\tan(\theta-)}{\sin(\theta+)}\right)^2$$

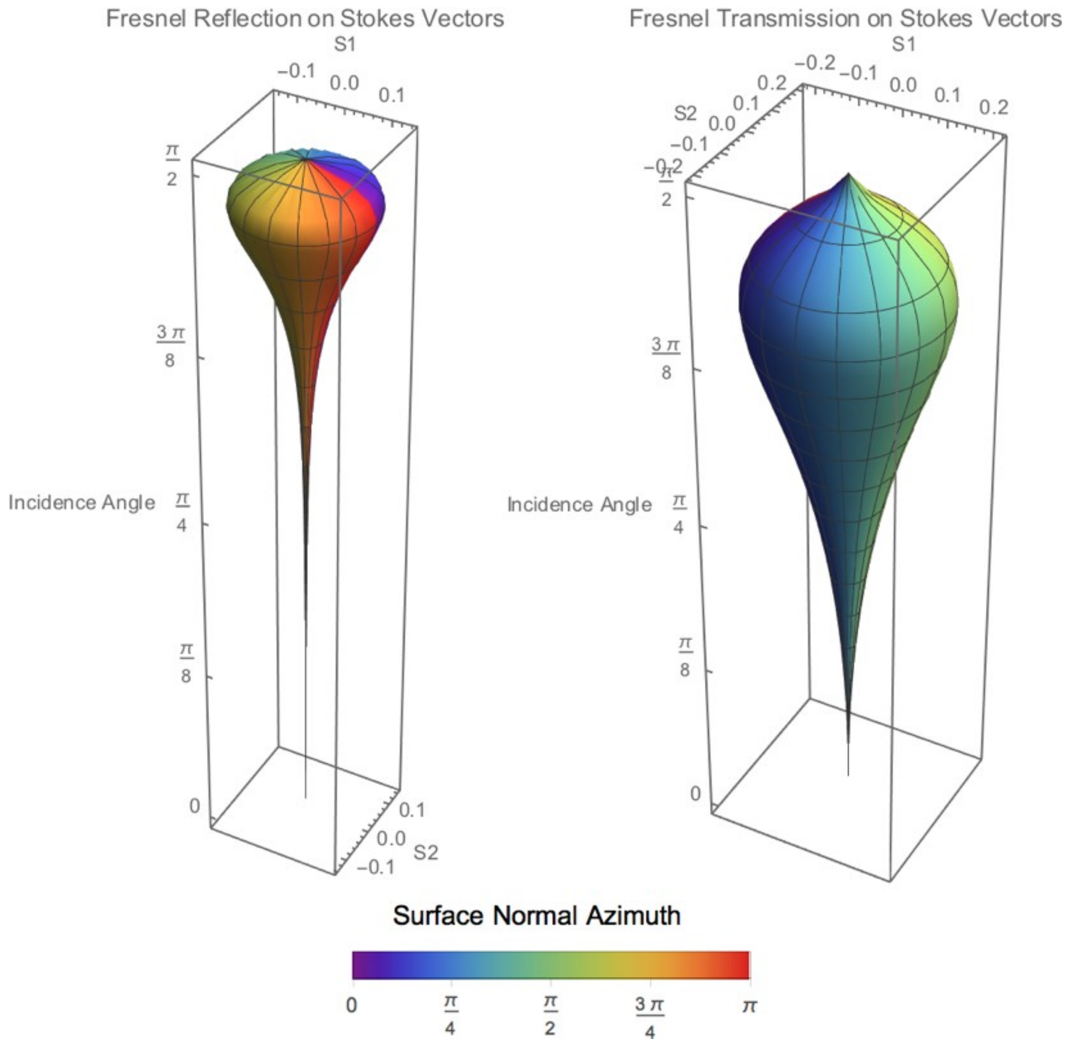
$$\theta_+ = \theta + \sin^{-1}\left(\frac{n_1 \sin(theta)}{n_2}\right)$$

$$\theta_- = \theta - \sin^{-1}\left(\frac{n_1 \sin(theta)}{n_2}\right)$$

Fresnel Reflection Terms



Reflection and Transmission Intensity



Jones representation of light-transport for reflective surfaces

$$\boldsymbol{E}_{0^\circ} = (1,0),\ \boldsymbol{E}_{90^\circ} = (0,1) \text{ and } \boldsymbol{E}_{45^\circ} = (1,1)\cdot\frac{1}{\sqrt{2}}.$$

$$M = \begin{pmatrix} rtm & 0 \\ 0 & rte \end{pmatrix}$$

$$M_\theta = \begin{pmatrix} cos\theta & -sin\theta \\ sin\theta & cos\theta \end{pmatrix} \cdot \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} cos(-\theta) & -sin(-\theta) \\ sin(-\theta) & cos(-\theta) \end{pmatrix}$$

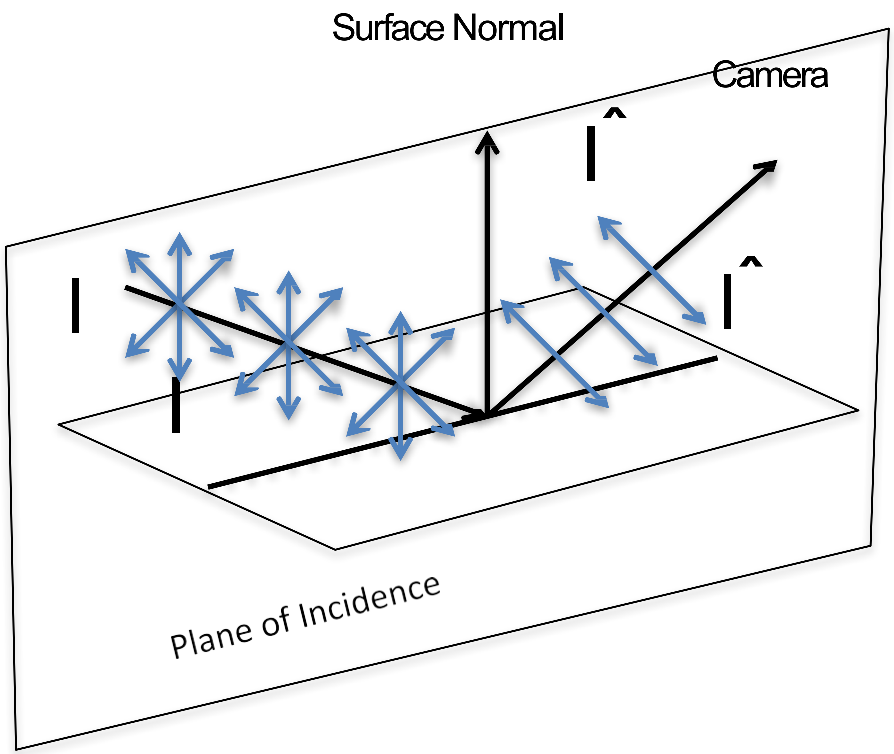
$$Na = 1/\sqrt{cos(\theta)^2/n^2 + sin(\theta)^2/n_1^2}$$

$$xe = (n_1 * sin(\theta))^2, \quad xm = (Na * sin(\theta))^2$$

$$rte = \frac{n_1*cos(\theta)-\sqrt{n_2^2-xe}}{n_1*cos(\theta)+\sqrt{n_2^2-xe}}, \quad rtm = \frac{n_1*n_1*\sqrt{n_2^2-xm}-n_2*n_2*\sqrt{n_1^2-xm}}{(n_1*n_1)*\sqrt{n_2^2-xm}+n_2*n_2*\sqrt{n_1^2-xm}}$$

Light-Surface Interaction

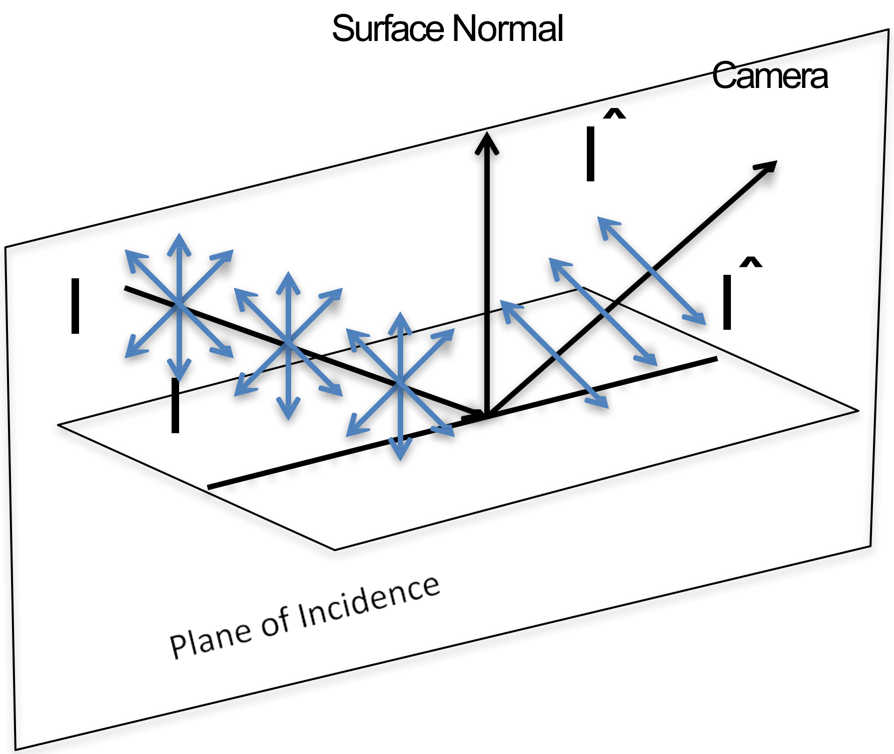
Polarization behavior changes at specular surfaces



Left view, Polarizer at 0 degrees

Light-Surface Interaction

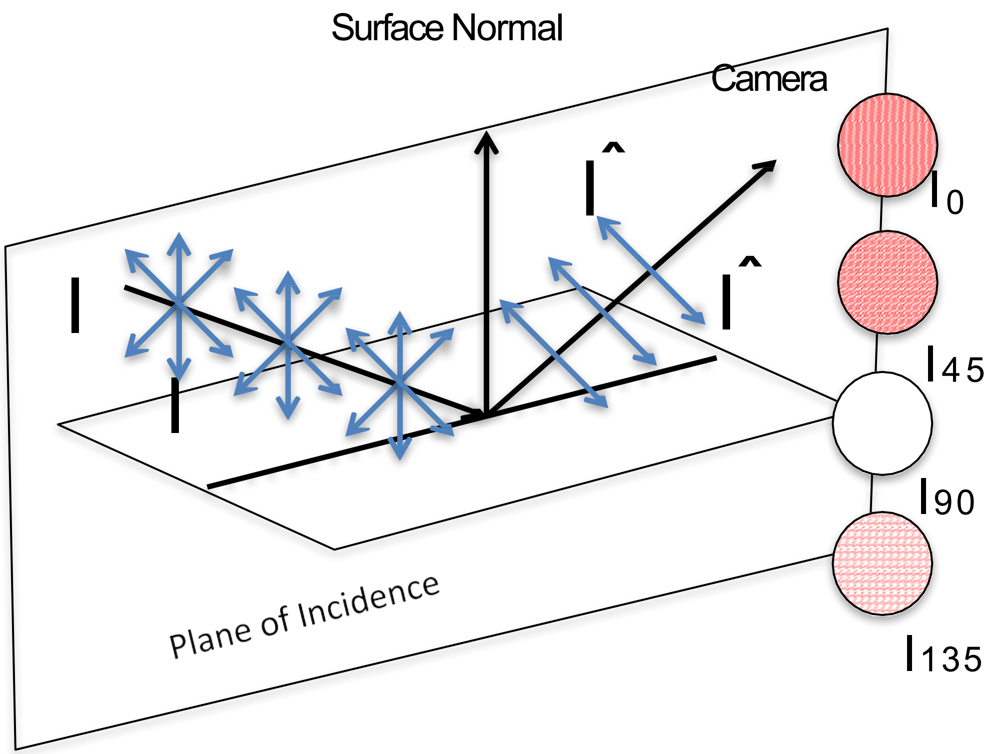
Polarization behavior changes at specular surfaces

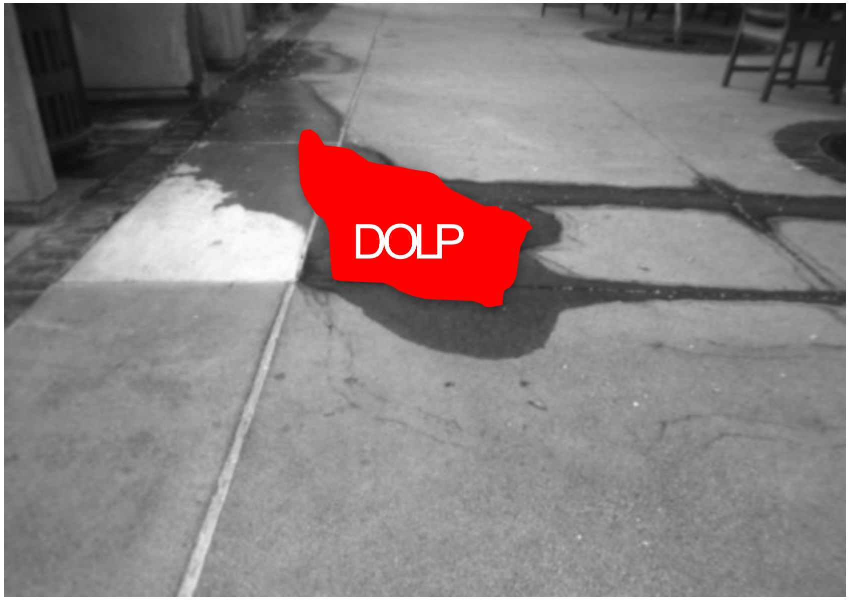


Left view, Polarizer at 90 degrees

Light-Surface Interaction

Polarization behavior changes at specular surfaces



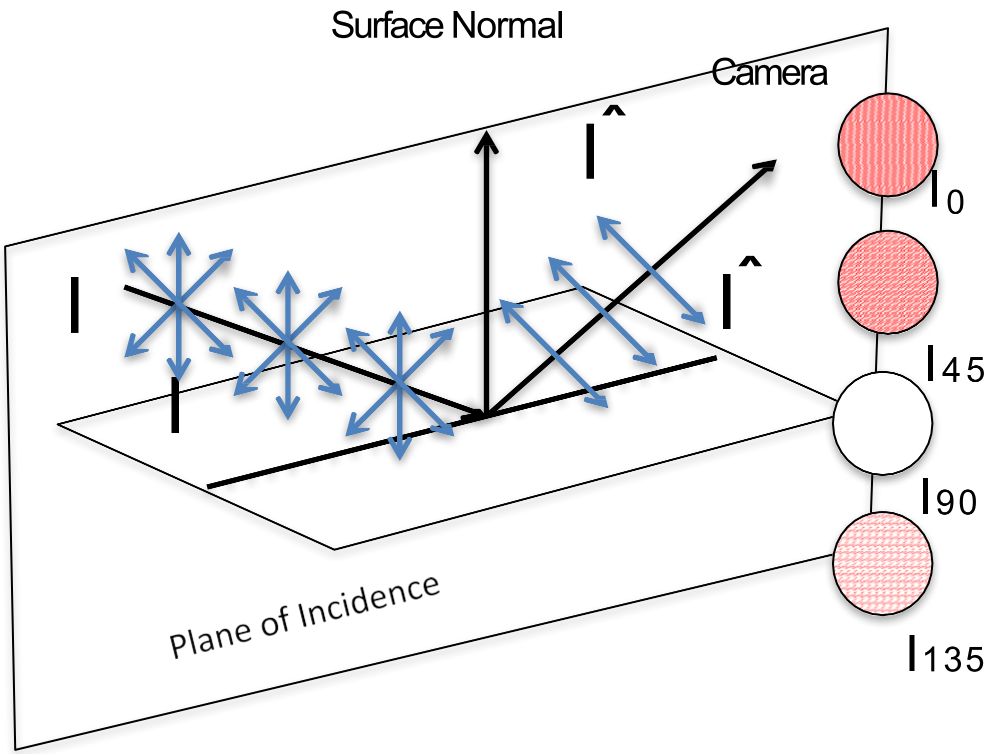


Left view, Polarizer at 0 degrees

$$DOLP = \frac{\sqrt{(I_{90} - I_0)^2 + (I_{135} - I_{45})^2}}{I_{90} + I_0}$$

Light-Surface Interaction

Polarization behavior changes at specular surfaces



Left view, Polarizer at 0 degrees

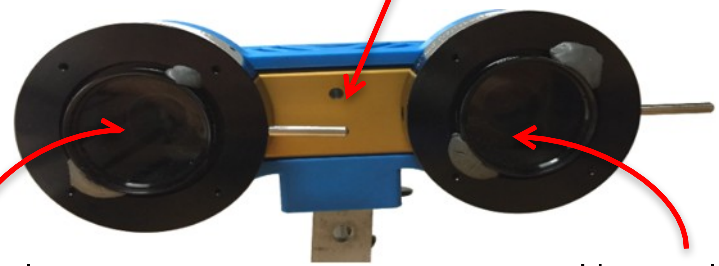
$$AOP = \frac{1}{2} ArcTan\left(\frac{I_{135} - I_{45}}{I_{90} - I_{0}}\right)$$

Surface normal is constrained to lie in plane of incidence

How to capture polarization

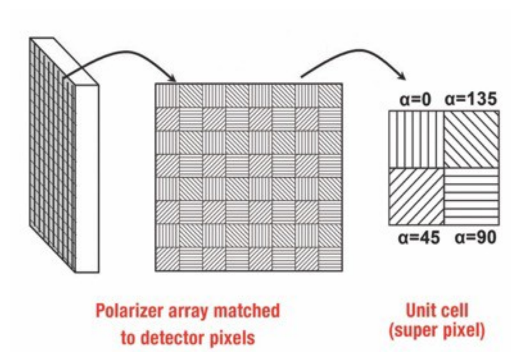
Polarization behavior changes at specular surfaces

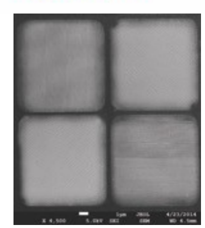
PointGrey Bumblebee 2



Linear polarizer (arbitrary rotation)

Linear polarizer (arbitrary rotation)





Course Overview

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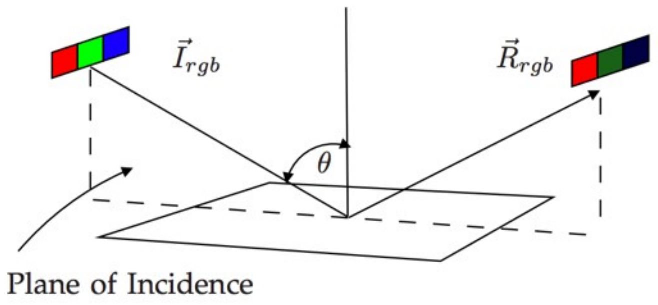
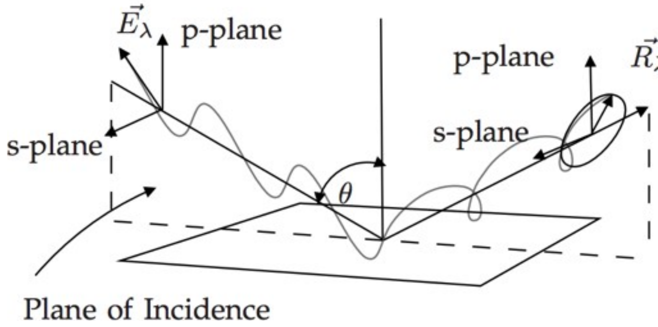
- **Build up of the Ray Tracer**

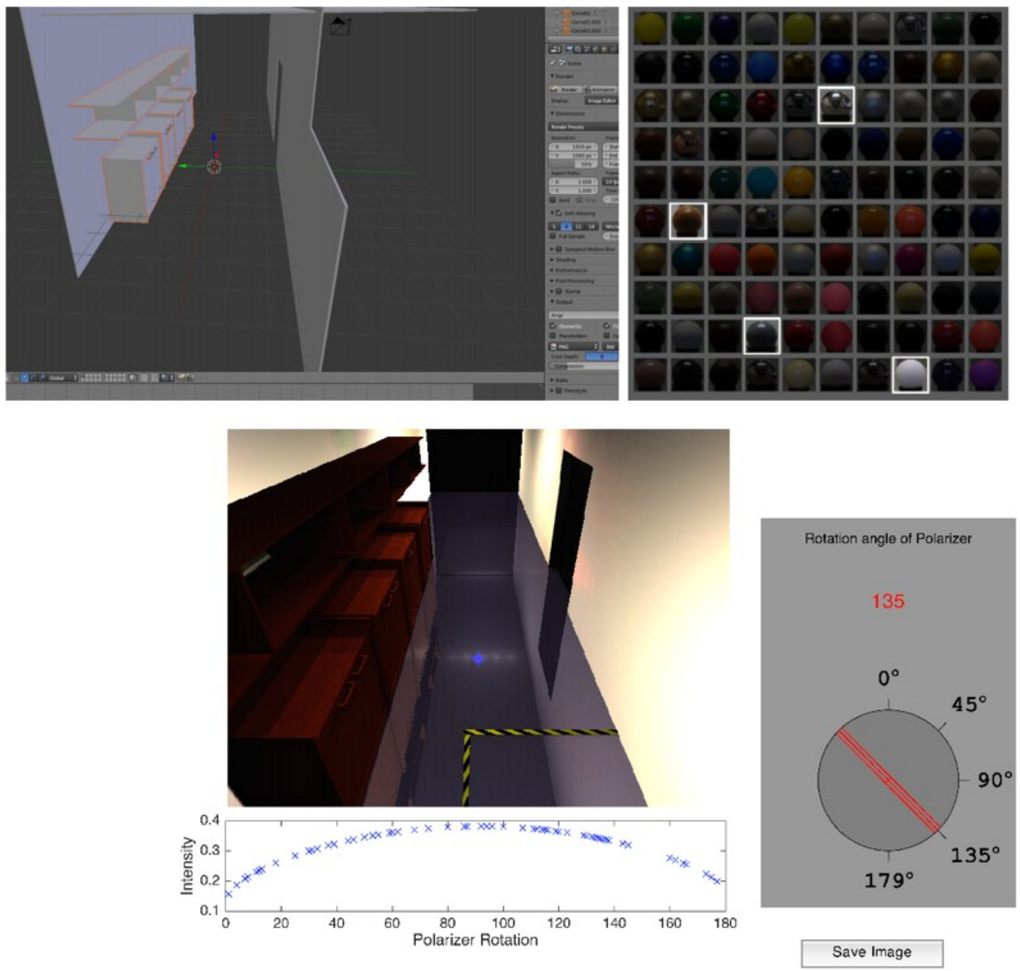
Take Whitted RT and alter the following

- RGB vector to Stokes/Jones
- Fresnel for Reflectance
- Fresnel for Transmittance
- Matrix interaction for Reflectance
- Matrix interaction for Transmittance
- Linear Polarizer for Viewing

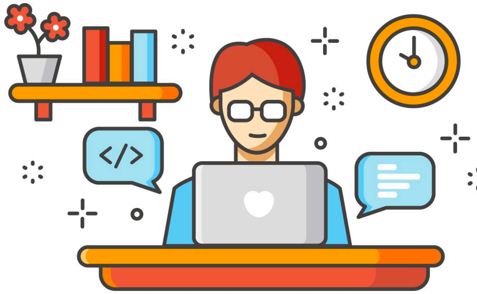




Simulate indoor polarized light transport in hallway scene



Step 1) Change RGB to Stokes

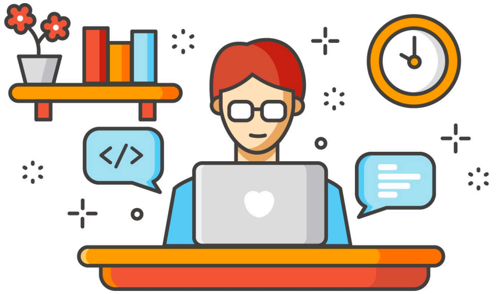


Your Turn!

- Please open the first code sample and follow the instructions

- You will be able to generate an image with enhanced information (Stokes/Jones) after completion of the instructions

Step 2) Add the Fresnel Term



Your Turn!

- Please open the second code sample and follow the instructions

- You will be able to generate the angular plot that shows slightly different behavior for perpendicular and parallel reflectance.

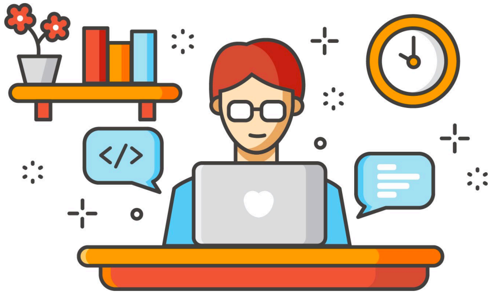
Step 3) Add the Matrix interaction

Your Turn!

- Please open the third code sample and follow the instructions

- You will be able to model the reflectance interaction of a polarized light vector with Fresnel behavior now

Step 4) Implement the linear polarizer



Your Turn!

- Please open the fourth code sample and follow the instructions

- You will be able to simulate a linear polarizer in front of your camera that you can rotate to a given angle.

Break

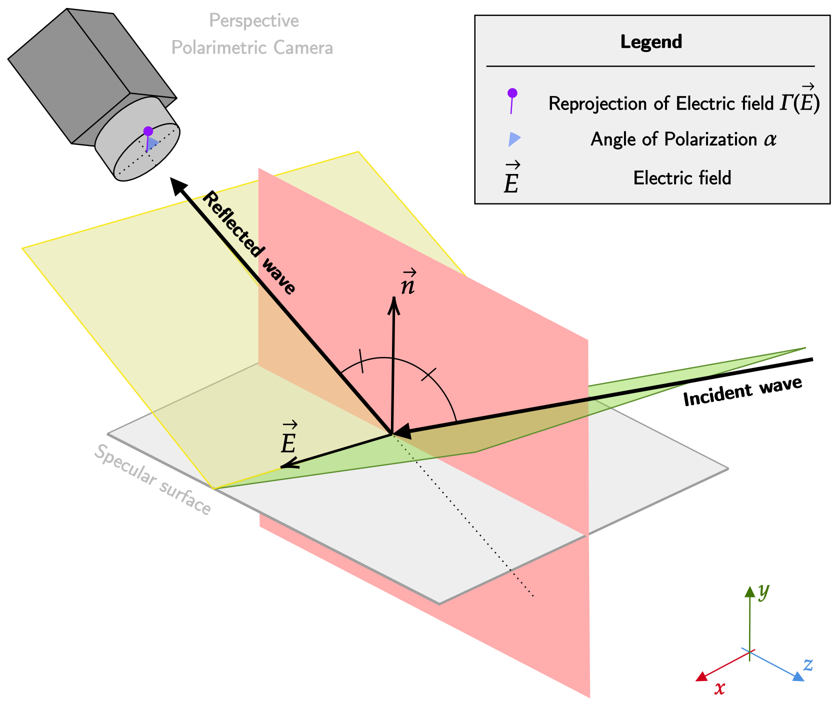
This concludes the first part of the course

Part 2 - Computer Vision

- Polarization basics
    - An unconventional sensor
    - Dealing with super-pixels
    - From raw information to informative images
- Image representation
- Applications in Computer Vision
- Dealing with the data - Augmentation

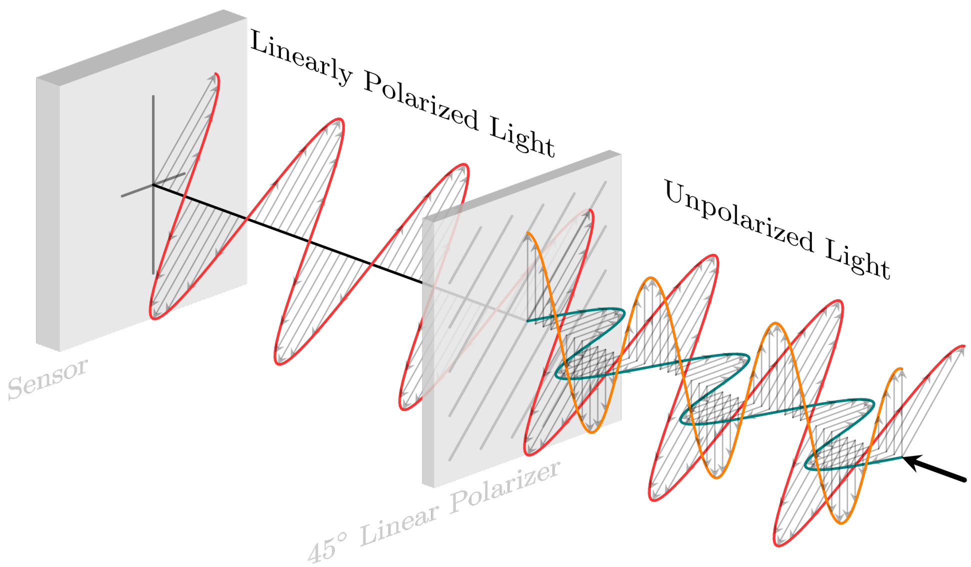
Polarization Basics

Polarimetry in Computer Vision



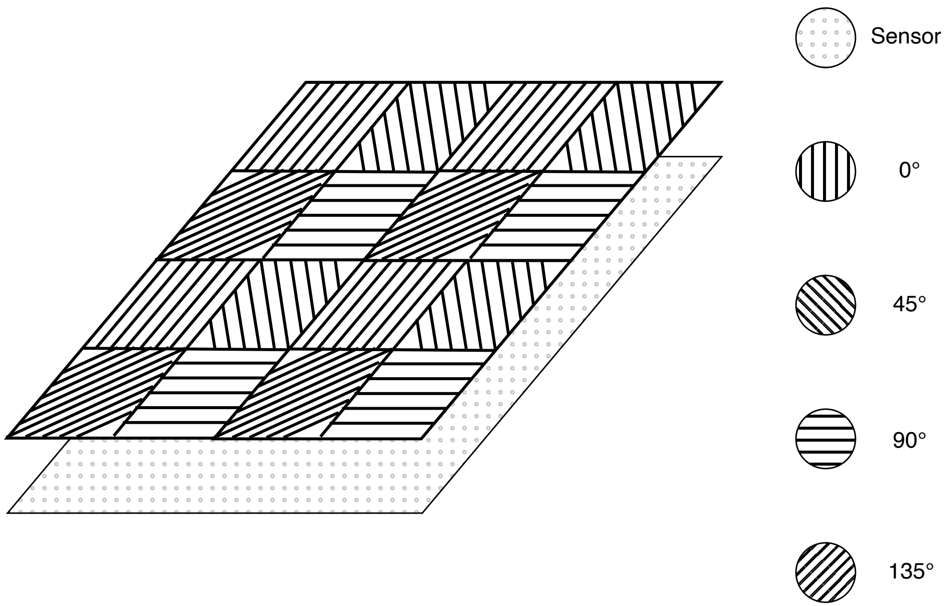
An unconventional sensor

Polarimetry in Computer Vision



An unconventional sensor

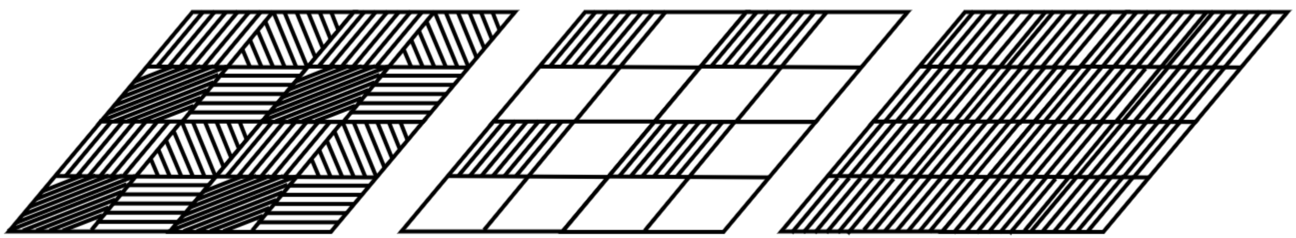
Polarimetry in Computer Vision



Dealing with super-pixels

Polarimetry in Computer Vision

- The extracted raw images are sparse due to pixel organization.
  - We subsequently need to interpolate[1,2] images (bilinear, bicubic,…).



1 - Bradley M. Ratliff, Charles F. LaCasse, and J. Scott Tyo , Interpolation strategies for reducing IFOV artifacts in microgrid polarimeter imagery

2 - https://github.com/BlanchonMarc/InterPol

Dealing with super-pixels

Your Turn!

Polarimetry in Computer Vision

Please open the first code sample and follow the instructions

Implement the function allowing to open and interpolate polarimetry.

You should obtain 4 distinct images, each representing a unique polarization angle,

and observing the same size as the original raw image.

From raw information to informative images

Polarimetry in Computer Vision

Polarimetric information is conventionally indexed to Stokes parameters S depending on the intensities of polarizers oriented at different angles $P_{\{0,45,90,135\}}$.

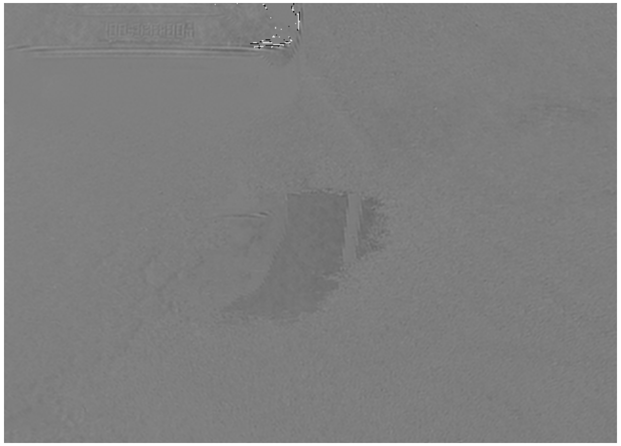
$$S = \begin{pmatrix} s_0 \\ s_1 \\ s_2 \\ s_3 \end{pmatrix} = \begin{pmatrix} P_0 + P_{90} \\ P_0 - P_{90} \\ P_{45} - P_{135} \\ 0 \end{pmatrix}, \tag{1}$$

with s_3 remaining null since the circular polarization is not acquired.

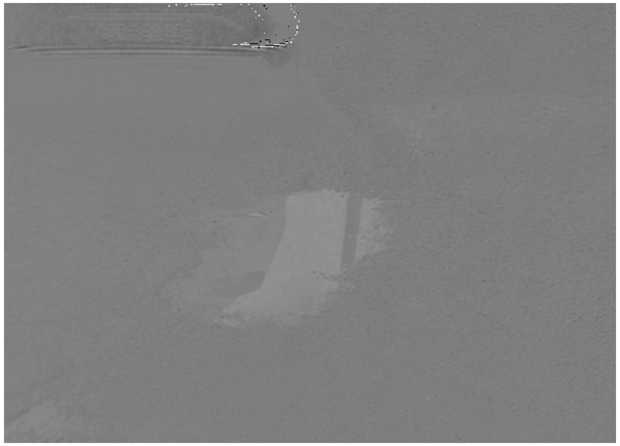
From raw information to informative images

Polarimetry in Computer Vision

S0



S1



S2

From raw information to informative images

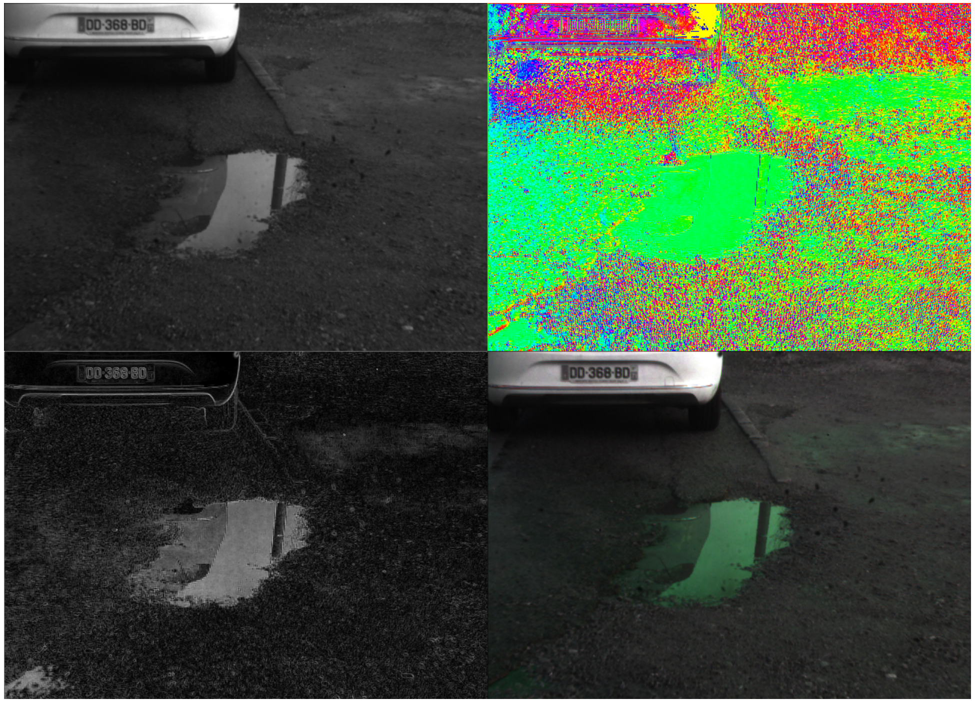
Polarimetry in Computer Vision

From Stokes parameters, one can derive three informative images characteristic of polarimetry: polarization angle α, degree of polarization ρ and intensity ι:

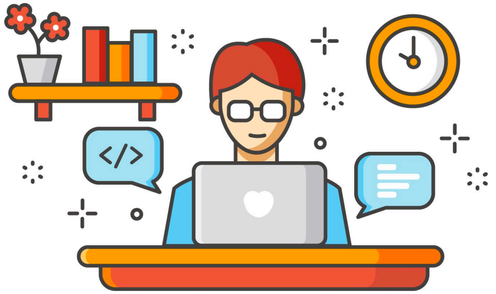
$$
\begin{cases}
\rho = \sqrt{(\frac{s_1}{s_0})^2 + (\frac{s_2}{s_0})^2} \\
\alpha = \frac{1}{2}\, arctan2(s_1, s_2) \\
\iota = \frac{P_0 + P_{45} + P_{90} + P_{135}}{2}
\end{cases}
.
$$

From raw information to informative images

Polarimetry in Computer Vision



From raw information informative images



Your Turn!

Polarimetry in Computer Vision

Please open the second code sample and follow the instructions

Implement the Stokes parameters function and the Polarization parameters function.

You should obtain two functions, one can return the three normalized Stokes parameters.

The other returns the intensity, the degree and the angle of polarization.

Image representation

Polarimetry in Computer Vision

- How can we use those images?
- What do they represent?
- Can we map this data to a specific colour space such that the image is representing the physics?

Image representation

Polarimetry in Computer Vision

- Raw concatenation

Image representation

Polarimetry in Computer Vision

- Hue - Luminance - Saturation (HSL) representation.

Image representation

Polarimetry in Computer Vision

Informative images are combined as proposed by Wolff and Andreou for display:

$$H \longrightarrow 2 * \mathrm{AoP}, \quad S \longrightarrow \mathrm{DoP}, \quad L \longrightarrow I/255.$$

L. B. Wolff and A. G. Andreou, “Polarization camera sensors,” Image and Vision Computing , vol. 13, no. 6, pp. 497–510, 1995.

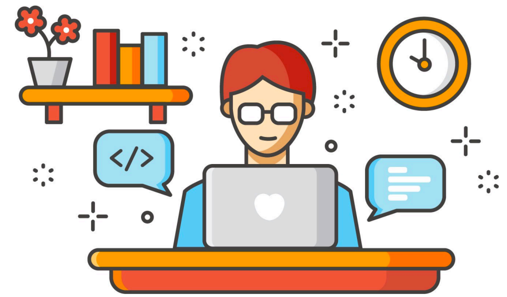
Image representation

Polarimetry in Computer Vision

What are the drawbacks of those image representations?

Image representation

Polarimetry in Computer Vision



Your Turn!

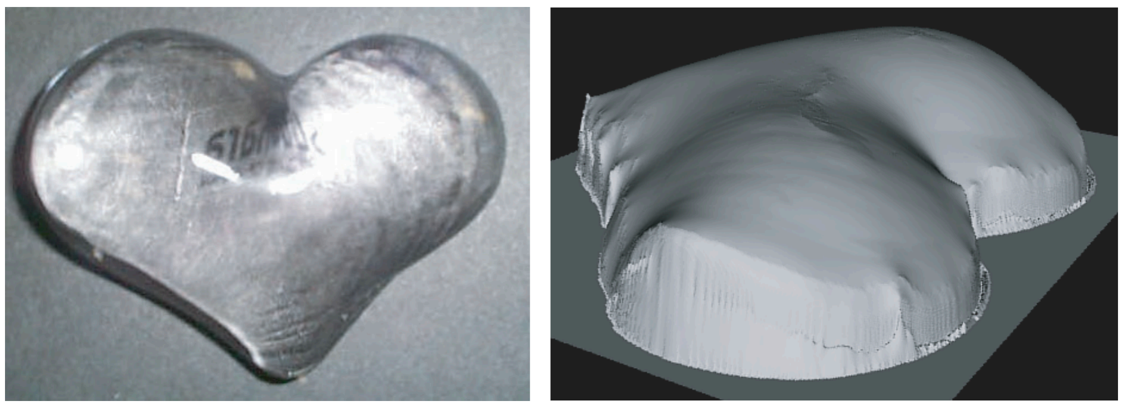
Please open the third code sample and follow the instructions

Implement the concatenation and HSL image representation using the informative images.

Applications in Computer Vision

Polarimetry in Computer Vision

- Shape from Polarization - Transparent objects



(a) (b)

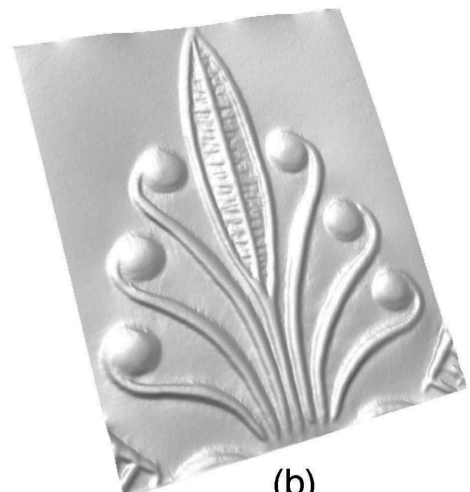
Miyazaki, Daisuke, Masataka Kagesawa, and Katsushi Ikeuchi. "Transparent surface modeling from a pair of polarization images." IEEE Transactions on Pattern Analysis and Machine Intelligence 26, no. 1 (2004): 73-82.

Applications in Computer Vision

Polarimetry in Computer Vision

- Shape from Polarization - Specular / Metallic objects

(a)



(b)

Morel, Olivier, Christophe Stolz, Fabrice Meriaudeau, and Patrick Gorria. "Active lighting applied to three-dimensional reconstruction of specular metallic surfaces by polarization imaging." Applied optics 45, no. 17 (2006): 4062-4068.

Applications in Computer Vision

Polarimetry in Computer Vision

- Pixel-wise semantic segmentation

Blanchon, Marc, Olivier Morel, Yifei Zhang, Ralph Seulin, Nathan Crombez, and Désiré Sidibé. "Outdoor scenes pixel-wise semantic segmentation using polarimetry and fully convolutional network." 2019

Applications in Computer Vision

Polarimetry in Computer Vision

- Pixel-wise semantic segmentation with multimodal fusion

Zhang, Yifei, Olivier Morel, Marc Blanchon, Ralph Seulin, Mojdeh Rastgoo, and Désiré Sidibé. "Exploration of Deep Learning-based Multimodal Fusion for Semantic Road Scene Segmentation." 2019.

Applications in Computer Vision

Polarimetry in Computer Vision

- Classification

(a) Detection results before fine tuning on (I_0, I_{45}, I_{135}), (S_0, S_1, S_2) and (S_0, AOP, DOP)

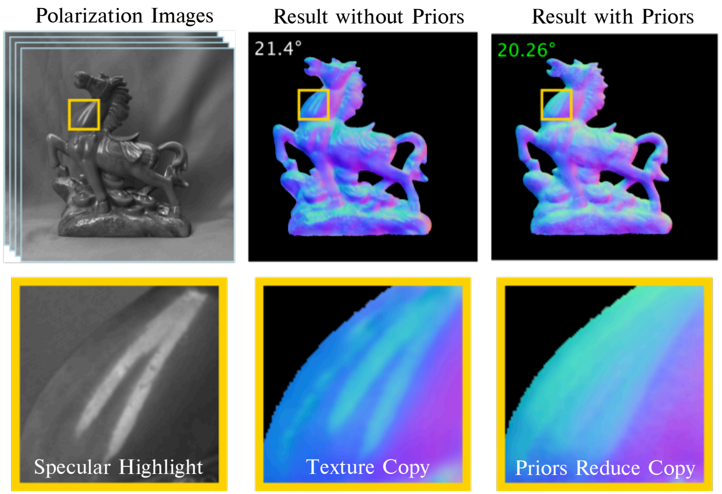
(b) Detection results after fine tuning on (I_0, I_{45}, I_{135}), (S_0, S_1, S_2) and (S_0, AOP, DOP)

Blin, Rachel, Samia Ainouz, Stéphane Canu, and Fabrice Meriaudeau. "Road scenes analysis in adverse weather conditions by polarization-encoded images and adapted deep learning." In 2019 IEEE Intelligent Transportation Systems Conference (ITSC), pp. 27-32. IEEE, 2019.

Applications in Computer Vision

Polarimetry in Computer Vision

- Deep Learning based Shape from Polarimetry



Kalra, Agastya, Vage Taamazyan, Supreeth Krishna Rao, Kartik Venkataraman, Ramesh Raskar, and Achuta Kadambi. "Deep polarization cues for transparent object segmentation." In Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition, pp. 8602-8611. 2020.

Dealing with the data - Augmentation

Polarimetry in Computer Vision

- Deep Learning and new learning based approach requires a sufficient amount of data.
- There is few dataset in physic based modality.
    - They are very often specialized and/or contain few images[1].

1 - Polabot - http://vibot.cnrs.fr/polabot.html

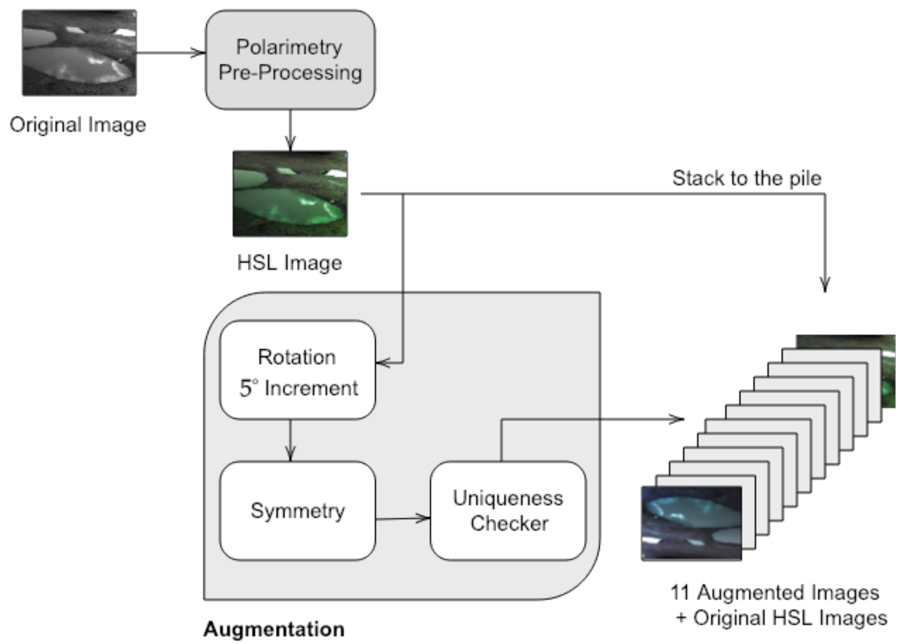
Dealing with the data - Augmentation

Polarimetry in Computer Vision

- The solution commonly adapted to deep learning and which is frequently used is **augmentation**.
  - It avoids overfitting
  - The principle is to create new images.
  - The augmentation **must** maintain the physical integrity of the modality.
    - Understanding the physics of the sensor.
    - Adapting the transformations.

Dealing with the data - Augmentation

Polarimetry in Computer Vision



Blanchon, Marc, Olivier Morel, Fabrice Meriaudeau, Ralph Seulin, and Désiré Sidibé. "Polarimetric image augmentation." arXiv preprint arXiv:2005.11044 (2020).

Dealing with the data - Augmentation

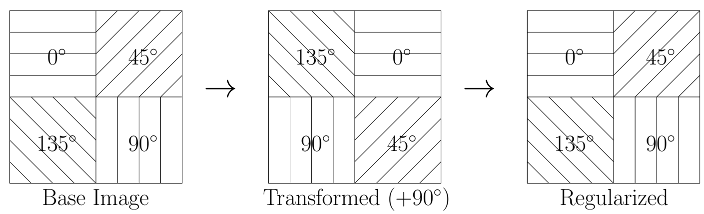
Polarimetry in Computer Vision

- Two types of augmentation will be discussed.
  - Rotation
  - Flipping

Dealing with the data - Rotation

Polarimetry in Computer Vision

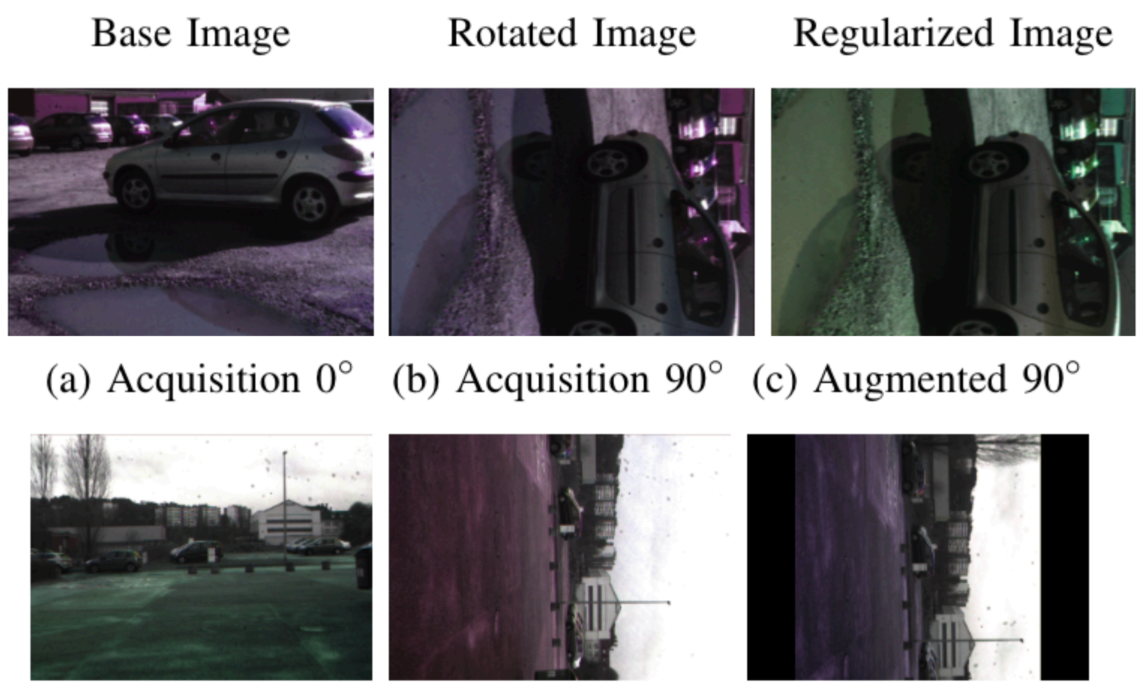
- Let's remember the pixel organization in polarimetry. Let's adapt the rotation to keep the polarimetric information.



$$H_{\text{rotated}} = R_\theta(H_{prev} - 2 * \mathbf{1}\theta).$$

Dealing with the data - Rotation

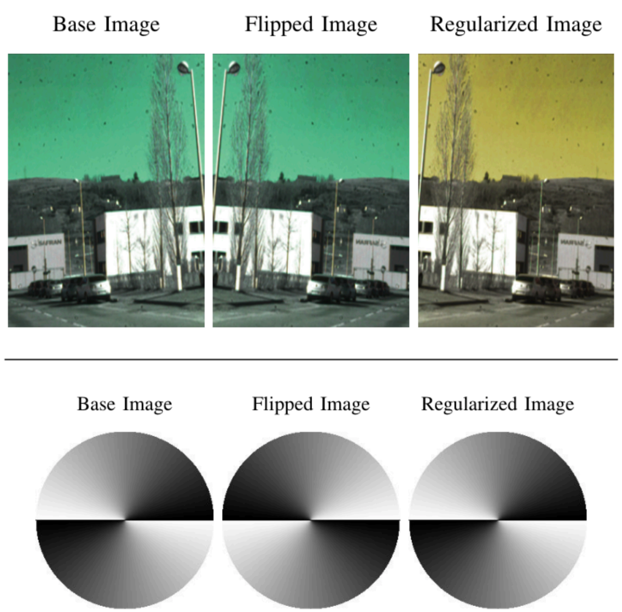
Polarimetry in Computer Vision



Dealing with the data - Flipping

Polarimetry in Computer Vision

- And let's apply the same approach to symmetry. This time, let's look at the impact of a transformation on the AoP.



$$H_{\text{flipped}} = -H_{prev}.$$

Dealing with the data - Regularizing to HSL space

Polarimetry in Computer Vision

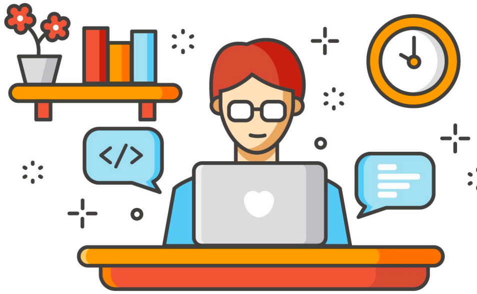
- Use the color space to your advantage.

$$H_{final} = H_{transformed} \pmod{360}$$

- Verifying the physical integrity.

$$I_\theta = \frac{\iota}{2}(1 + \rho\cos(2\phi - 2\theta)),$$

Dealing with the data - Regularizing to HSL space



Your Turn!

Polarimetry in Computer Vision

Please open the fourth code sample and follow the instructions

Implement the augmentation procedure in the designed spot.

Do not deal with uniqueness and/or combination.

Fin.

Thank you for your attention.