Problem 9
Optical Compass

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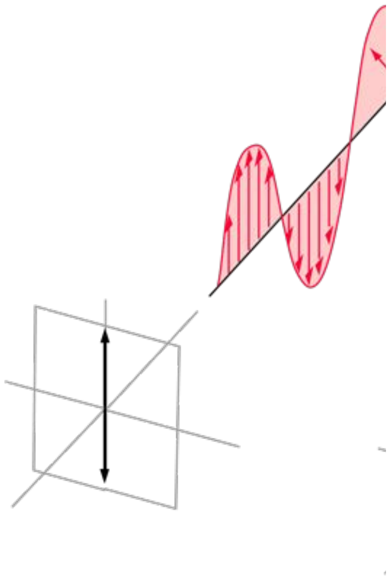
Prompt

- Bees locate themselves in space using their eyes' sensitivity to light polarization.
  - Partially polarized light
    - Polarization degree
    - Polarization direction
    - Mean intensity

1. Design an inexpensive optical compass using polarization effects to obtain the best accuracy.
2. How would the presence of clouds in the sky change this accuracy?

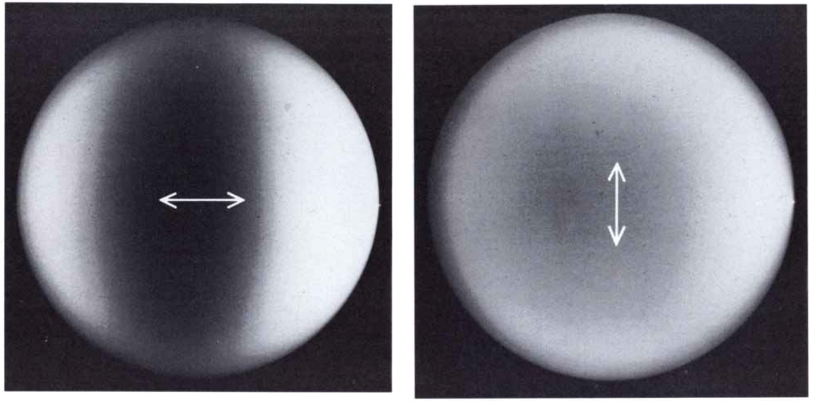
Theory: Polarization

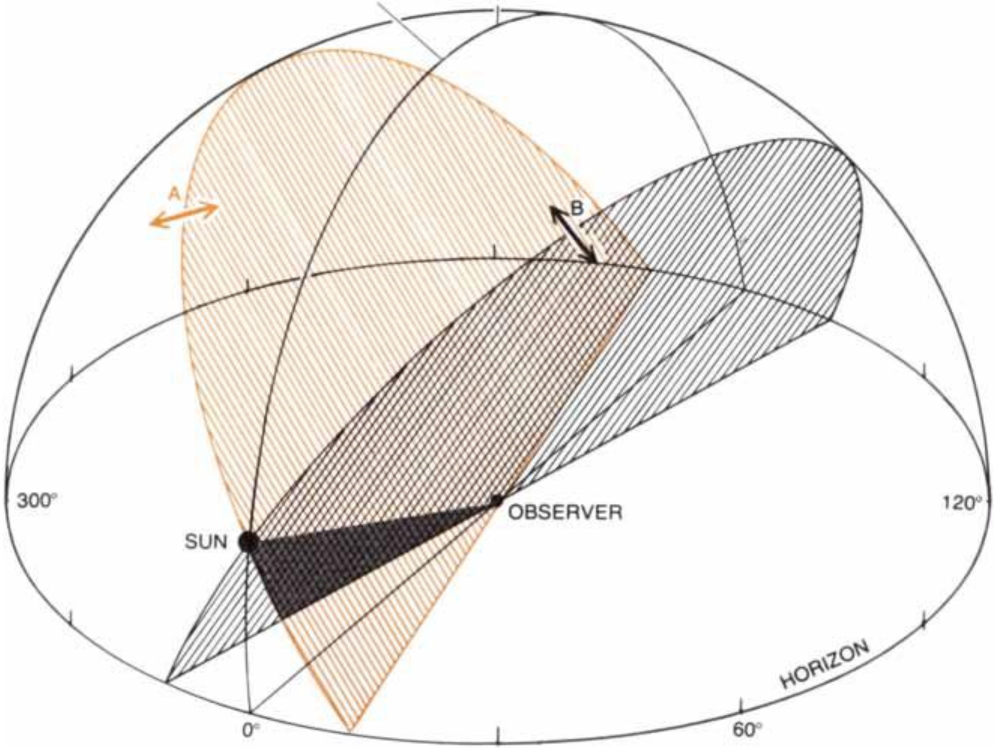
- Light: transverse electromagnetic wave
- Unpolarized: All planes of propagation equally probable
- Linearly Polarized: light in the form of a plane wave in space



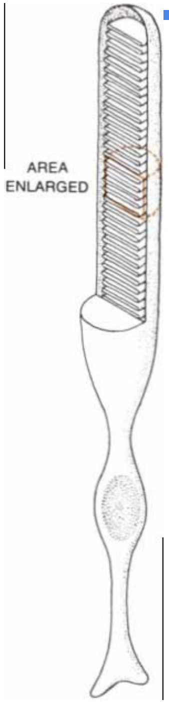
How Bees Orient: Polarized Light

- Sunlight = unpolarized
- Atmosphere ⇒ polarization
- Degree, Direction of polarization
  - Filter axis parallel to polarization axis
    - max polarized light

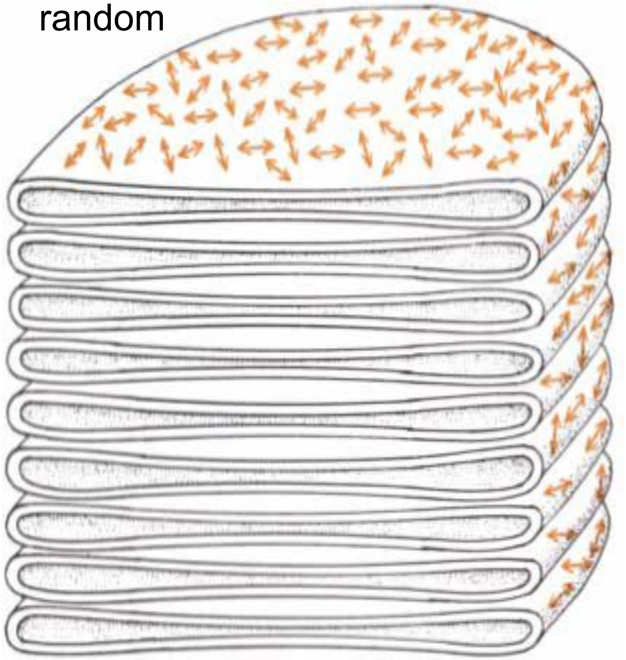


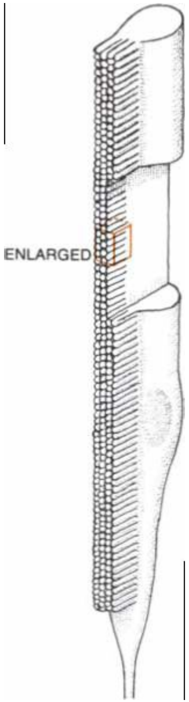


How Bees Orient: Visual Cells



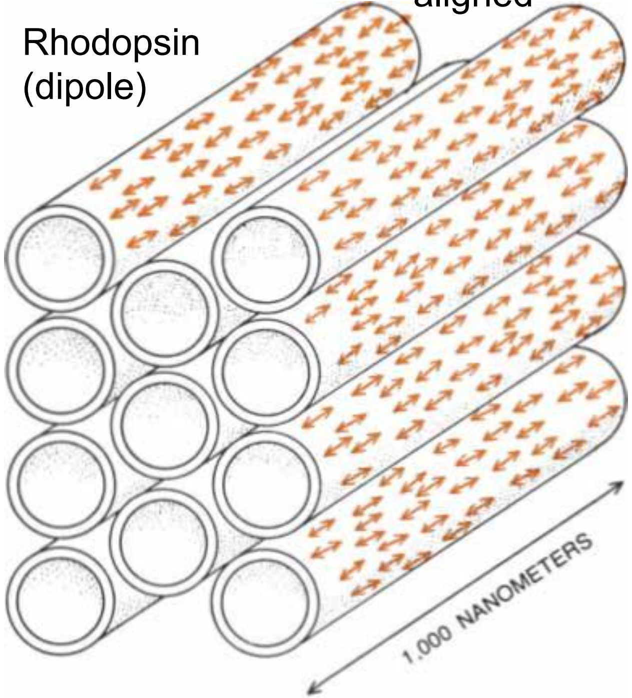
random





Rhodopsin
(dipole)

aligned



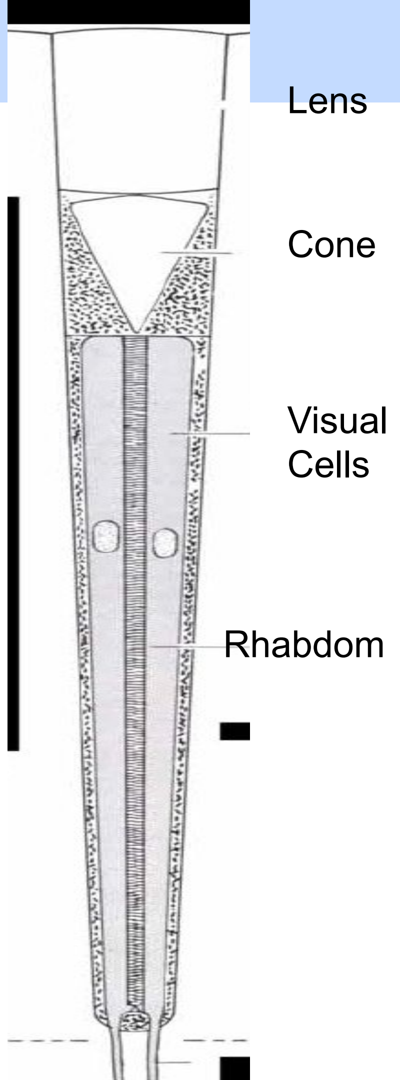
Visual cell

Photoreceptor membrane

Visual cell

How Bees Orient: Eye Functionality

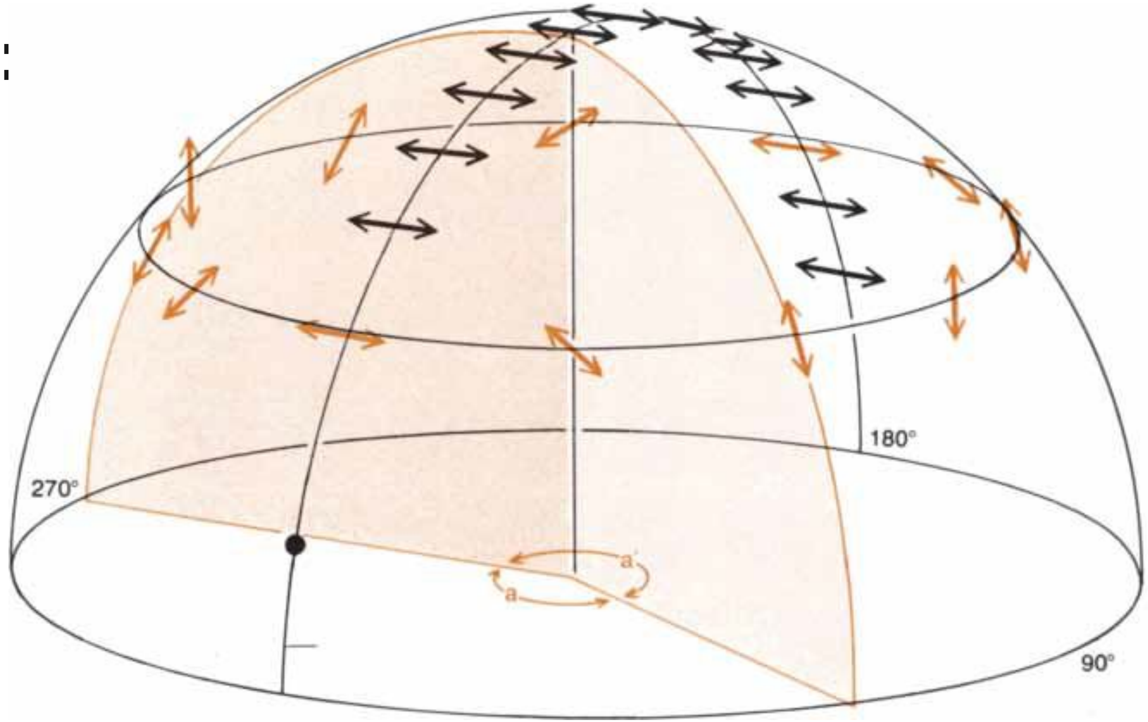
- Optical devices ⇒ wavelength sensitive
  - < 410 nm = functional in UV range (not visible)
- 1 eye ≈ 5,000 subunits, 1 subunit = 1 lens system
- 1 lens system = 8 long + 1 short visual cells
  - 3 UV receptors: 2 long + 1 short
- Rhabdom twisted 180 degrees: CC or CCW
  - UV receptors: ~~polarization~~
- Principle of Parsimony ⇒ 3 channels ⇒ polarization
  - CC & CCW short receptors = independent polarization analyzers
  - UV sensitive cell



How Bees Orient:

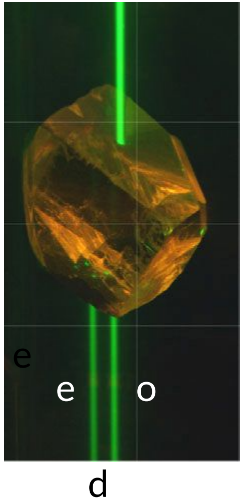
- For a high enough DOP...

- Sunstone
- Dichroic compass



Sunstone Theory: Birefringence

- Orientation-Dependent refractive indices of refraction
    - Refractive index = relative change in speed of light within material
- “Double refraction of light”: ordinary & extraordinary beam
    - walk -off distance, d



- Potential Materials: calcite crystal, packing tape

Dichroic Compass

- Dichroic filter = polarizing filter + birefringent film
- Setup: 2 dichroic filters (different birefringent films)
  - Angle of 45 degrees with polarizers
- Maximize difference in color between the two filters
  - One points to sun
  - The other points in direction of polarization of sky

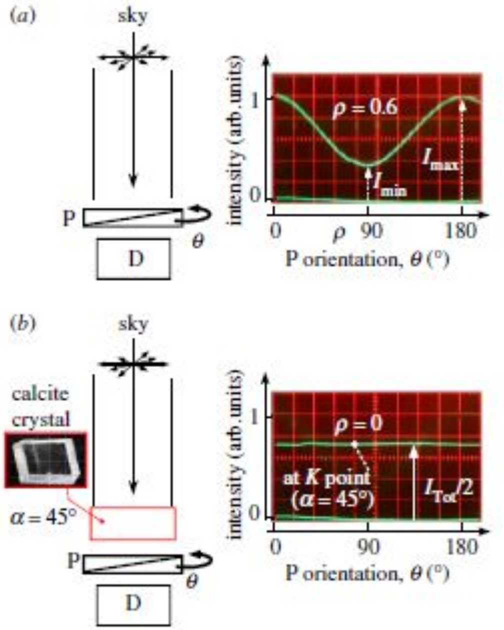
Procedure (Sunstone)

- ID isotropy point
    - any partially polarized light is completely depolarized
    - Intensity of both beams is equal
    - Angle of top face = direction of sun

$$\rho = (I_{\max} - I_{\min})/(I_{\max} + I_{\min}).$$

$$I_o = \left(\frac{I_{\max} + I_{\min}}{2}\right)(1 + \rho \cos 2\alpha)$$

$$I_e = \left(\frac{I_{\max} + I_{\min}}{2}\right)(1 - \rho \cos 2\alpha).$$



Task 2: Presence of Clouds

- Clouds = large water droplets
  - scatter all colors equally ⇒ unpolarized light (vs. $1/\lambda^4$ scattering)

- Sunstone: minimal effect
- Dichroic Compass: severe effect

Future Goals/Improvements

- Experimentally Verify Proposed Theory/Procedure
- Digitally map polarized sky (Comprehensive)
- Computer Analysis (Consistency)

Acknowledgements

- Wehner, Rudiger. “Polarized-Light Navigation by Insects”. Scientific American, Volume 235, pp. 106-115. Accessed October 26, 2019.
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- https://www.polarization.com/compass/compass2.html

- Roberto

Additional: Sunstone Details

- Alpha = angle between crystal's ordinary axis & given light's main axis
  - Main axis determined by max, min intensity