

MAE 545 (Spring 2017)

Special Topics - Lessons from Biology for Engineering Tiny Devices

Lectures: T, Th 11:00 AM-12:20 PM, W 1:30-3:00 PM, Friend Center 111

Office hours: EQUAD D414 (or by appointment)

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- **text books: none**
- **lecture slides will be posted on Blackboard**

<http://blackboard.princeton.edu>

course: MAE545_S2017

Assignments

- **presentation of research paper in class**
- **final paper (final project)**

Structural colors Course overview

Structural colors of animals and plants appear due to the selective reflection of ambient light on structural features underneath the surface.

H. Wang and K-Q. Zhang, Sensors 13, 4192 (2013)

V. Saranathan et al., J. R. Soc. Interface 9, 2563 (2012)

Wrinkling

Wrinkling of thin films on soft substrates can be used to make flexible electronics and to tune drag, adhesion and wetting.

Golf balls (reduced drag)

Gecko (strong adhesion) Lotus leaves (hydrophobic)

Growth and forms in nature

Brain Gut

Beaks

Leaf Flower Shells

From transformable shapes to self-folding robots

opening/closing of flowers self-folding robots

<https://www.youtube.com/watch?v=1M-vQdyY6OE> <https://vimeo.com/98276732>

swelling of patterned gels

Patterns in nature

Turing patterns

Random walks

Polymer random coils

Brownian motion Swimming of E. coli

or cell nucleus (in eukaryotes). Compare with figure 9(*A*) which shows confined DNA. (*B*) The **Protein search for a binding site on DNA**

Protein filaments and molecular motors

Actin filament

Microtubule

Cargo transport Crawling of cells Contraction of

muscles

 10_{nm}

Viruses and drug delivery

assembly of viral capsids

packing of viral DNA inside the capsid

infection of cells

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drug delivery

DNA Origami

C. E. Castro et al., Nature methods (2011)

MAE 545: Lecture 1 (2/7) Structural colors

1*.*7*µ*m

Structural color

reflection of ambient light on structural features underneath the surface. **structural color Structural colors of animals and plants appear due to the selective**

b a **White light coming from the sun consists of all colors.rainbow** 1*.*7*µ*m **incoming reflected** contract the contract of the contract of **light light** 7755 8 \Box \Box showing wing-scale cross-sections of M. ^rheteno^r. c, TEM images ofa wing-scale 42° cross-section of the there at the there at the there are very species of the theorem and the theorem and the t The high layer number of \mathcal{C} rhetenor in b can intense in b can intense in b can intense intense intense in reflectivitythatcontrasts with the more diffuselycoloured appearance of M. didiu^s, in which an overly second layer of second layer of \sim Figure 2 Iridescents and polychaete worms. A, Scanning electron micrography. A, Scanning electron micrography. . Bars, a, 1 cm; b, \mathcal{L} and b–d, transmission electron micrograph (TEM) images of transmission electron micrograph (TEM) in a section of transverse sections of transverse sections of transverse sections of the section of the section of colour as is seen in many Avian orders, is the product of coherent, in many Avian orders, in the product of co **transmitted** $\sqrt{2}/\sqrt{2}$ $\sum_{i=1}^{\infty}$

Structural colors Jian Zi*, Xindi Yu, Yizhou Li, Xinhua Hu, Chun Xu, Xingjun Wang, Xiaohan Liu*, and Rongtang Fu Surface Physics Laboratory (National Key Laboratory) and T-Center for Life Sciences, Fudan University, Shanghai 200433, People's Republic of China

inguingui articles and the summer. **Structural colors of animals and plants appear due to the selective** reflection of ambient light on structural features underneath the surface. **WE GO THE COLORED BARBULES, WHICH COLORED BARBULES, WHICH COLORED BARBULES, WHICH COLORED BARBULES, WHICH COLOR tion. Simulations reveal that the photonic-crystal structure pos-**

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Peacock feather eyes nious and simple: controlling the constant and the number of the nu

Morpho butterfly

Plum-throated Cotinga answered. In particular, the precise physical mechanism that

Marble berry

colour as is seen in many Avian orders, is the product of coherent, in many Avian orders, is the product of co ratherthan incoherent,scatterfromthe spatial variation in refractive index of meduling in feather barbs or of collagen fibres in feather barbs or of collagen fibres in $1\,\mu\mathrm{m}$

rsif.royalsocietypublishing.org

J.R.

The high occupancyand high layer number ofM. ^rheteno^r in b createsan intense **beetle** reflectivitythatcontrasts with the more diffuselycoloured appearance of M. didiu^s, in

which an overly interested second layer of second

1*.*7*µ*m

(*g*) (*h*) (*i*) **bleak fish**

sions, presenting 1μ m

In other species of butterfly, orientation of butterfly, orientation and adjustments to the align-term of butterfly, orientation and adjustments to the align-term of butterfly, or end of the align-term of the align-term of

 $\frac{14}{\sqrt{2}}$ bars present at the periphery of the medullary barb cells from the pale blue-grey primary coverts of S. lunatus, (e) TEM image of a

 $\frac{1}{1}$ is a rectangular lattice. The only $\frac{14}{1}$ \mathcal{A} are the lattice constant (rod spacing) and the number \mathcal{A}

1*µ*m

 $1\mu{\rm m}$

Chrysina aurigans 250nm \mathbf{R}

. Bars, a, 1 cm; b,

Dynamic structural colors

Chameleon (speed 8x)

J. Teyssier et al., Nat. Comm. 6, 6368 (2015)

changes the spacing of periodic structure **communications** of cilia, which change the spacing of periodic structure **Changes in osmotic concentration lead to the** swelling of cells in excited chameleon. This **from which the ambient light is reflected.** *(relaxed) Male m2 (excited)*

green color

200nm 200nm

315 nm 15

Comb Jelly (real time)

https://www.youtube.com/watch?v=Qy90d0XvJlE

pacing or periodic structure
examples the communication of the extendion of periodic 208 V. Cha, which change the Orientation of periodic **Rainbow color waves are produced by the beating of cilia, which change the orientation of periodic structure from which the ambient light is reflected.**

 $F_{\rm eff}$ (c) The combined from its contraction from its contraction from its combined from its combined from its combined from its contraction from its contraction from its contraction from its contraction from its contra 1*µ*m

Dynamic colors in cephalopods

octopus squid

https://www.youtube.com/watch?v=9MB2ltsAPnQ

Dynamical color change in cephalopod is achieved by modulation of size and spacing of both the pigment cells and the cells reflecting light.

electromagnetic waves

Wave equation

Solutions are traveling waves with velocity c.

waves in ropes under tension

- **tensile force** *F*
- ⇢ **mass density**
- *A* **cross-section area**

waves on liquid surfaces

- $c =$ $\sqrt{g\lambda}$ 2π
- **gravitational const.** *g*
- **water depth** *h*
- **wavelength**

 $c =$

1

 $\sqrt{\epsilon\mu}$

sound waves

- **bulk modulus**
	- **mass density**

shear waves

$$
c=\sqrt{\frac{\mu}{\rho}}
$$

- **shear modulus** *µ*
- ρ **mass density**
- *K*
	- \boldsymbol{D}

Plane waves

Planes of constant phases:

$$
\vec{k}\cdot\vec{r}=\mathrm{const}
$$

Solutions of wave equation can be described as a linear superposition of plane waves:

$$
u(x,t) = \sum_{\vec{k}} A_{\vec{k}} e^{i(\vec{k} \cdot \vec{r} - \omega t)}
$$

$$
k = \frac{2\pi}{\lambda}
$$
 wavevector

 $\omega = 2\pi\nu$ angular frequency

Plane waves travel in direction of \vec{k} with velocity:

$$
c = \frac{\omega}{k} = \lambda \nu
$$

Note: velocity of plane waves may depend on the wavevector $c(\vec{k})$!

Interference

constructive interference

Constructive interference occurs when the two waves are in phase: waves offset by $m\lambda$, $e^{ikm\lambda} = e^{i2\pi m} = +1$ 20 $e^{ik(m+1/2)\lambda}$

destructive interference

Propagation of light in medium

speed of light $c_0 = 3 \times 10^8 \text{m/s}$ $c = c_0/n$ **frequency** ν_0 $\nu = \nu_0$ **wavelength** λ_0 $\lambda = \lambda_0/n$ $c_0 = \nu_0 \lambda_0$ $c = \nu \lambda$

 $x_1 + nx_2$

 λ_0

Optical path length is geometric distance multiplied by the index of refraction!

total number of cycles

*x*1

 $+$

*x*2

 λ

=

 $\overline{\lambda_0}$

Reflection of waves

Reflection of light at the interface between two media

Refraction of light

Snell's
$$
n_1 \sin \theta_1 = n_2 \sin \theta_2
$$
 Total internal $\theta_2 > \arcsin(n_1/n_2)$

Rainbow

Rainbow forms because refraction index *n* **in water droplets depends on the color (wavelength) of light.**

 $n_{\text{purple}} > n_{\text{blue}} > n_{\text{green}} > n_{\text{yellow}} > n_{\text{orange}} > n_{\text{red}}$

Interference on thin films

difference between optical path lengths of the two reflected rays

$$
OPD = n_2 \left(\overline{AB} + \overline{BC} \right) - n_1 \overline{AD}
$$

$$
OPD = 2n_2 d \cos(\theta_2)
$$

no additional phase difference due to reflections

 $n_1 < n_2 < n_3$ $n_1 > n_2 > n_3$

constructive interference $OPD = m\lambda$

destructive interference

 $OPD = (m+1/2)\lambda$

$$
m=0,\pm 1,\pm 2,\ldots
$$

additional π phase **difference due to reflections**

 $n_1 < n_2 > n_3$ $n_1 > n_2 < n_3$

constructive interference

destructive interference $OPD = (m+1/2)\lambda$ $OPD = m\lambda$

Interference on soap bubbles

constructive interference for different colors happens at different angles

$$
2dn_{\rm soap}\cos(\theta_2)=(m+1/2)\lambda
$$

 $m = 0, \pm 1, \pm 2, \ldots$

soap bubble

visible spectrum

Single structural color

structures with uniform spacing **Single reflected color on**

iridescence that provides high-contrast colour flicker with minimal

Morpho butterfly

1*.*7*µ*m

Marble berry

 $250nm$

cross-section of therelated speciesM. didiu^s reveal its discretelyconfigured multilayers. **Chrysochroa raja bettle**

Silver and gold structural colors

29

Many colors reflected on structures with varying spacing

chirped structure

the integrating-sphere analysis, the leaf of *Ficus macrophylla* **disordered layer spacing bleak fish**

a leaf background, and in *C. grayanus* that the colour will

 \sim 100 μ from *A. parvulus* and *C. grayanus*, other than the proportional

Bragg scattering on crystal layers

Comb jelly **Reating cilia are changing crystal orientation**

Scattering on disordered structures

(*g*) (*h*) (*i*) **Disordered structures with a characteristic length scale.**

Figure 2. Diversity of non-iridescent feather barb structural colours in birds and morphology of their underlying three-dimensional **This length scale determines what light wavelengths are preferentially scattered. This gives rise to blue colors in birds above.**