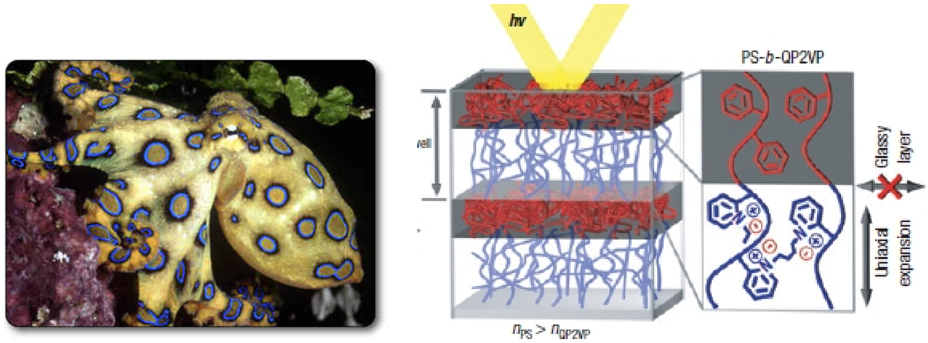
Problem Set 5: Cephalopod Camouflage
ENGN/BIOL 267—Winter 2020
Due: 09 April 2020, 9am



(a) (b)

Figure 1: (a): Blue Ringed Octopus. Under stress, the intensity of the blue rings is accentuated. (b):Schematic of tunable photonic gel. Image from: Kang, Y. et al. Nature Materials, 2007, 6, 957.

1. **An ideal situation: Ideal iridophore stacks**

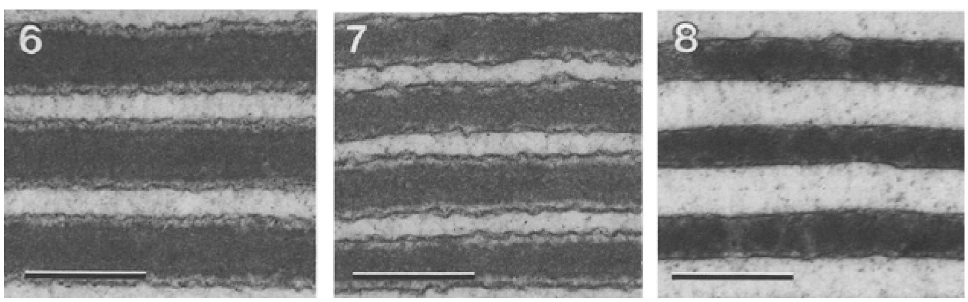


Figure 2: Iridophore stacks in squid (*Loligo brevis*). Dark bands are reflectin plates; white bands are cytoplasm. Scale bar = 250 nm. Image 6–8: Iridophores that reflect, respectively, red/gold; a mixture of colors; and green-blue. Image from: Cooper, KM et al. Cell Tissue Res, 1990, 259: 15-24.

   (a) Using Fig. 2, plate 6 (red/gold iridophore), estimate d_p and d_c, the thickness of the iridophore plates and cytoplasm, respectively. Determine whether the stack is *ideal*. Show calculations to justify your answer. Assume that the respective indices of refraction are[1]: $n_p = 1.44$ and $n_C = 1.33$.

   Also, using these measurements, compute/estimate the wavelength (color) of light that is maximally reflected (assuming normal incidence).

   (b) Repeat part 1a for the stack in Fig. 2 plate 8 (green-blue iridophore).

   (c) Does the stack maintain an ideal configuration across the visible spectrum? Use your answers from parts 1a and 1b to argue your case.

[1]value for iridophore plate determined by: A Ghoshal et al.(2013). Optical parameters of the tunable Bragg reflectors in squid. *Journal of The Royal Society Interface*, 10(85), 20130386.

(d) Cooper et al noted that the stack shown in Figure 2, plate 7 reflected a mixture of colors—i.e., selectivity/chromatic tuning was poor. Make careful observations of this stack and describe at least 2 reasons why this might have been the case. Justify your answer by relating form to function (biology to physics). Hint: look very carefully at the Fig. 2 and think how it differs from the pictures we draw on the board (or show in the powerpoint) for the ideal physics model.

2. **Multiplate Course**

In class, we developed a convenient physical model describing an (ideal) stack, with just 2 protein plates sandwiching one cytoplasm layer reflecting back a total of 3 light rays. Now consider an octopus that has acquired a mutation, such that the protein plates in the iridophore stacks have now consist of two distinct proteins, with different indices of refraction n_1 and n_2, respectively. The corresponding thicknesses are d_1 and d_2, respectively. Some further tests revealed that the n_1 material is the original reflectin protein, and that the other mutant protein is an exotic one, with $n_2 = 1.89$. The cytoplasm is still the same as it ever was—n_c and d_c have not changed. See Fig. 3.

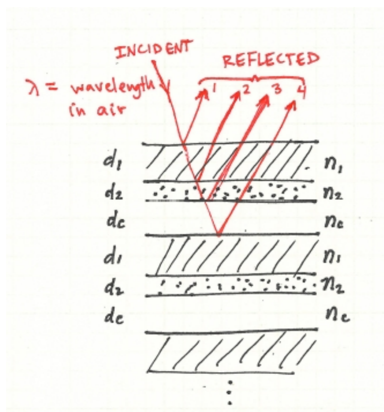


Figure 3: A mutant's multiplate stack. The reflecting plates now consist of two proteins, the original reflectin 1 (slashes), and protein 2 (stippled). Cytoplasmic spaces are still present. The incident ray and first 4 reflected rays are shown. The angle of incidence is close to 0, but is greatly exaggerated here for clarity.

(a) Develop expressions for the total phase shift of each reflected wave, ϕ_1, ϕ_2, ϕ_3, and ϕ_4, respectively. Leave your answer in algebraic terms—i.e., do NOT plug in numbers yet for physical variables (e.g., indices of refraction).

(b) Excited about the new discovery of the mutant, you immediately rush it into the lab for further optical tests, whereupon you discover yet another amazing properly—the stack is still ideal! What does this imply about the relation between all of the indices of refraction and thicknesses? (For example, in a normal cephalopod we had $4n_c d_c = 4n_p d_p$). Hint: carefully consider the phase shifts found in part a, knowing that the reflected waves should all be *in phase*.

(c) Upon further testing, you are able to ascertain that one of the reflectin protein plate has a thickness of $d_1 = 100$ nm. Therefore, what is the thickness of the mutant protein layer d_2 and the thickness of the cytoplasm layer d_c?

(d) Excited by your discovery, you return to the ocean whereupon you find an entire colony of these mutants. While observing them, a pesky crab creeps closer and eventually grabs one of the mutants, who has changed color under duress. Before the crab can get his snackin' on, you retrieve a section of skin to bring back to the lab. Upon further experiment, you make yet another exciting discovery, that the index of refraction of the mutant protein changed under stress to $n_2^{'} = 1.70$. All other parameters (d_c, d_1, d_2, n_c, and n_1) remained the same. What is the wavelength of light that will be maximally reflected, λ_{max}? *Carefully* draw a ***phasor diagram*** to show the relative phases of reflected waves to help justify your answer.

3. **All the Colors of the Rainbow**

   Invent a useful product integrating technology inspired by the amazing color-changing cephalopods. Make its real-world application explicit. Be sure to describe it both in general terms and **quantify** your design. Be specific as possible, drawing upon our study of the bioinspired IR reflectors by Xu et al (and any other similar work you find on google scholar etc.) For example, let's say you wanted to make a new video display updating at 24 frames per second incorporating iridophores and chromatophores. What spectrum (range) of wavelengths would you need to achieve? How would you achieve this spectrum and time-scale in practice? What materials would you use and why? What actuators would you incorporate, whether electrical or mechanical or other? These are just sample questions to help guide your thinking. Again, let your creativity run wild and invent whatever product you think useful (and/or awesome) for a real world application.