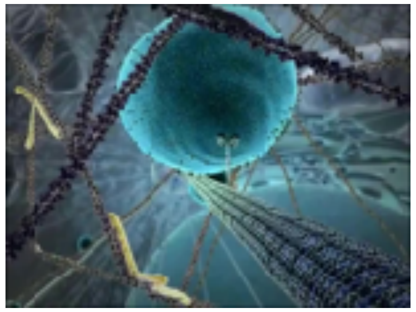
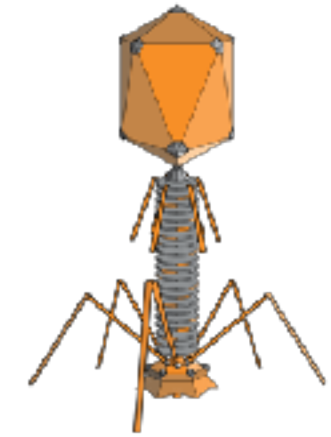
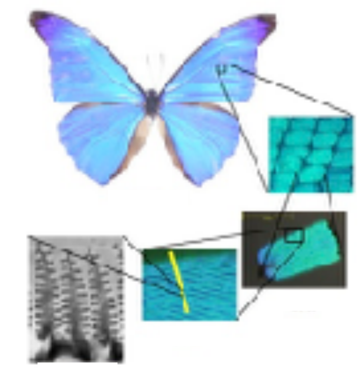
MAE 545 (Spring 2017)





Special Topics - Lessons from Biology for Engineering Tiny Devices

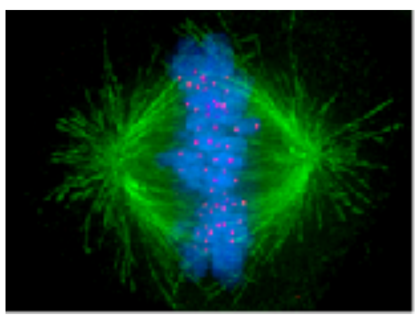


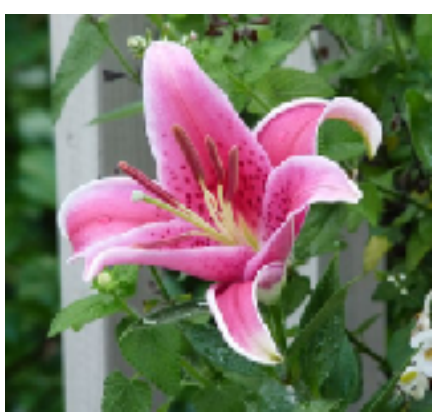
Lectures:

T, Th 11:00 AM-12:20 PM,
Friend Center 111

Office hours:

W 1:30-3:00 PM,
EQUAD D414
(or by appointment)





Andrej Košmrlj

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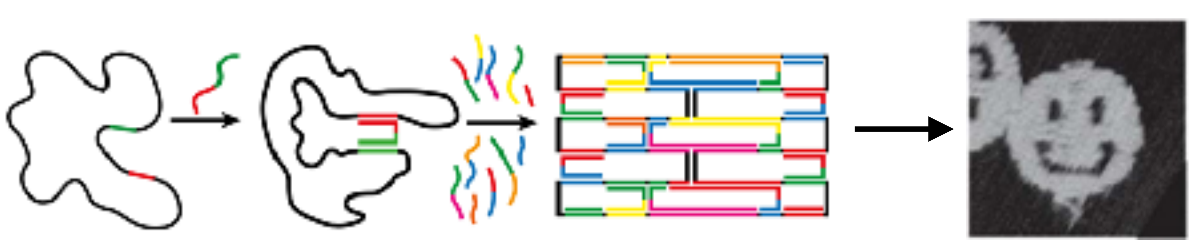
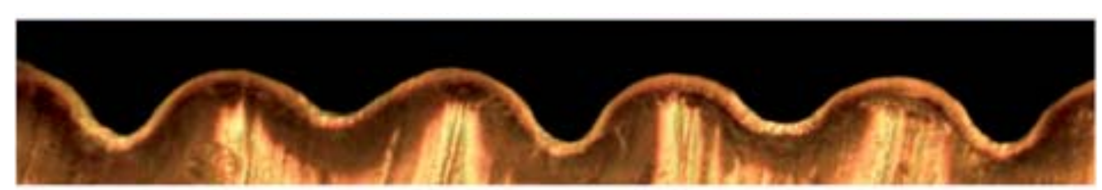




Lecture Notes

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

  http://blackboard.princeton.edu

  course: MAE545_S2017

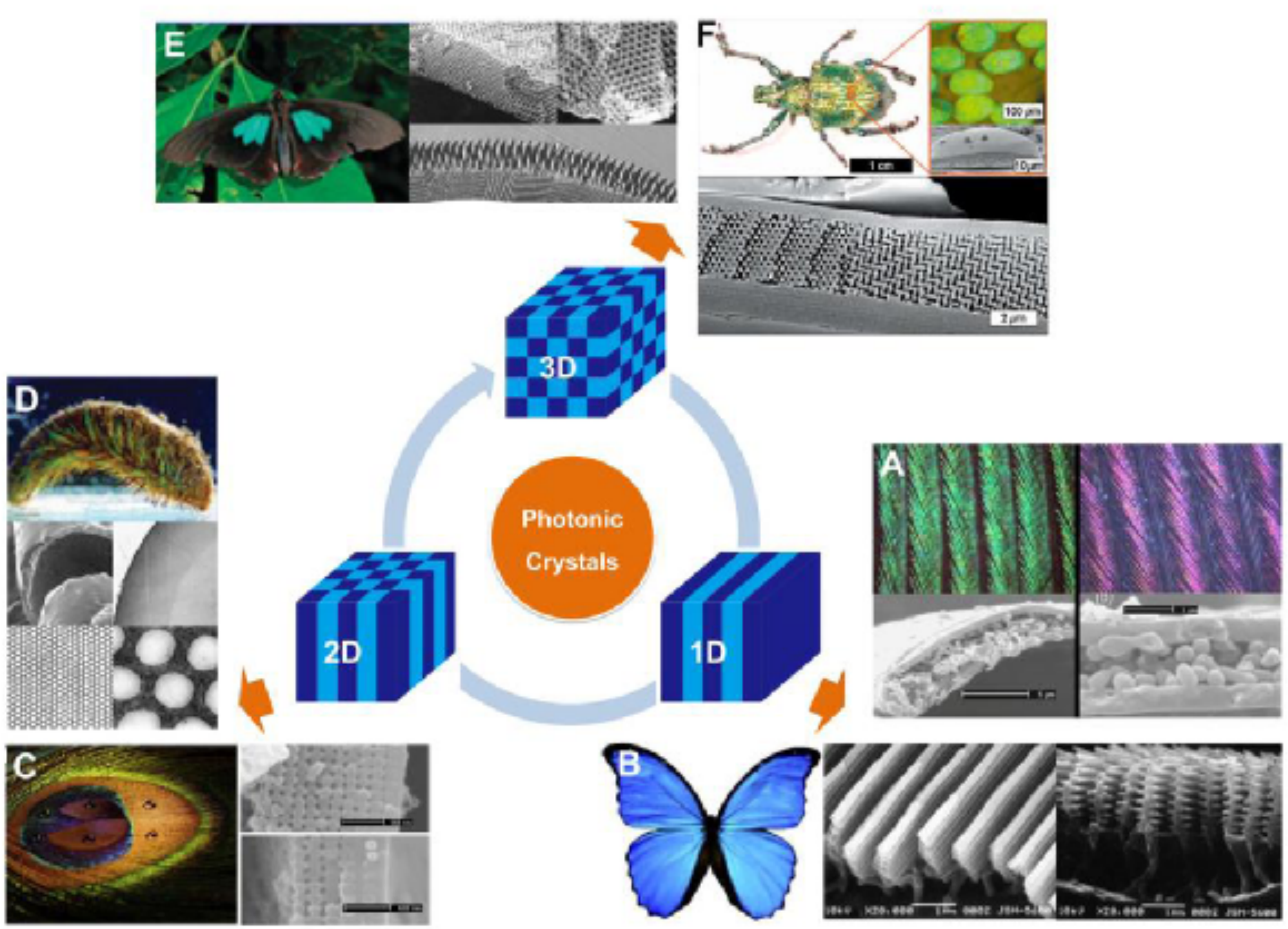
Assignments

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

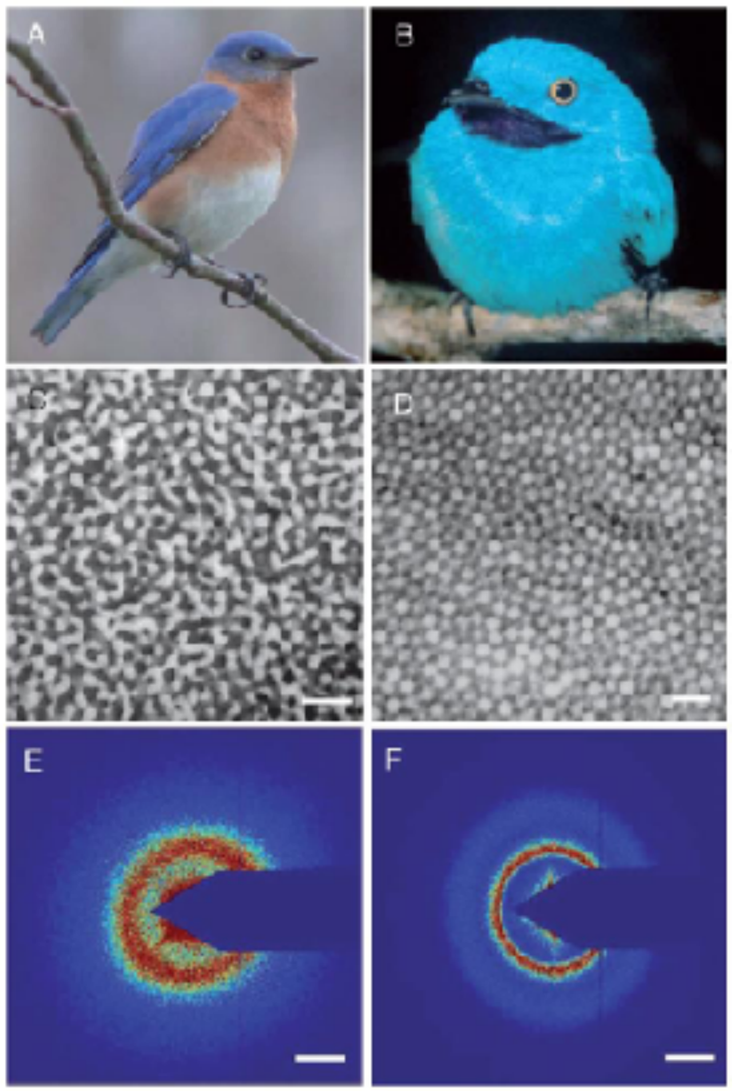
Course overview

Structural colors

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)

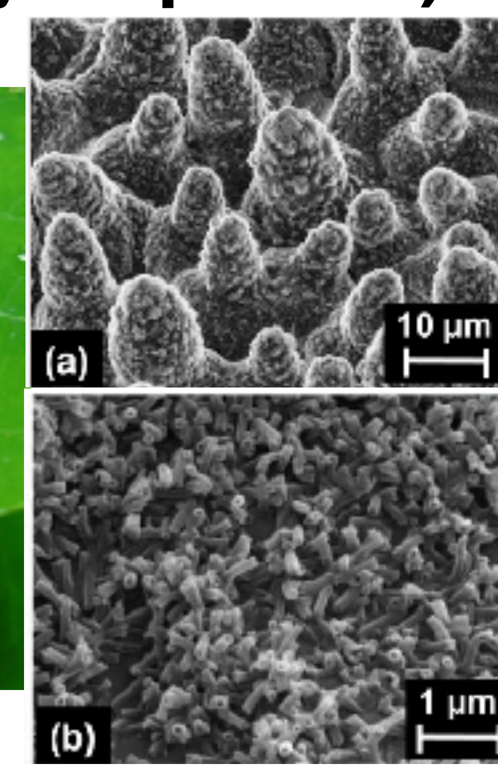
Wrinkling

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

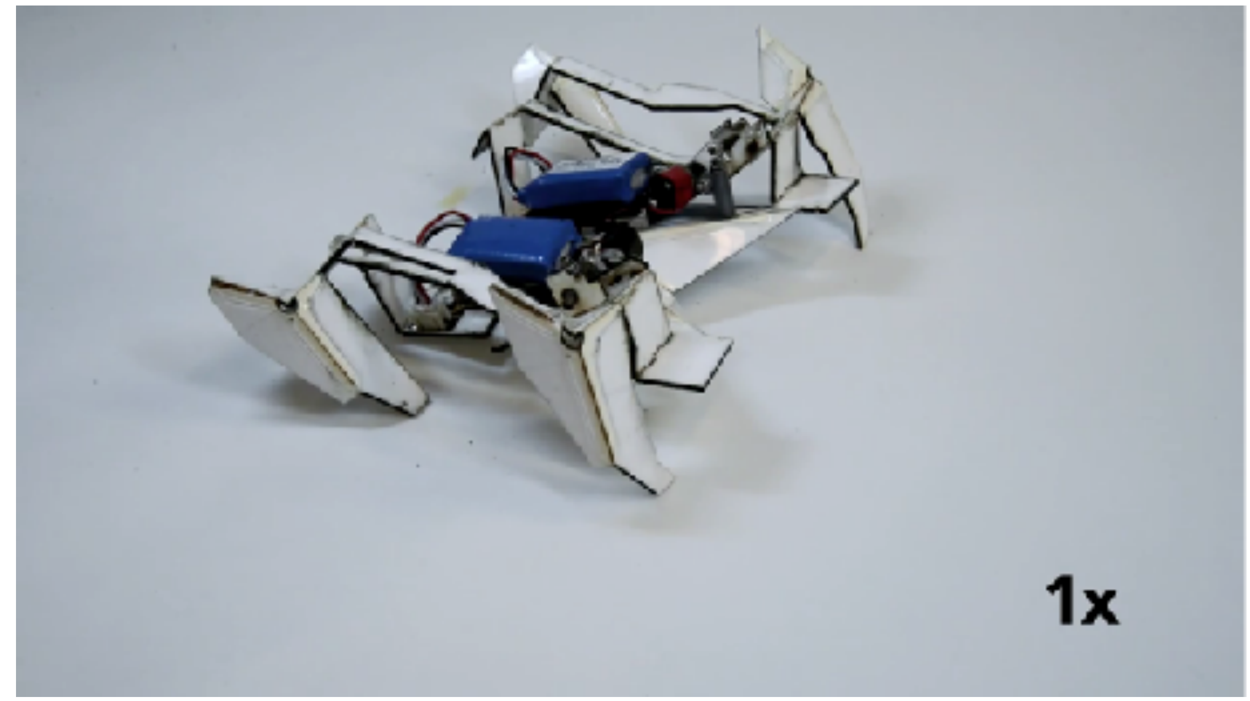
Shells

From transformable shapes to self-folding robots

opening/closing of flowers

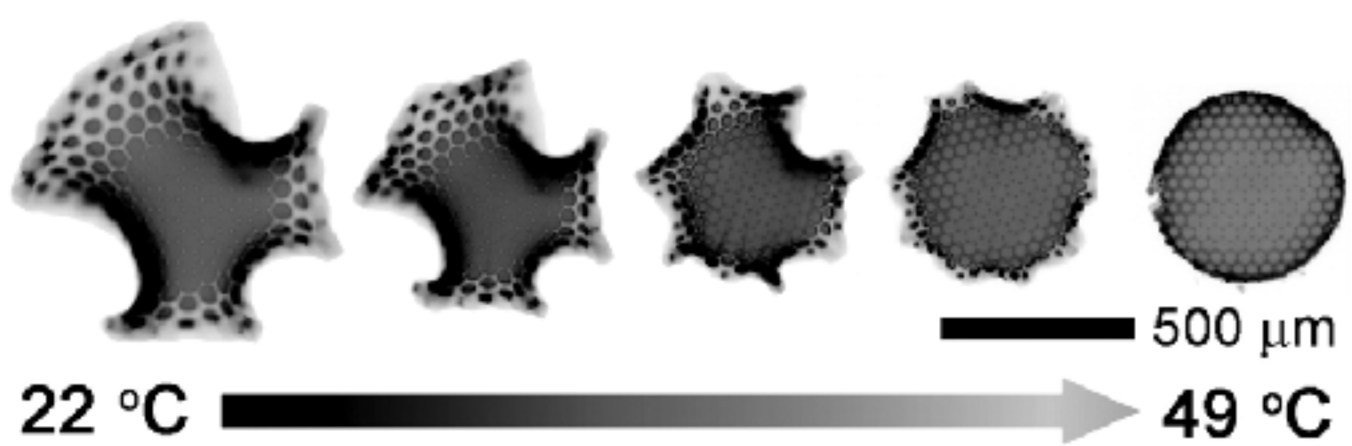
https://vimeo.com/98276732

self-folding robots



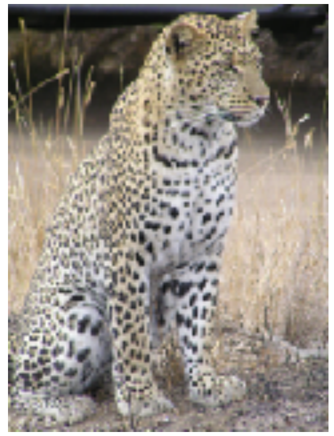
https://www.youtube.com/watch?v=1M-vQdyY6OE

swelling of patterned gels



Patterns in nature

zebra



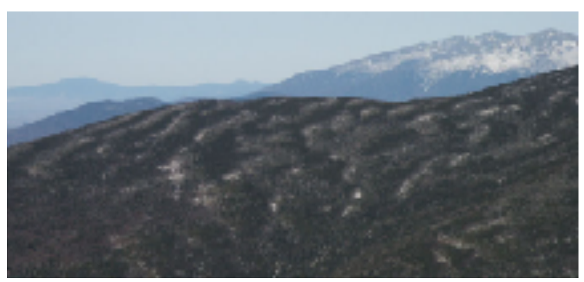
leopard

royal angelfish

peacock

giant pufferfish

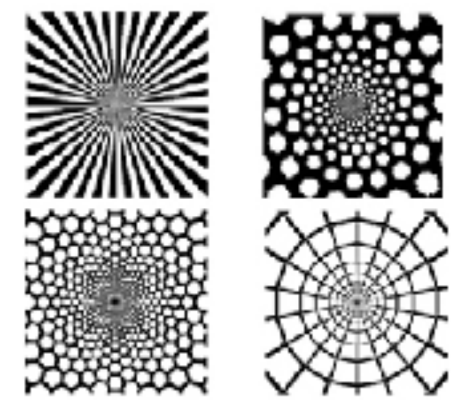
tiger bush



fir waves

mussels

clouds

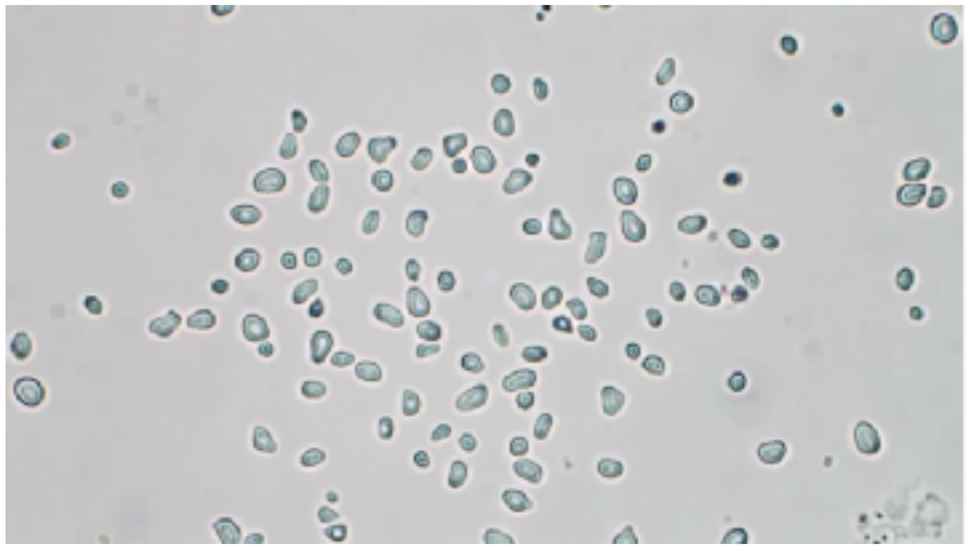


hallucination patterns

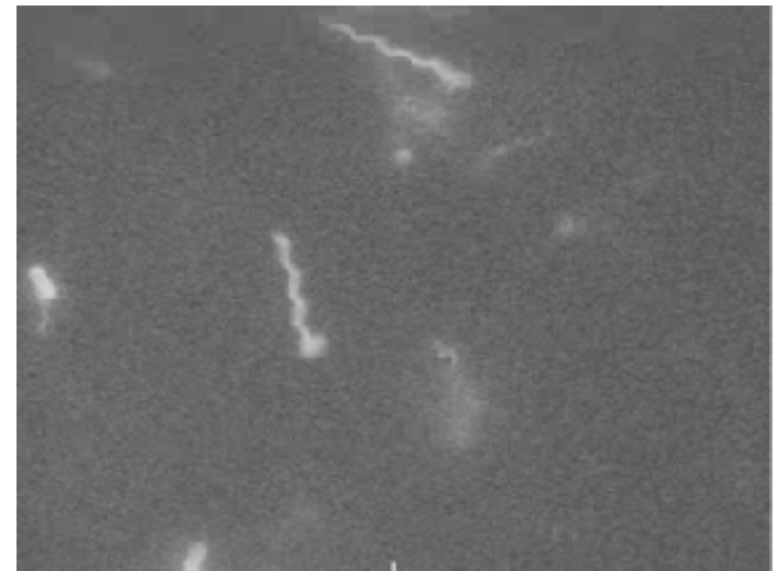
Turing patterns

Random walks

Brownian motion

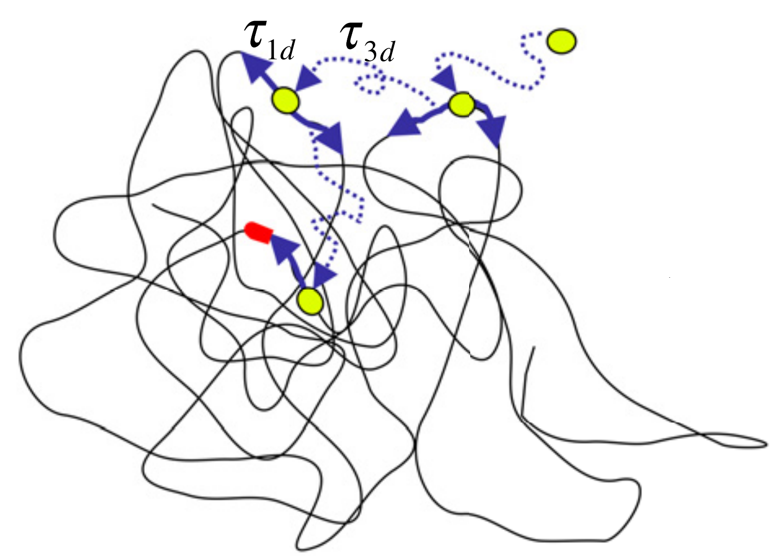


Swimming of E. coli



Polymer random coils

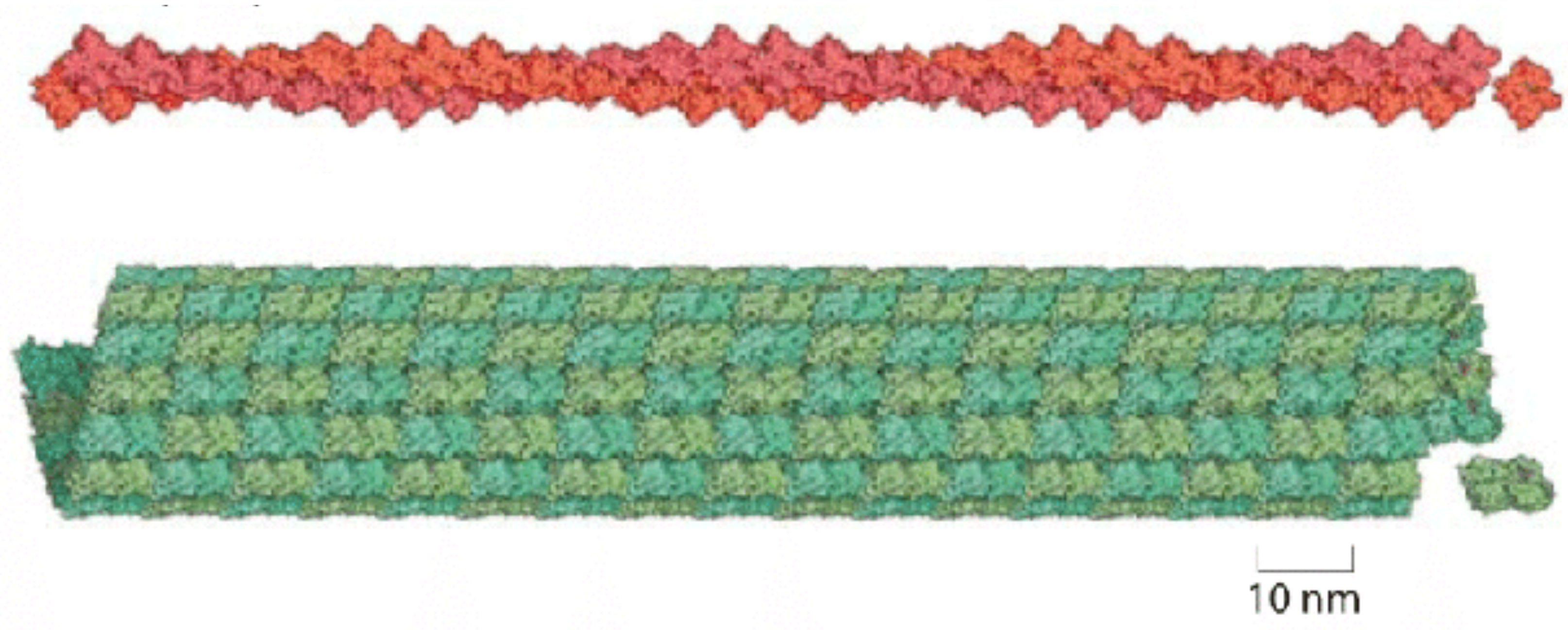
Protein search for a binding site on DNA



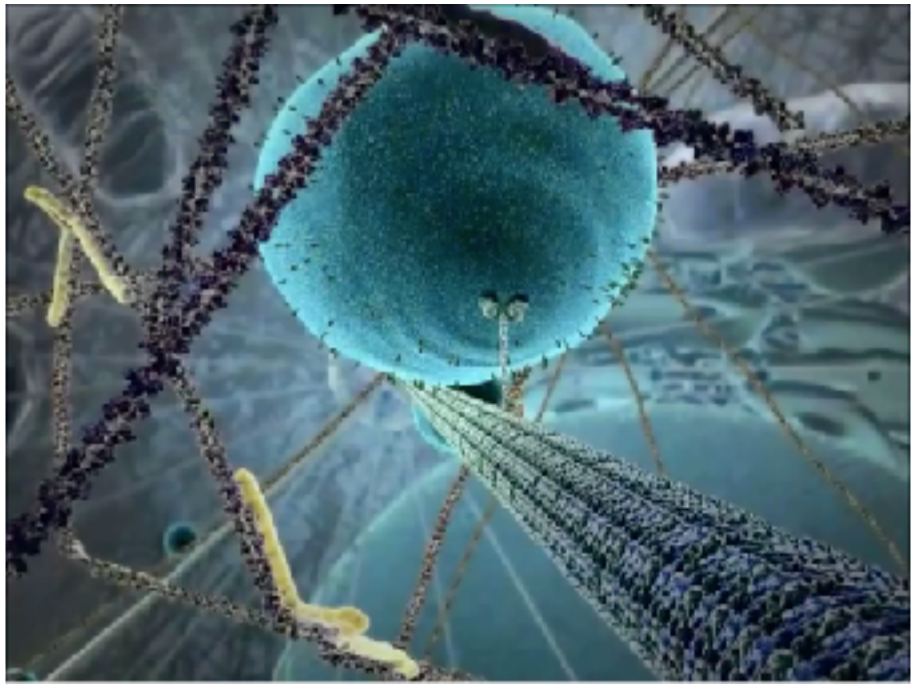
Protein filaments and molecular motors

Actin filament

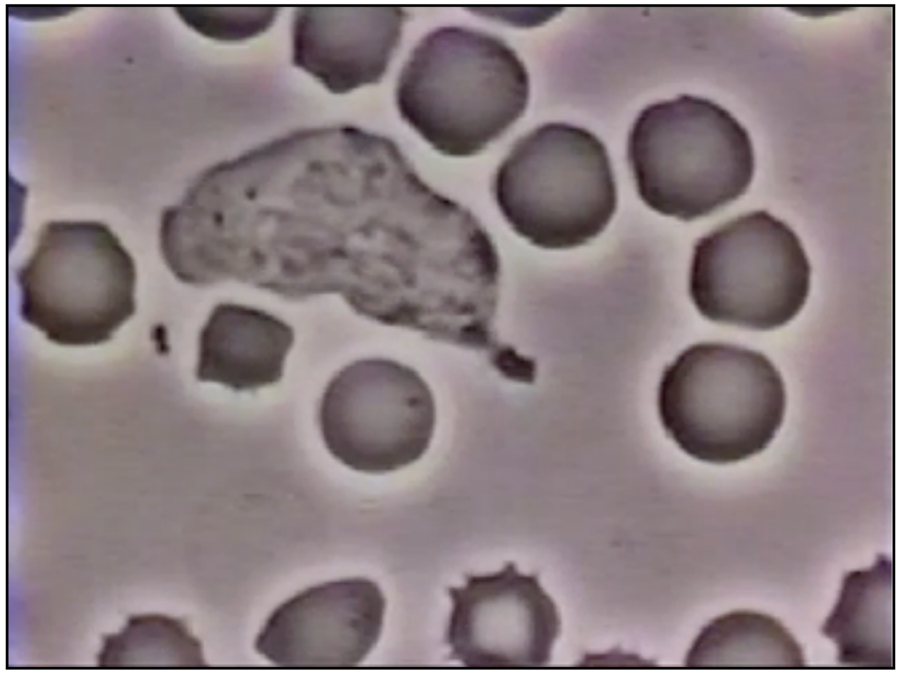
Microtubule



Cargo transport



Crawling of cells



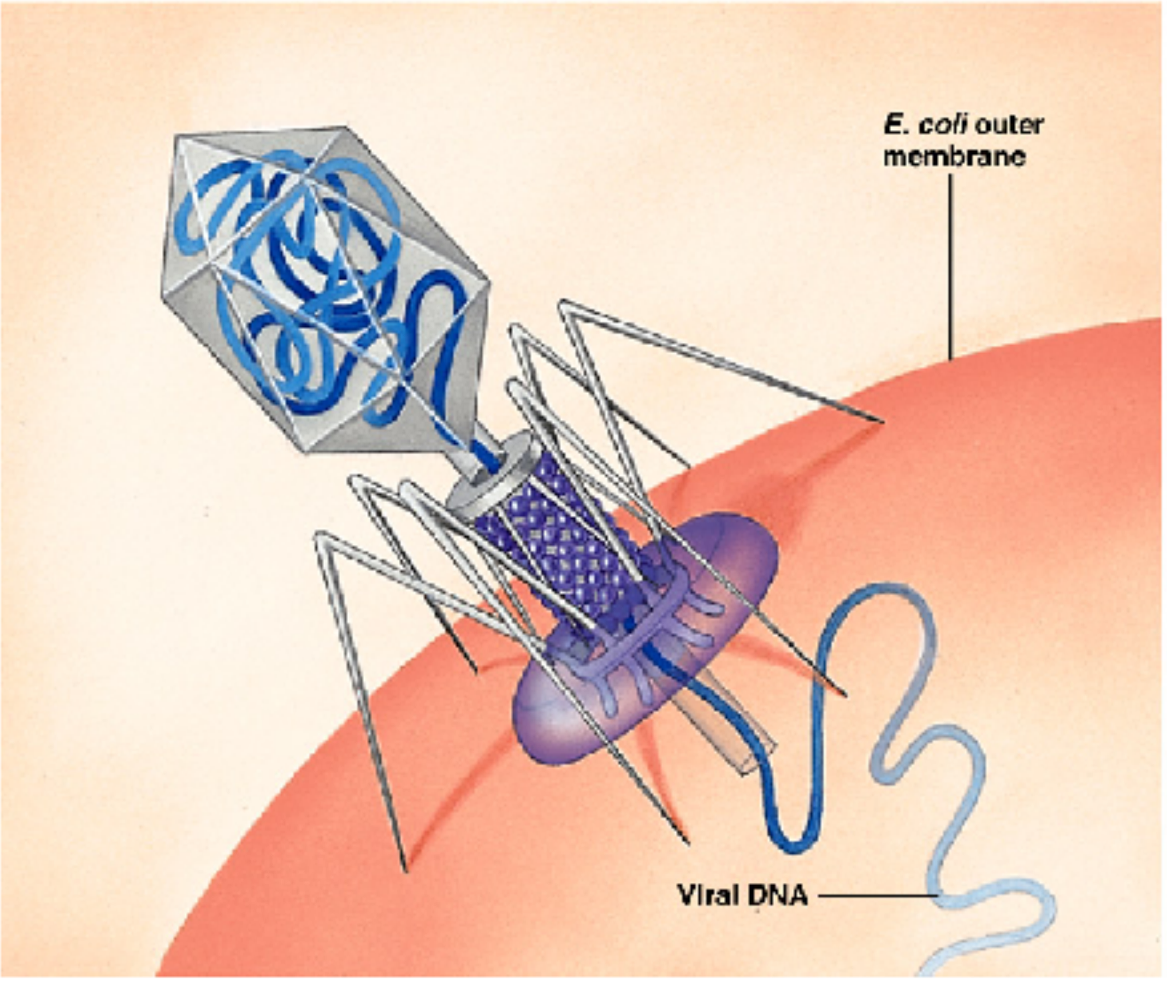
Contraction of muscles

Viruses and drug delivery

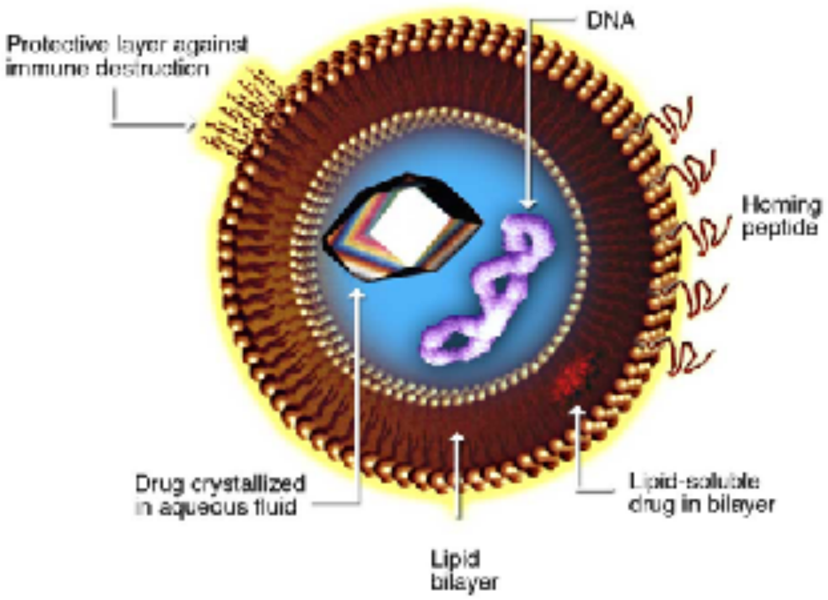
assembly of
viral capsids

packing of viral DNA
inside the capsid

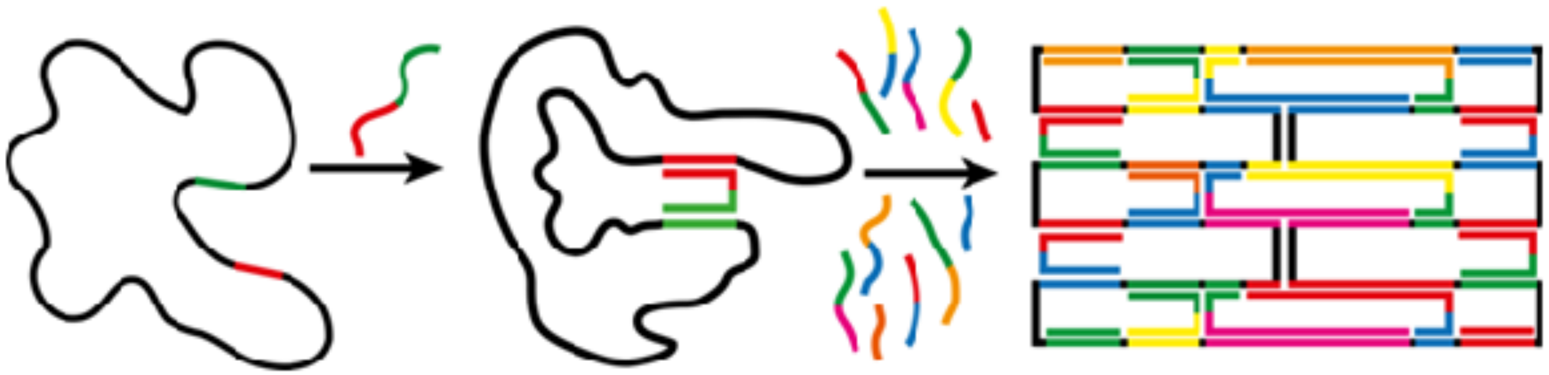
infection of cells

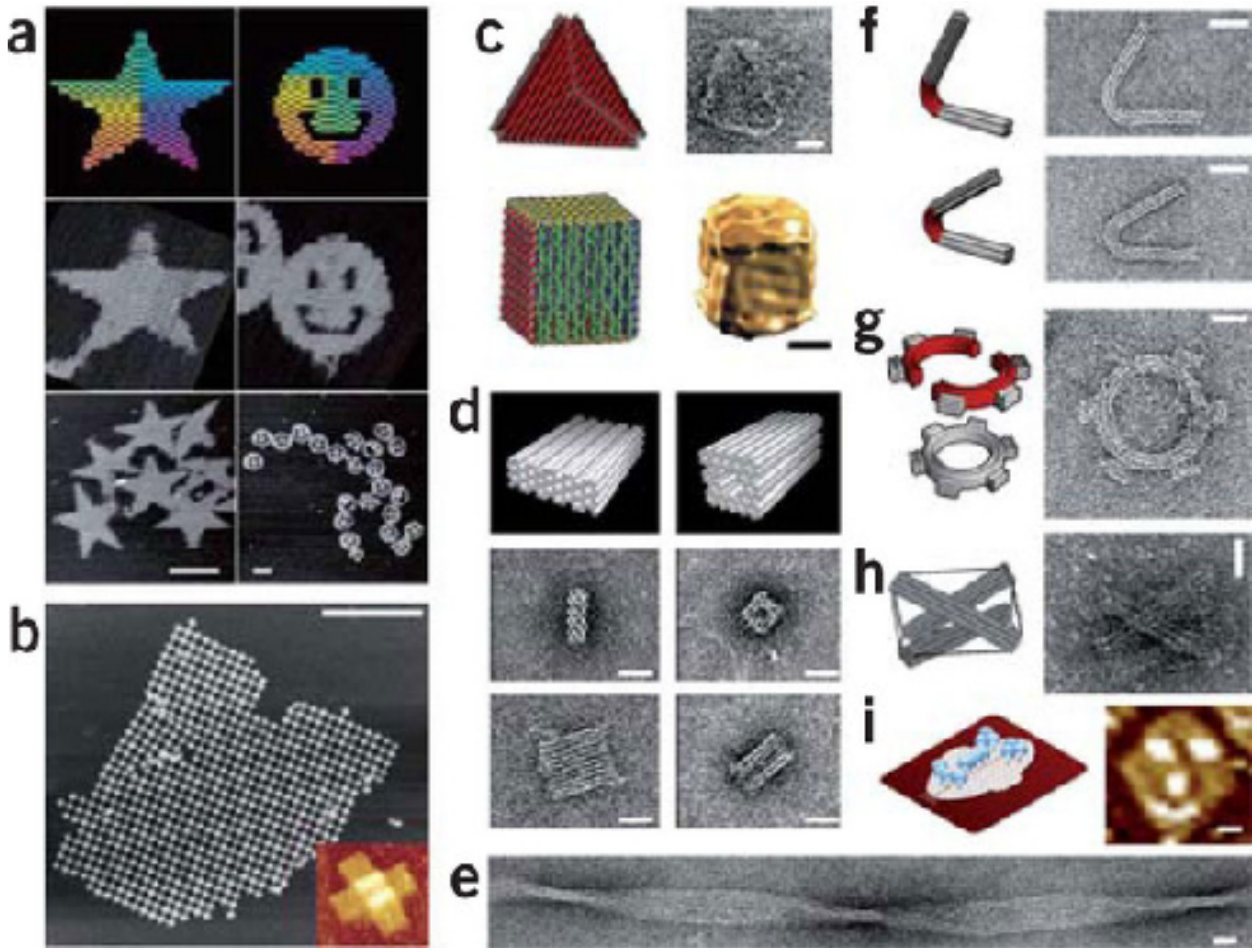


drug delivery



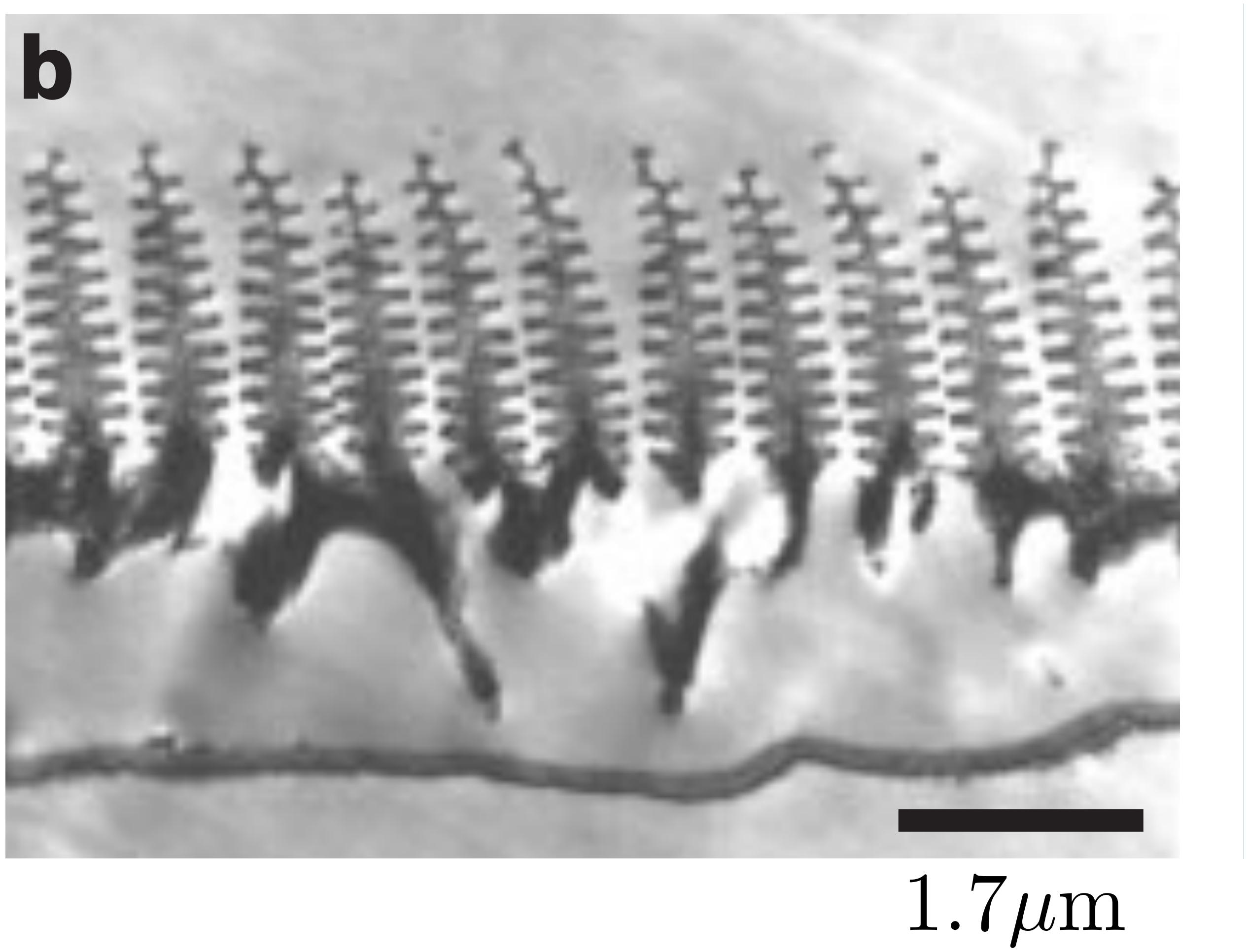
DNA Origami





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

Structural colors

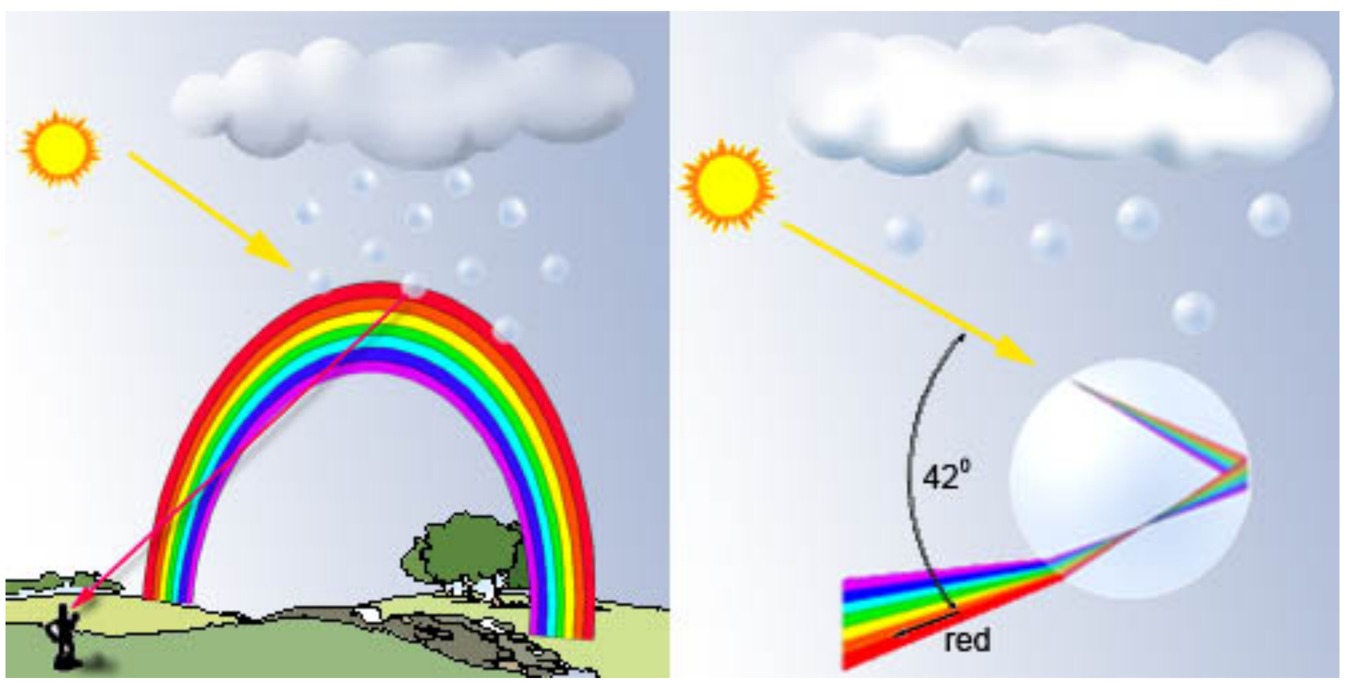


Structural color

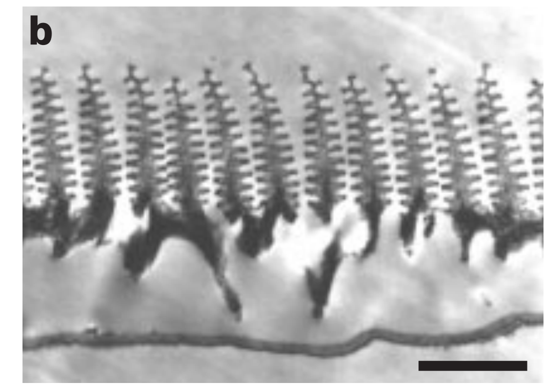
Structural colors of animals and plants appear due to the selective reflection of ambient light on structural features underneath the surface.

White light coming from the sun consists of all colors.

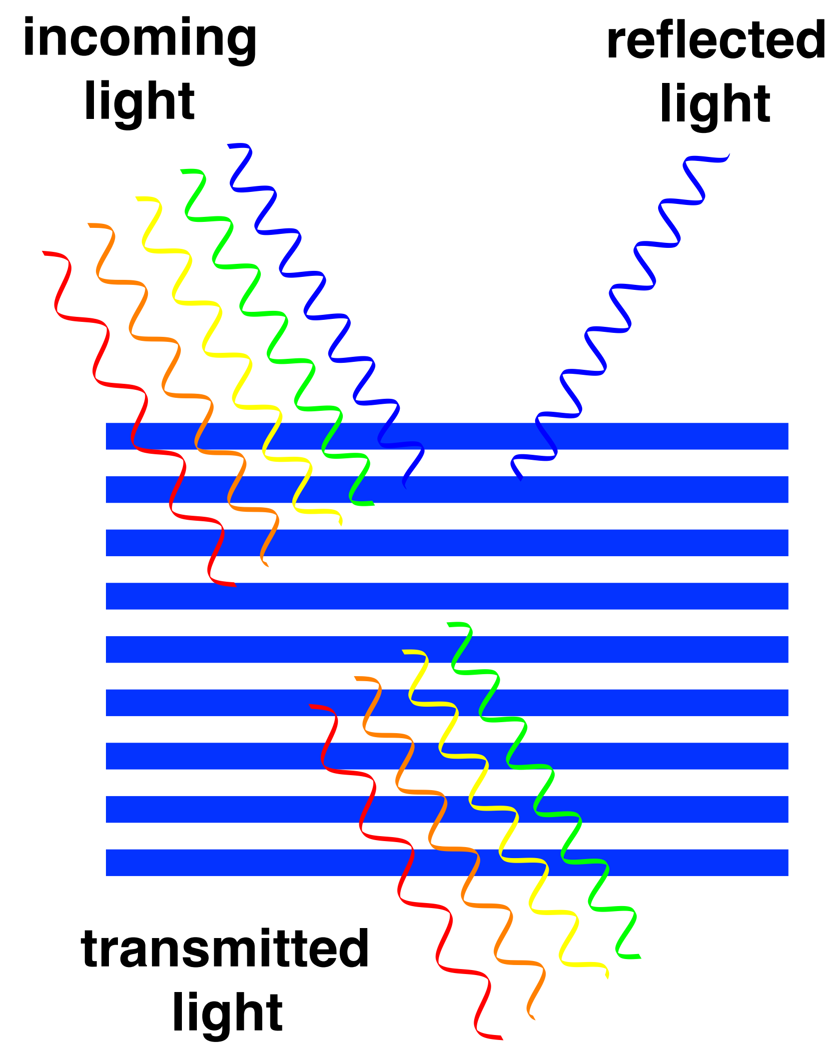
rainbow



structural color



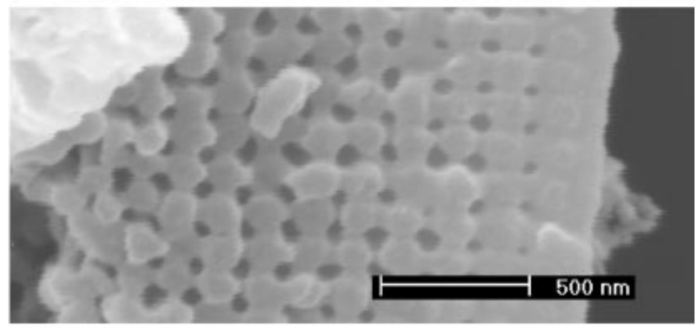
$1.7\mu m$



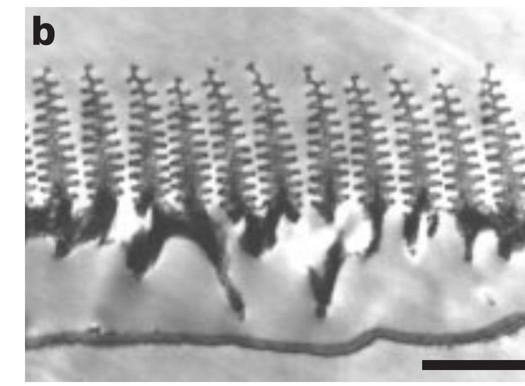
Structural colors

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

Peacock feather eyes

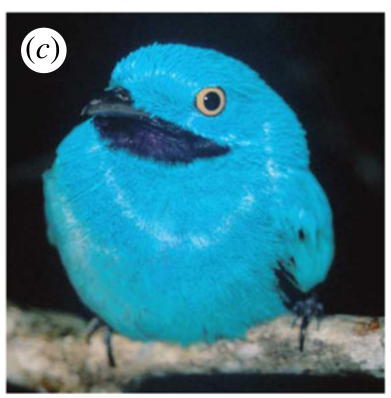


Morpho butterfly

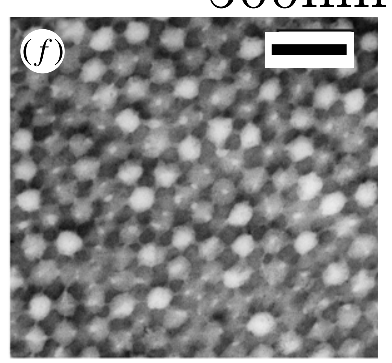


$1.7\mu m$

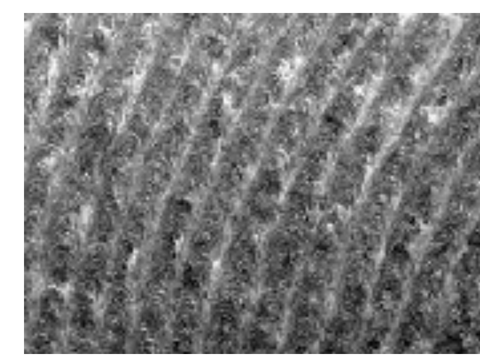
Plum-throated Cotinga



500nm

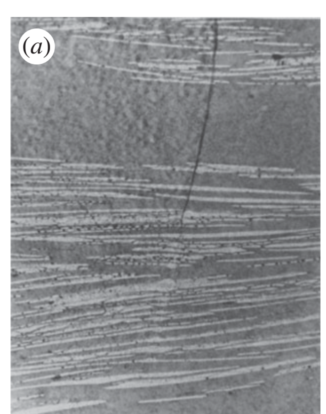


Marble berry



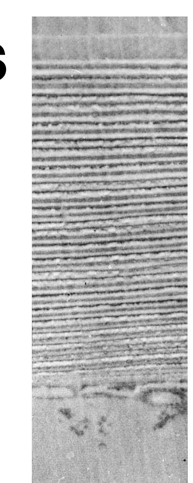
250nm

bleak fish



$1\mu m$

Chrysina aurigans beetle



$1\mu m$

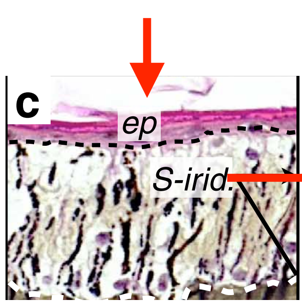
Dynamic structural colors

Chameleon (speed 8x)

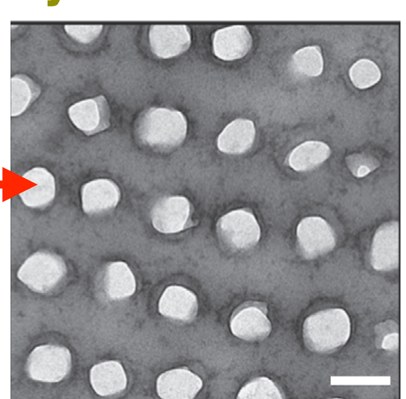
J. Teyssier et al., Nat. Comm. 6, 6368 (2015)

Changes in osmotic concentration lead to the swelling of cells in excited chameleon. This changes the spacing of periodic structure from which the ambient light is reflected.

skin

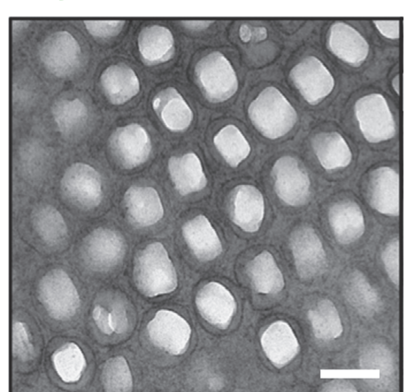


yellow color



200nm

green color

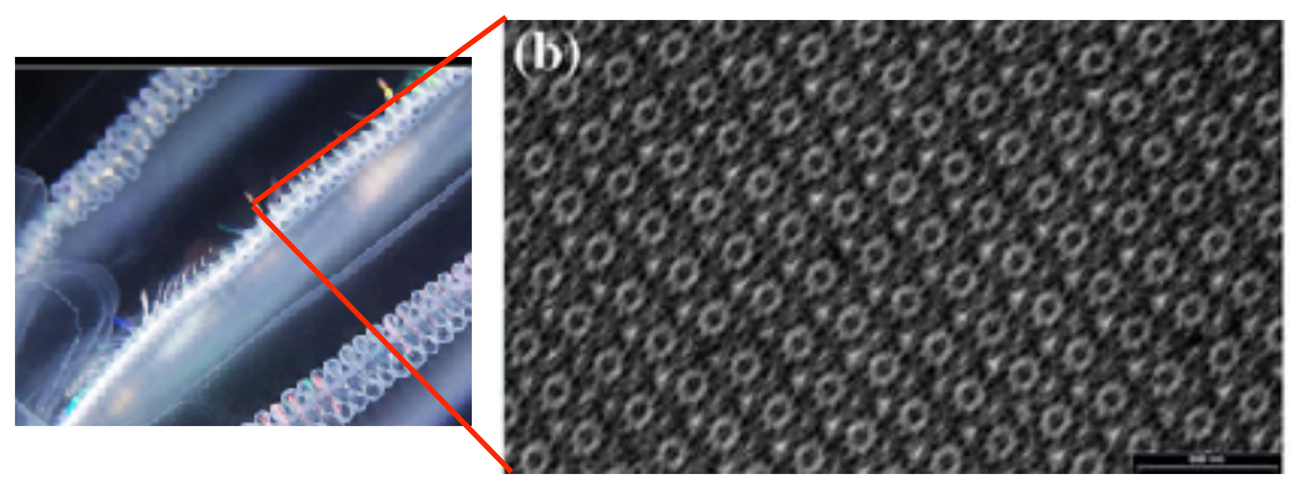


200nm

Comb Jelly (real time)

https://www.youtube.com/watch?v=Qy90d0XvJIE

Rainbow color waves are produced by the beating of cilia, which change the orientation of periodic structure from which the ambient light is reflected.



$1\mu m$

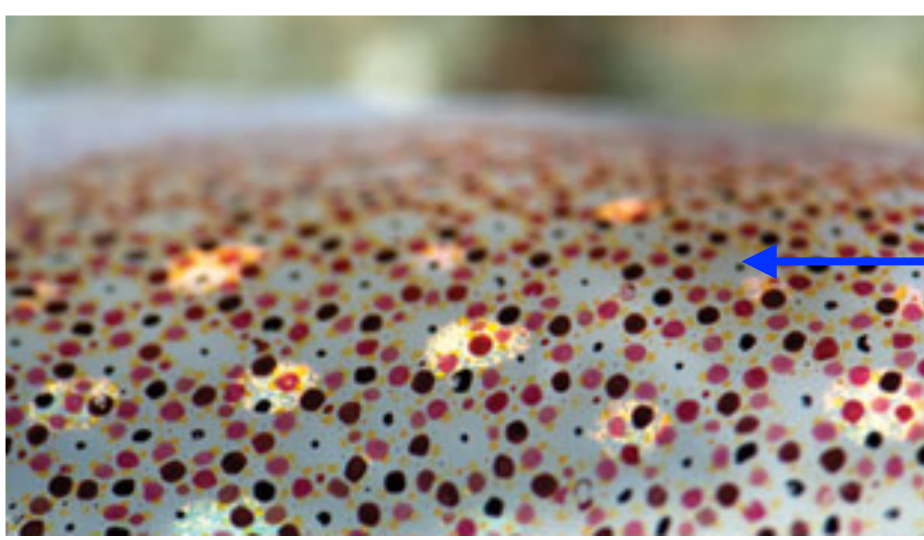
Dynamic colors in cephalopods

octopus

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

squid

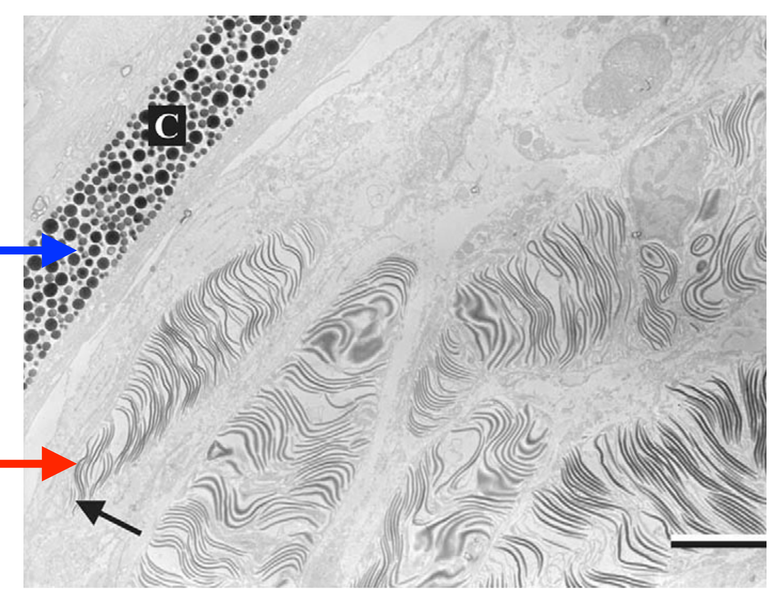
Dynamical color change in cephalopod is achieved by modulation of size and spacing of both the pigment cells and the cells reflecting light.



squid skin surface

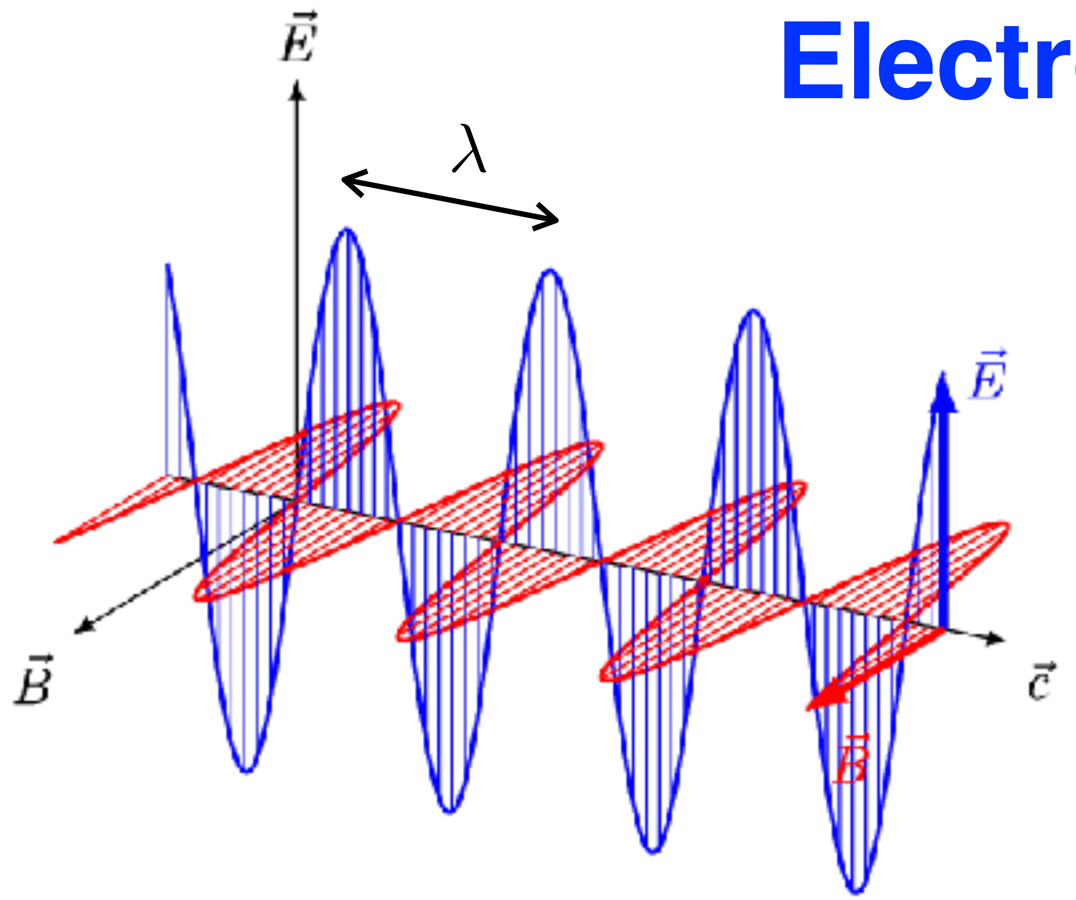
chromatophores (pigment cells)

iridophores (reflecting light)



$7.5\mu m$

Electromagnetic waves



electric field

magnetic field

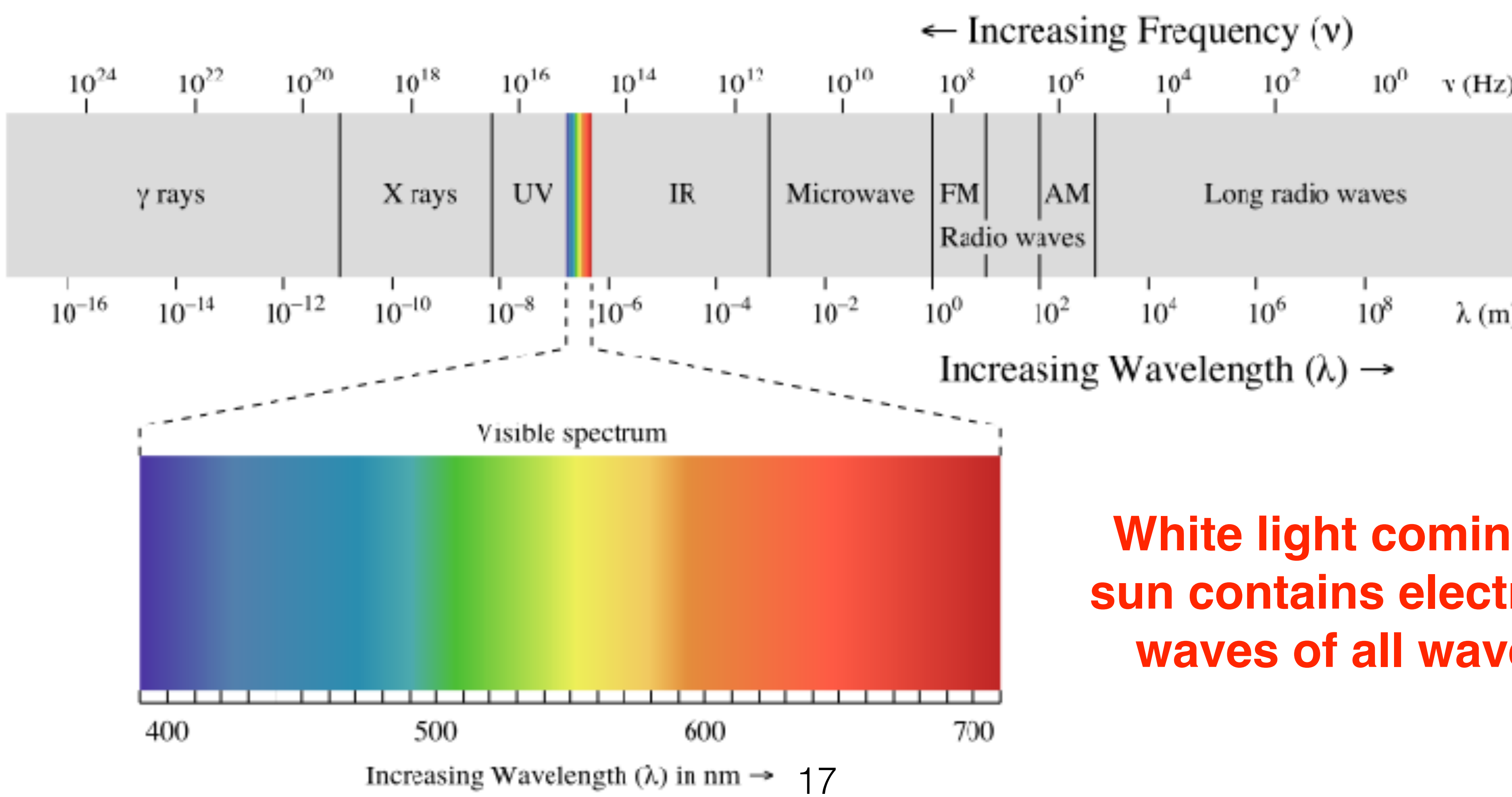
$$c^2 \vec{B}_0 = \vec{c} \times \vec{E}_0$$

speed of light

$$c_0 = \lambda \nu = 3 \times 10^8 \mathrm{m/s}$$

wavelength λ

frequency ν



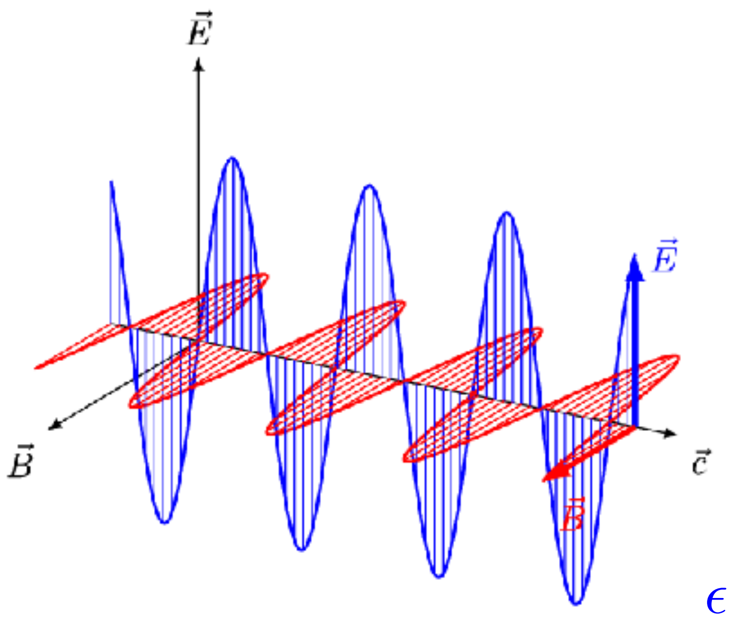
White light coming from the sun contains electromagnetic waves of all wavelengths!

Wave equation

$$\frac{\partial^2 u}{\partial t^2} = c^2 \nabla^2 u$$

Solutions are traveling waves with velocity c.

electromagnetic waves



$$c = \frac{1}{\sqrt{\epsilon\mu}}$$

ϵ permittivity

μ permeability

waves in ropes under tension

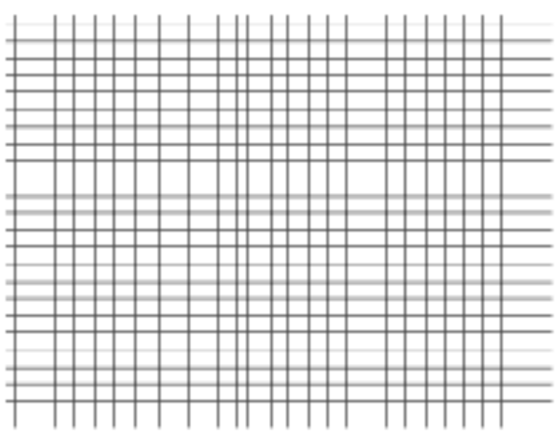
$$c = \sqrt{\frac{F}{\rho A}}$$

F tensile force

ρ mass density

A cross-section area

sound waves

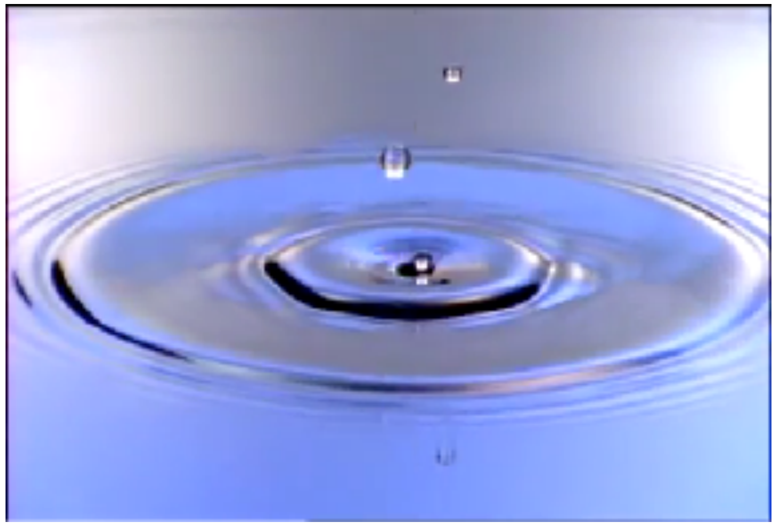


$$c = \sqrt{\frac{K}{\rho}}$$

K bulk modulus

ρ mass density

waves on liquid surfaces



shallow water

$$c = \sqrt{gh}$$

deep water

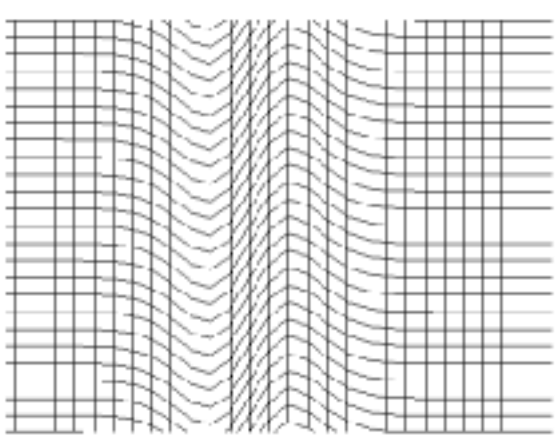
$$c = \sqrt{\frac{g\lambda}{2\pi}}$$

g gravitational const.

h water depth

λ wavelength

shear waves

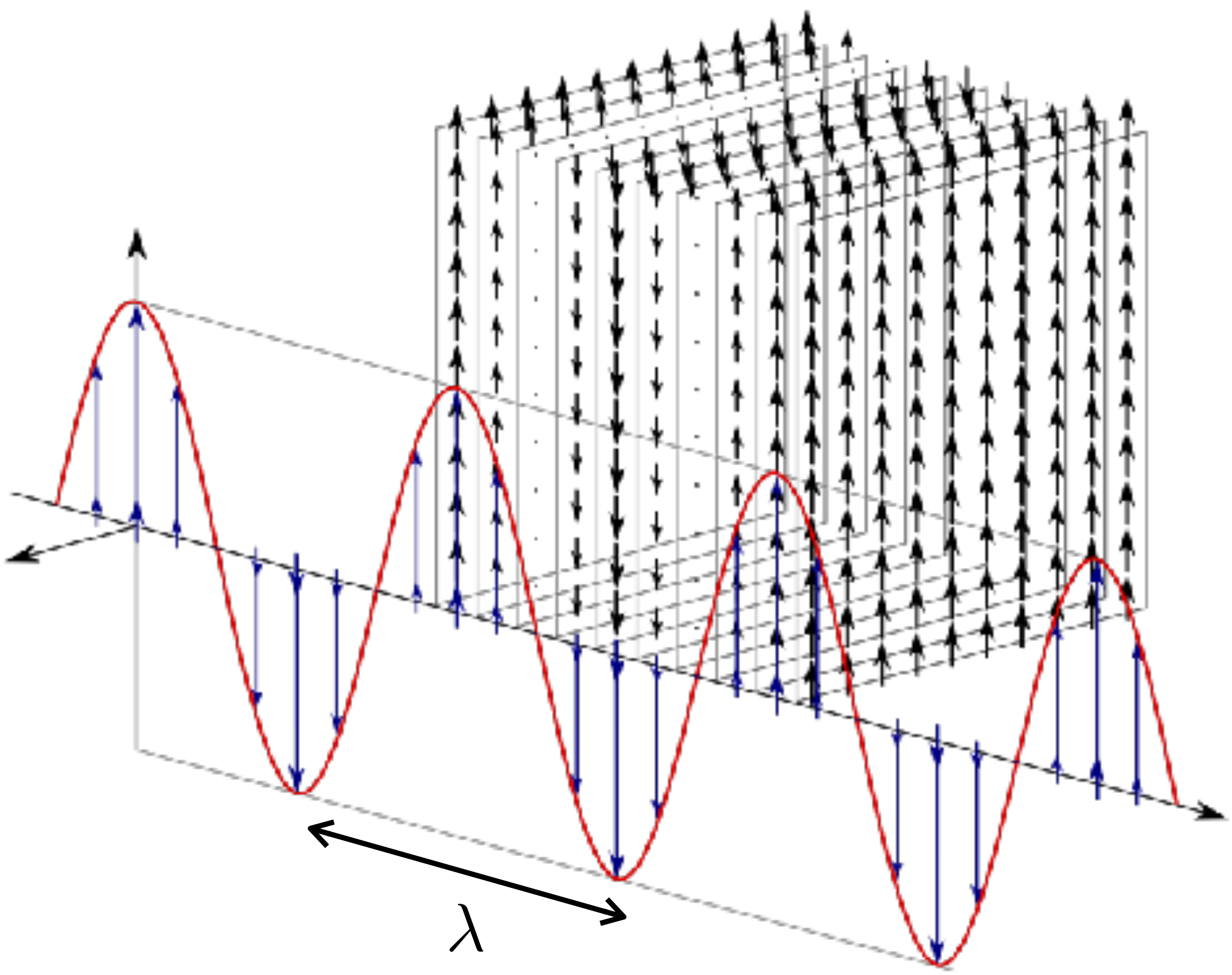


$$c = \sqrt{\frac{\mu}{\rho}}$$

μ shear modulus

ρ mass density

Plane waves



Planes of constant phases:

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

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**

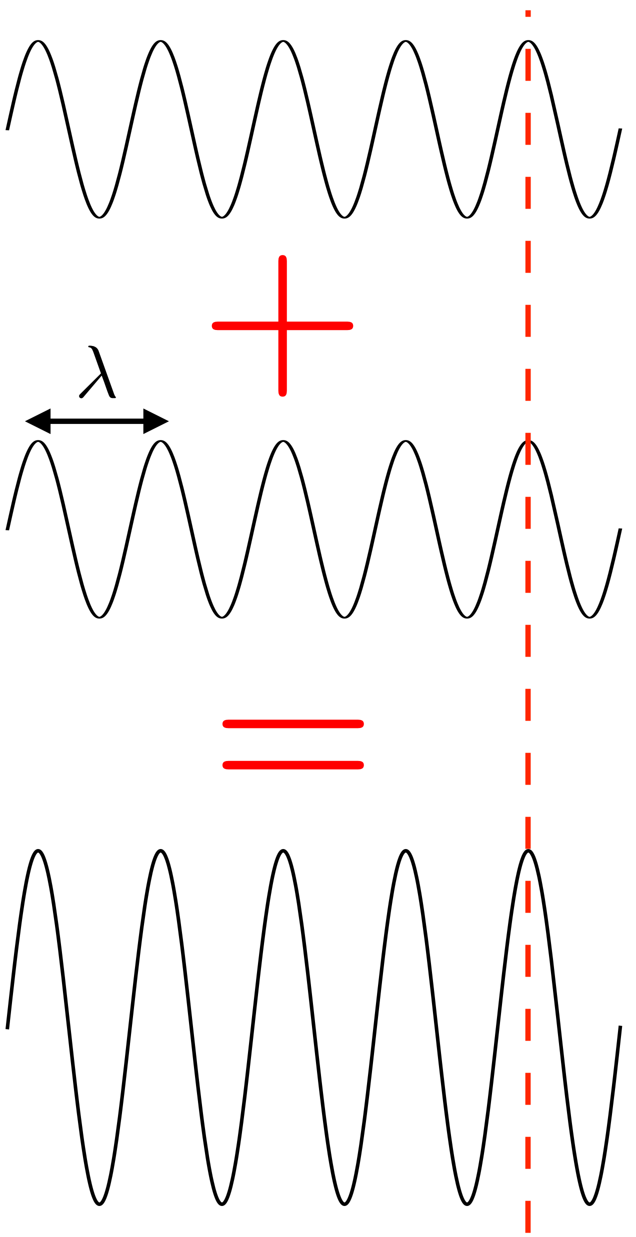
Plane waves travel in direction of $\vec{k}$ with velocity:

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

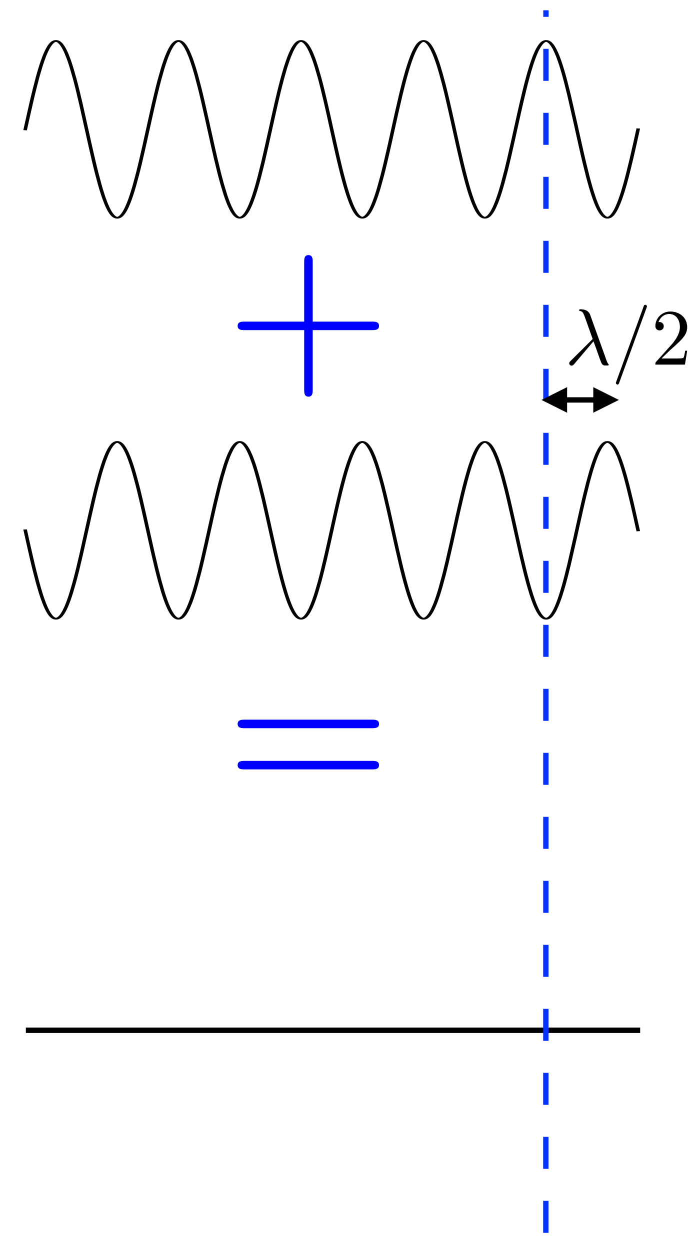
Note: velocity of plane waves may depend on the wavevector $c(\vec{k})$!

Interference

constructive interference



destructive interference



Constructive interference occurs when the two waves are in phase: waves offset by $m\lambda$,

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

$$e^{ikm\lambda} = e^{i2\pi m} = +1$$

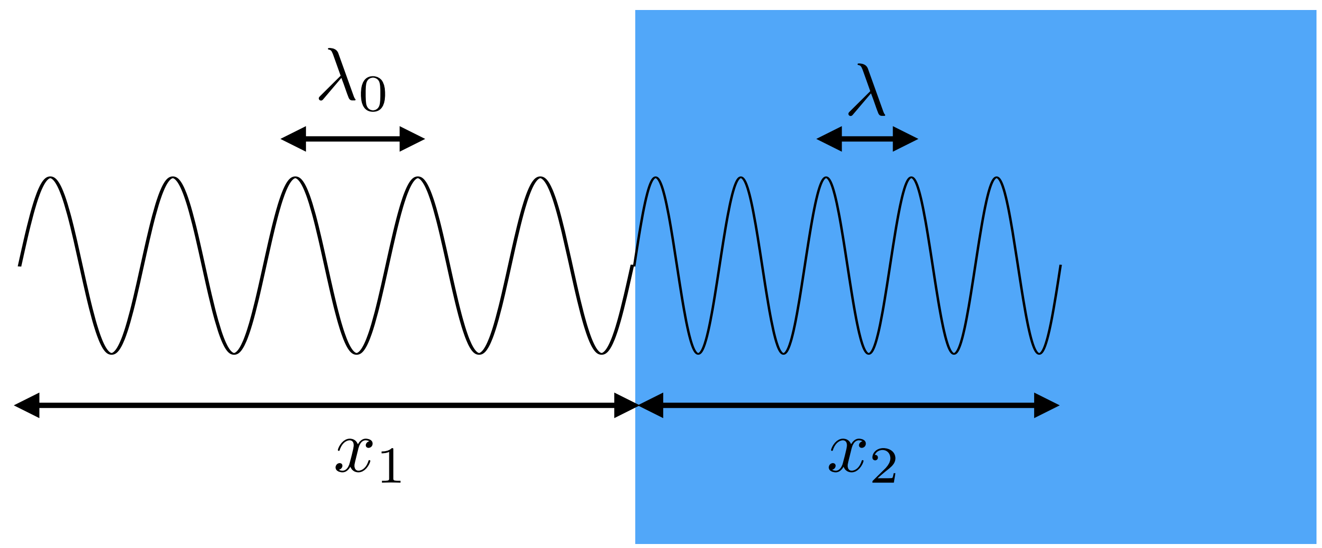
Destructive interference occurs when the two waves are out of phase: waves offset by $(m + 1/2)\lambda$,

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

$$e^{ik(m+1/2)\lambda} = e^{i(2\pi m + \pi)} = -1$$

Propagation of light in medium

	vacuum	medium with index of refraction *n>1*



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

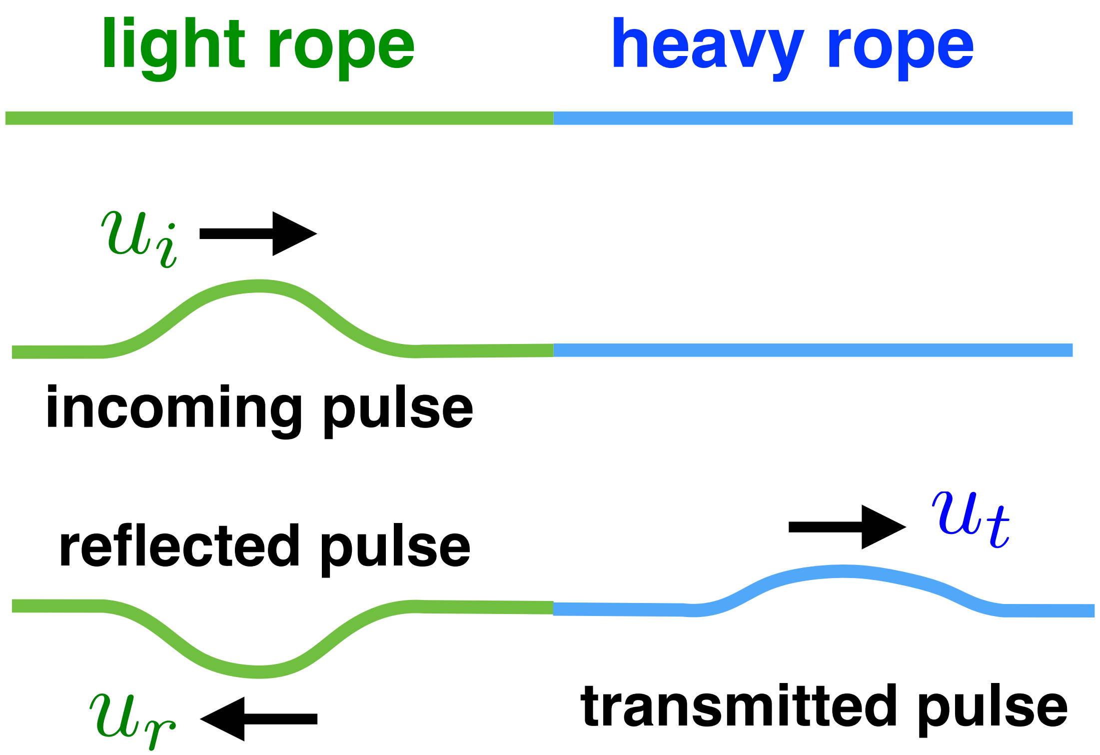
---

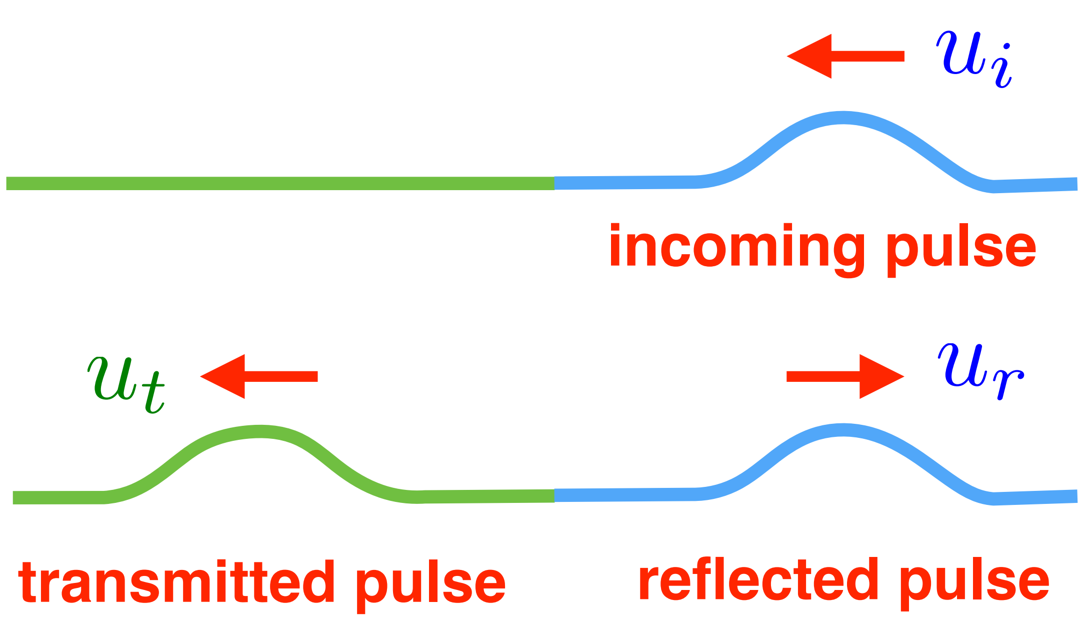
total number of cycles

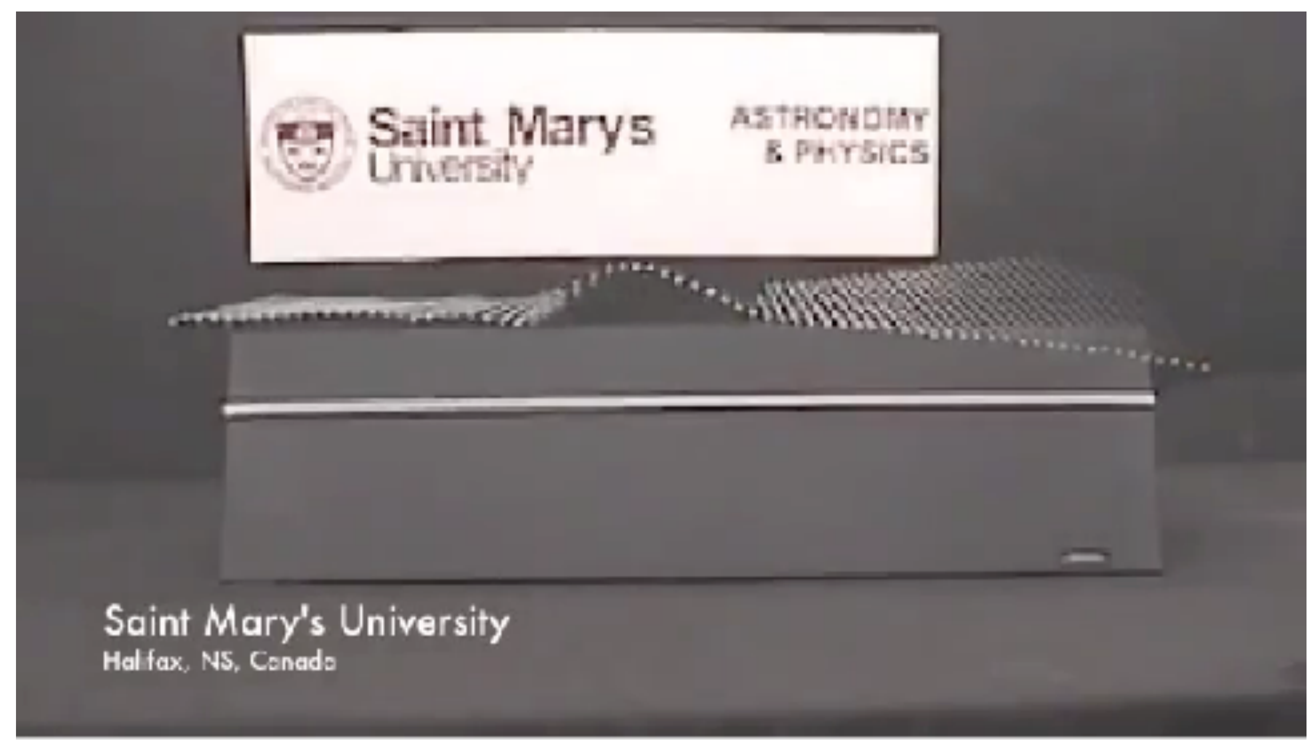
$$\frac{x_1}{\lambda_0} + \frac{x_2}{\lambda} = \frac{x_1 + n x_2}{\lambda_0}$$

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

Reflection of waves







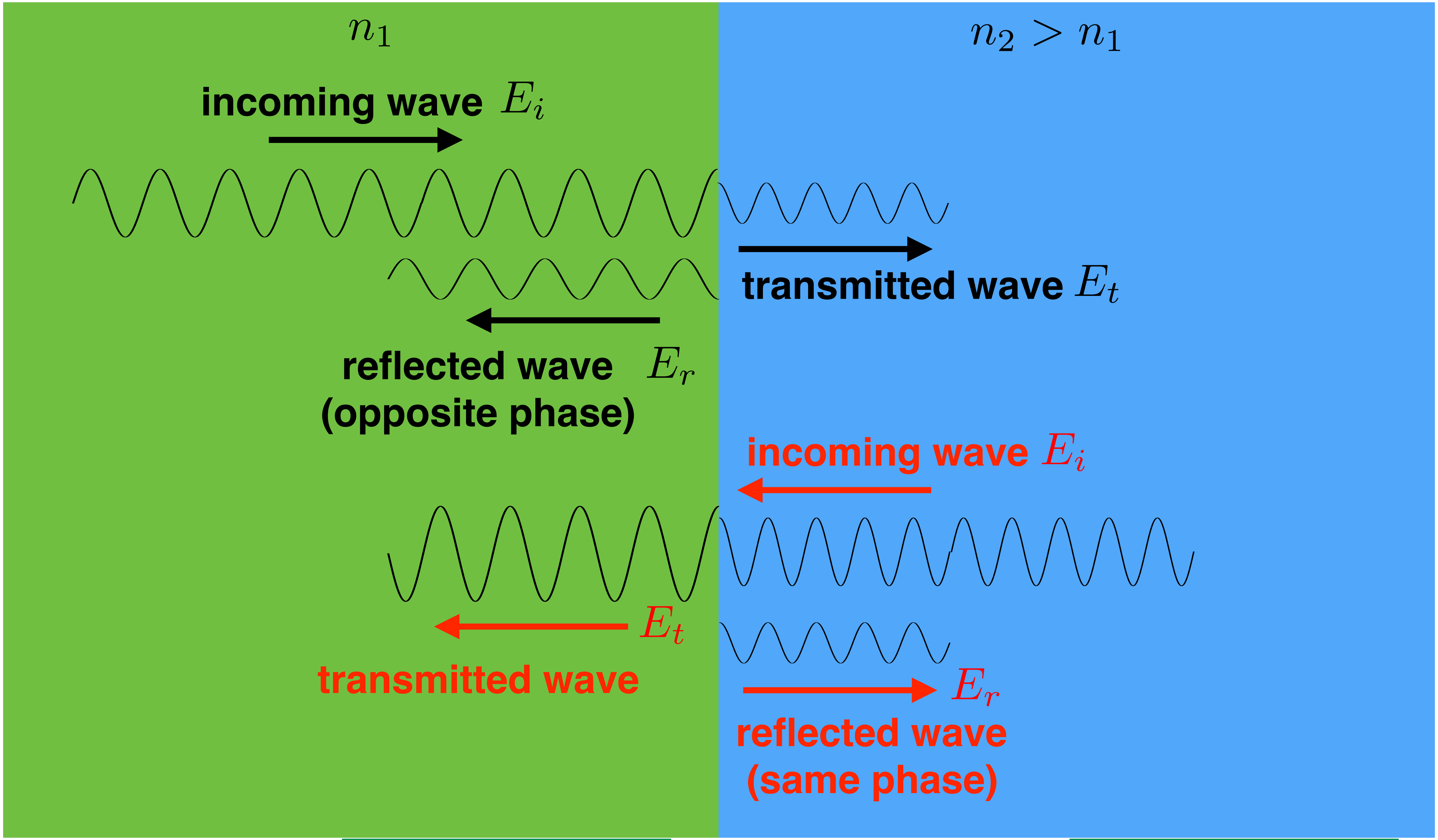
amplitude of reflected pulse

$$\frac{u_r}{u_i} = \frac{c_2 - c_1}{c_1 + c_2}$$

amplitude of transmitted pulse

$$\frac{u_t}{u_i} = \frac{2c_2}{c_1 + c_2}$$

Reflection of light at the interface between two media



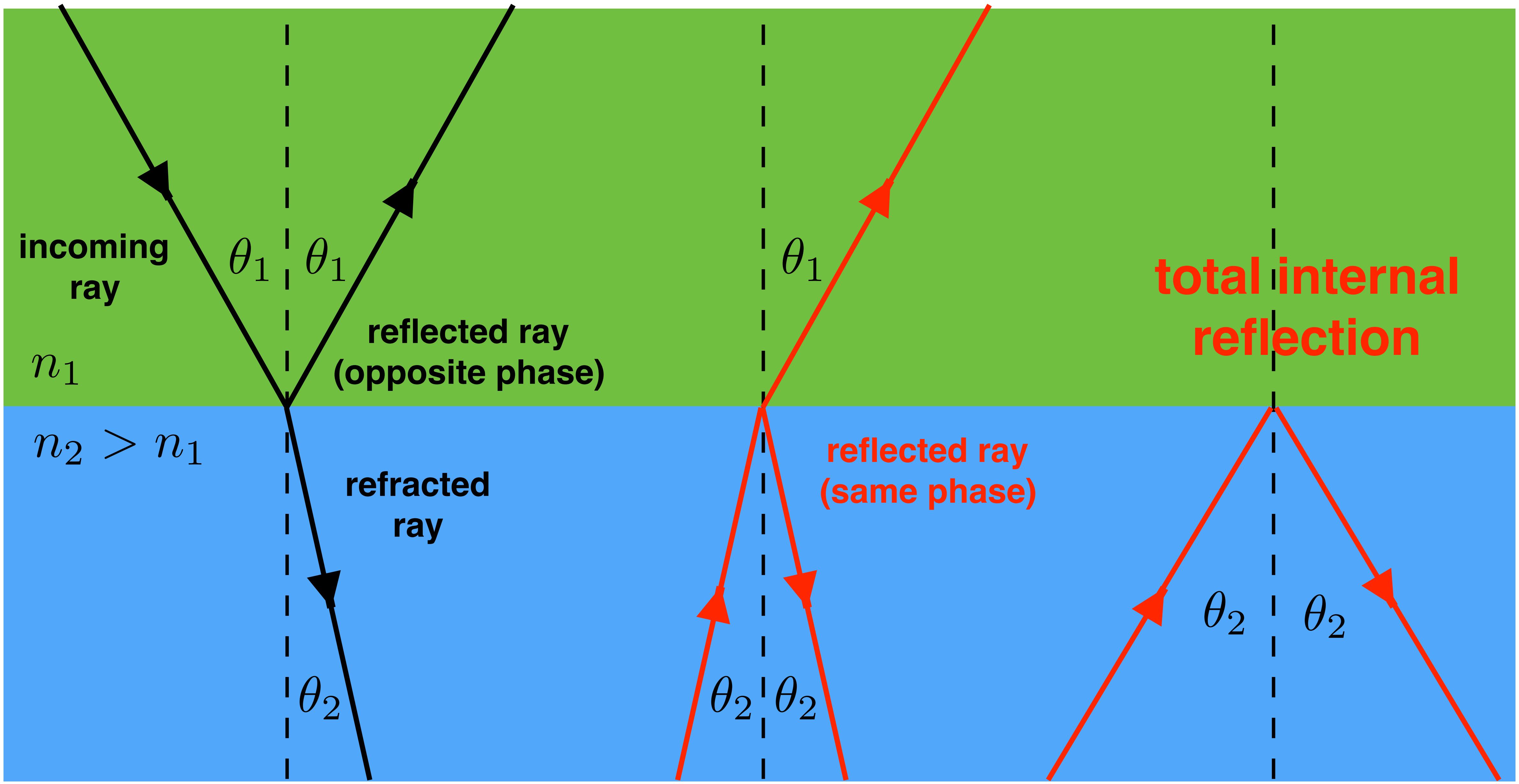
amplitude of reflected electric field

$$\frac{E_r}{E_i} = \frac{n_1 - n_2}{n_1 + n_2}$$

amplitude of transmitted electric field

$$\frac{E_t}{E_i} = \frac{2n_1}{n_1 + n_2}$$

Refraction of light



Snell's law

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

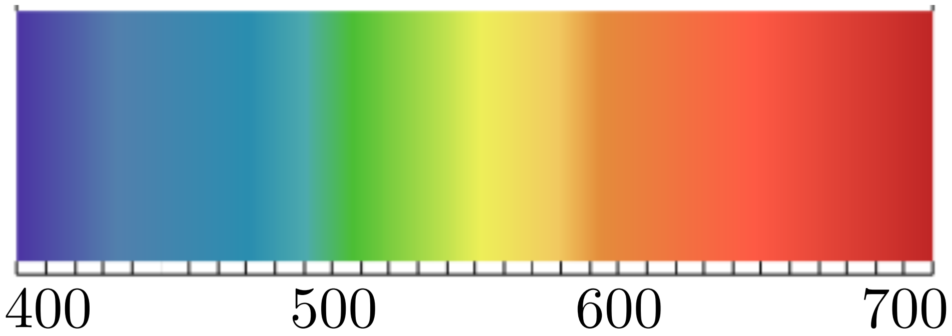
Total internal reflection

$$\theta_2 > \arcsin(n_1/n_2)$$

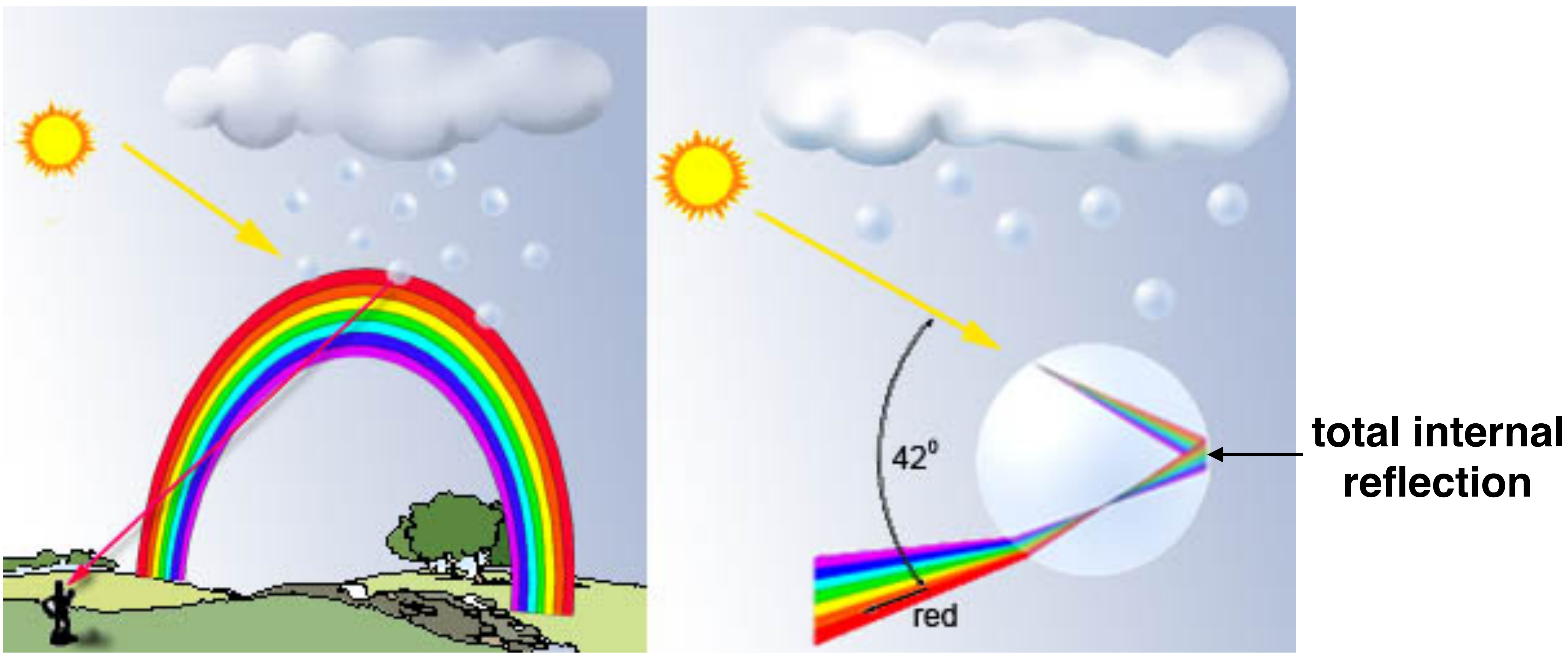
Rainbow

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

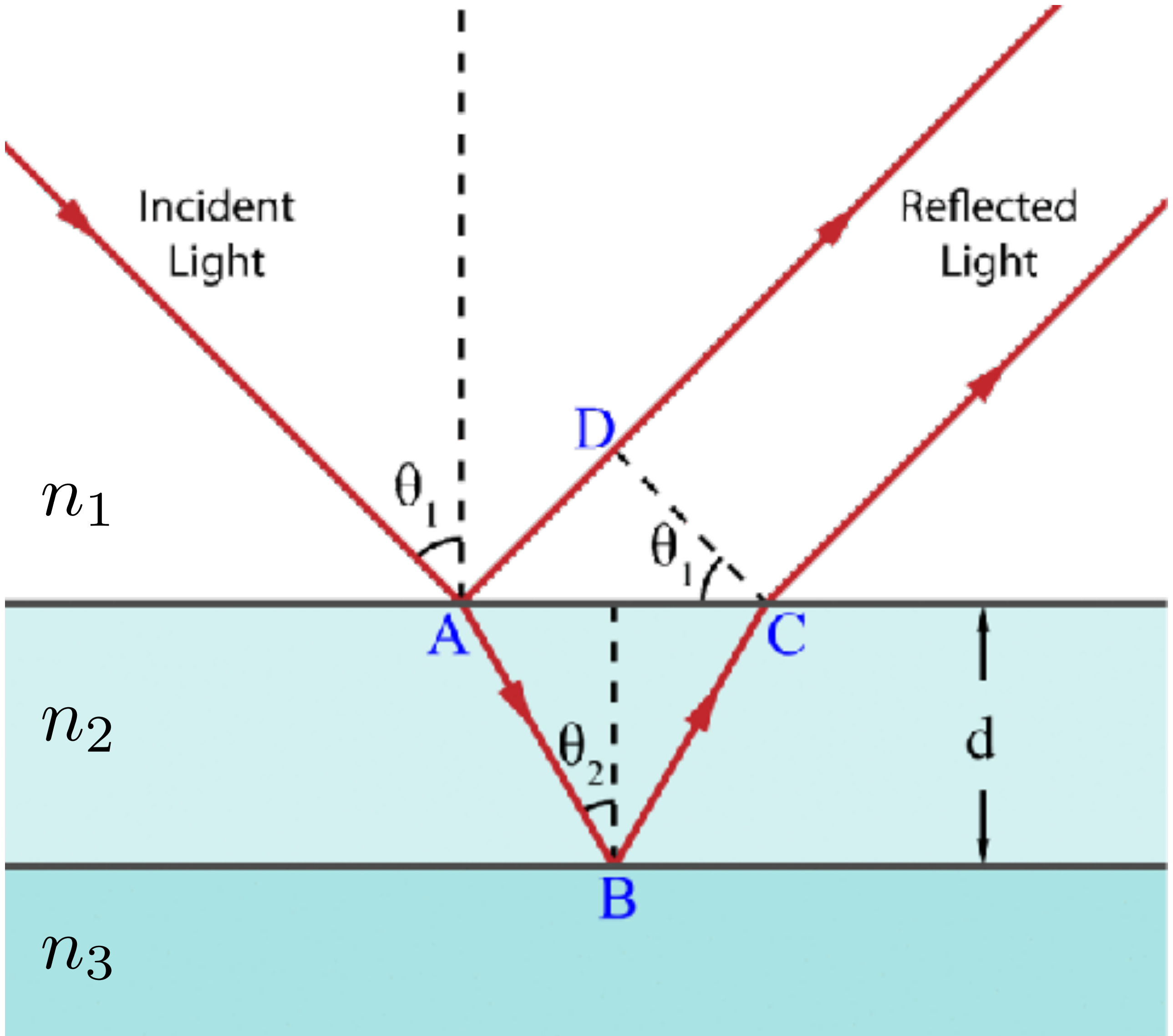
$$n_{\text{purple}} > n_{\text{blue}} > n_{\text{green}} > n_{\text{yellow}} > n_{\text{orange}} > n_{\text{red}}$$



wavelength $\lambda[\text{nm}]$



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

$n_1 < n_2 < n_3$ $\quad$ $n_1 > n_2 > n_3$

constructive interference

$$OPD = m\lambda$$

destructive interference

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

$$m = 0, \pm1, \pm2, \ldots$$

additional π phase difference due to reflections

$n_1 < n_2 > n_3$ $\quad$ $n_1 > n_2 < n_3$

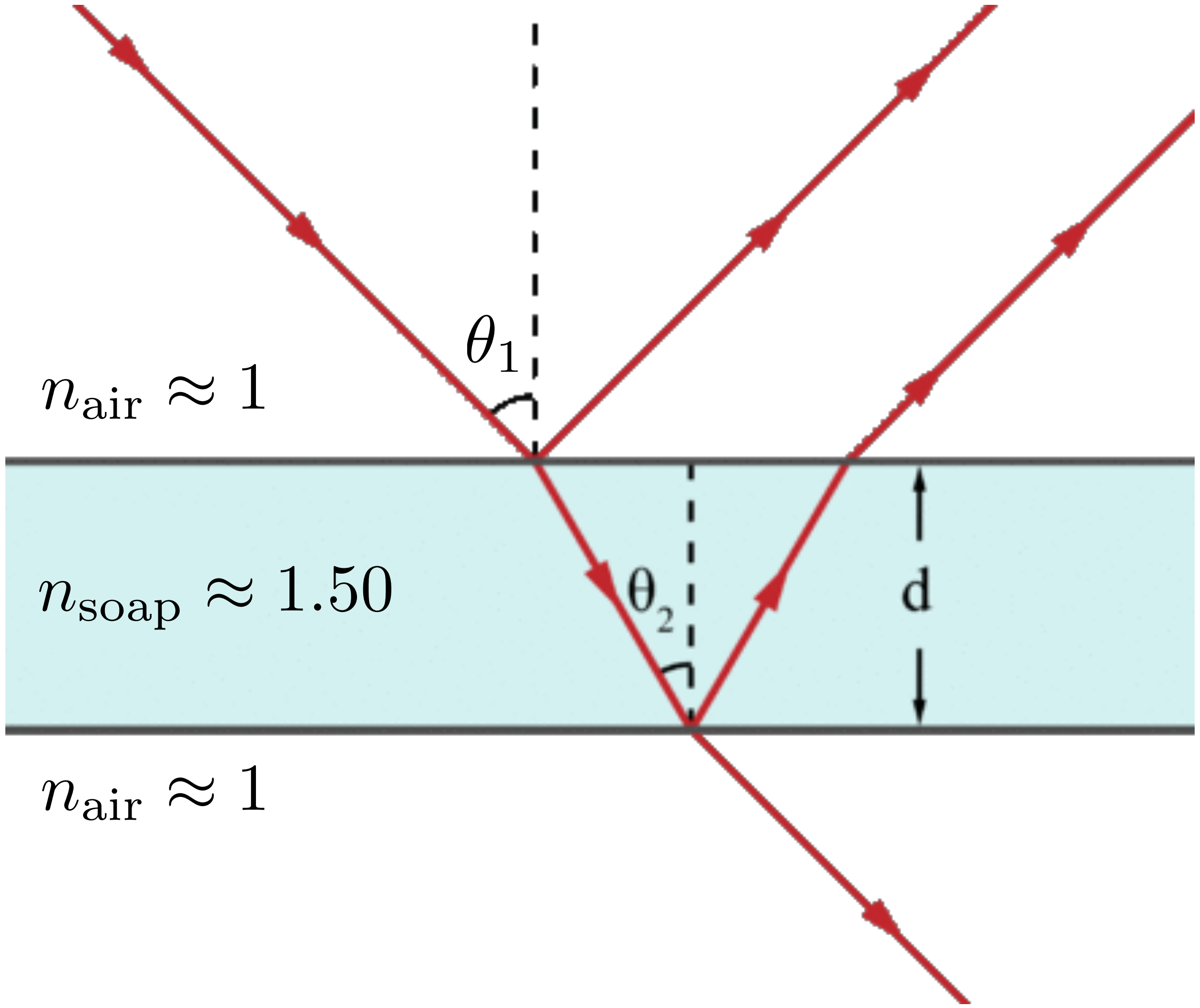
constructive interference

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

destructive interference

$$OPD = m\lambda$$

Interference on soap bubbles



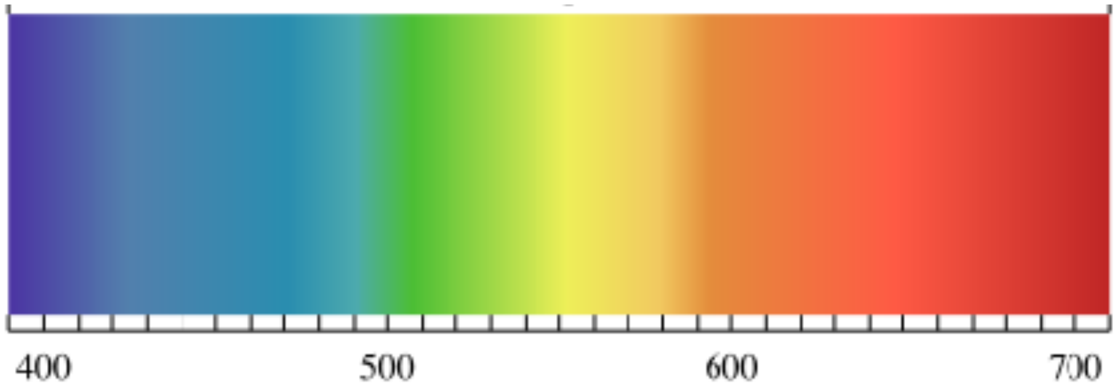
soap bubble

constructive interference for different colors happens at different angles

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

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

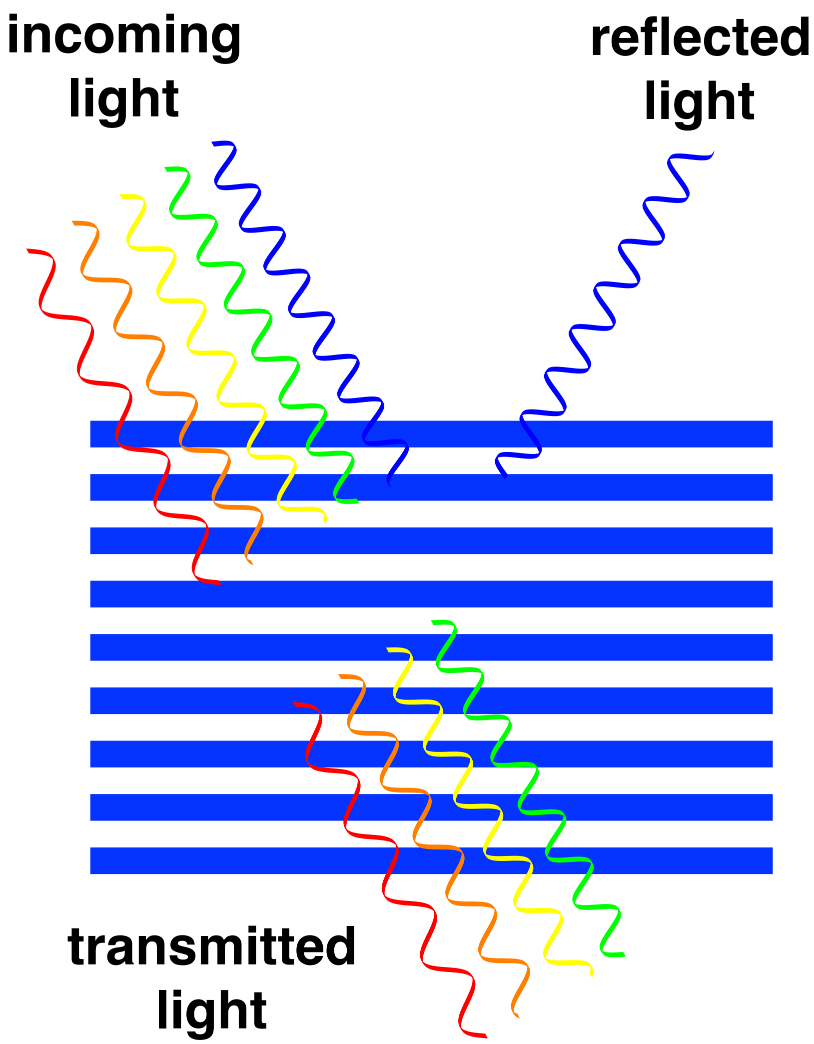
visible spectrum

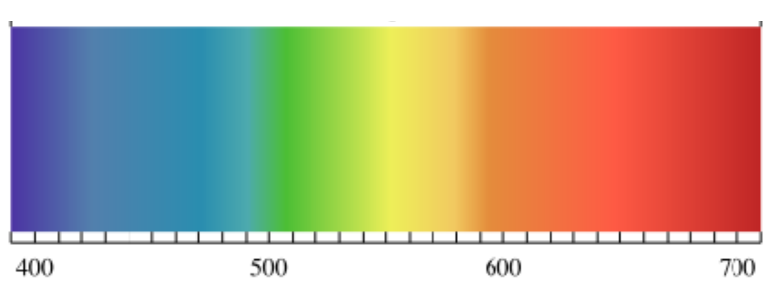


wavelength $\lambda[\text{nm}]$

Single structural color

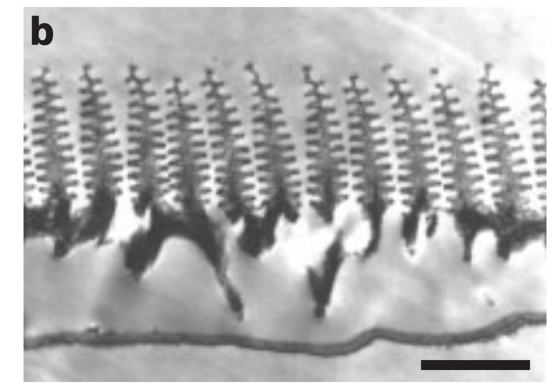
Single reflected color on structures with uniform spacing





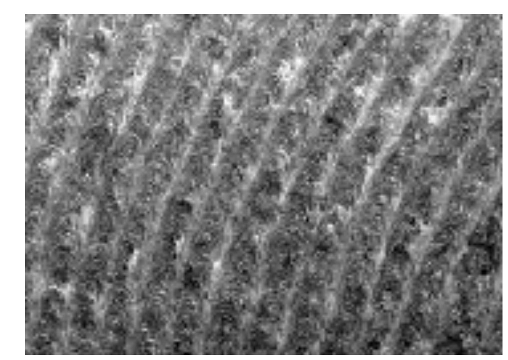
wavelength $\lambda[\text{nm}]$

Morpho butterfly



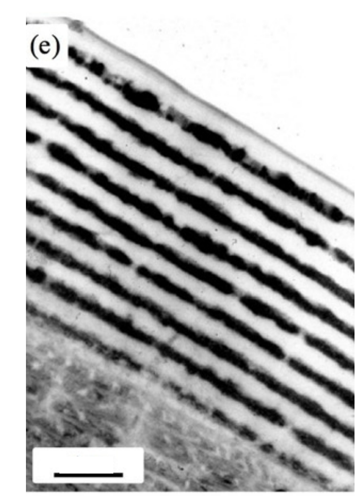
$1.7\mu m$

Marble berry



250nm

Chrysochroa raja bettle



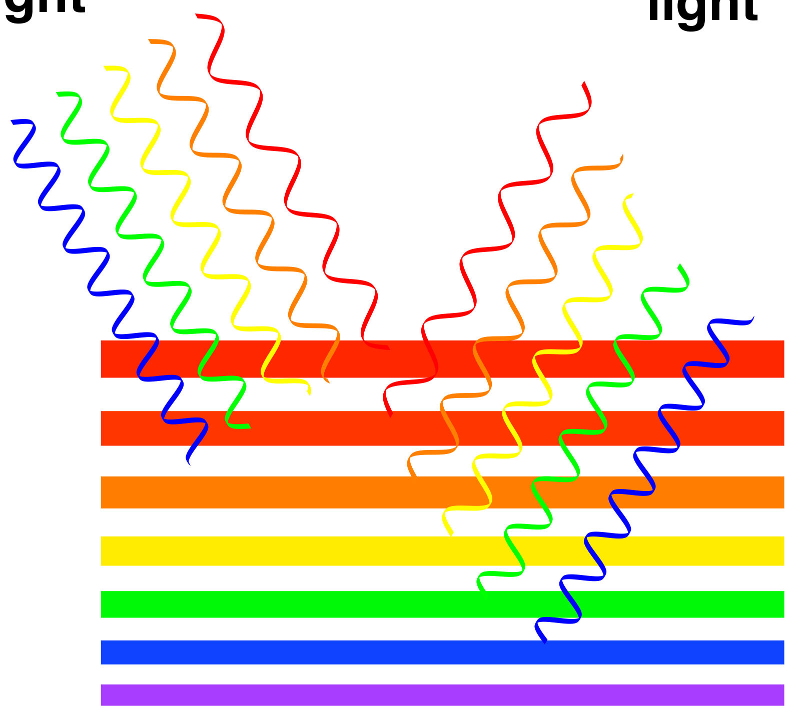
$1\mu m$

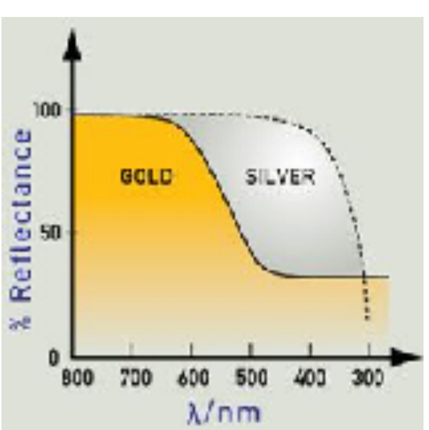
Silver and gold structural colors

Many colors reflected on structures with varying spacing

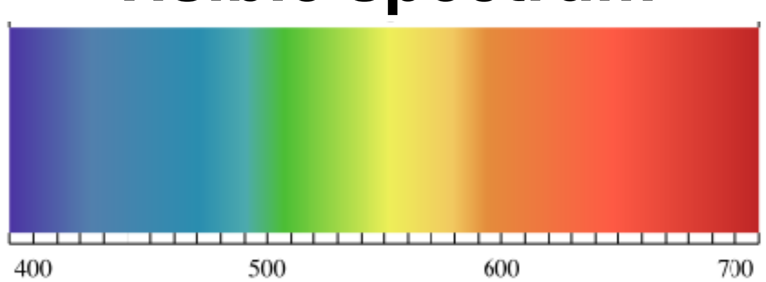
incoming light

reflected light





visible spectrum

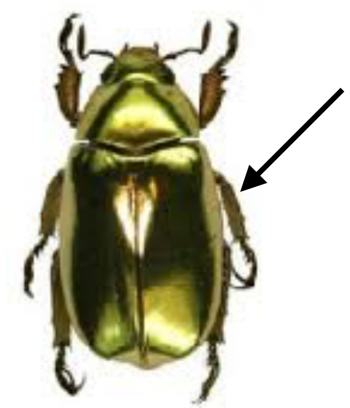


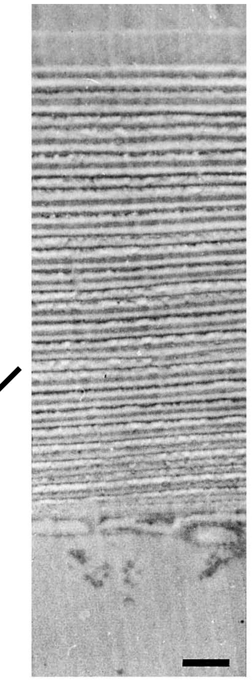
wavelength $\lambda[\mathrm{nm}]$

chirped structure

Chrysina limbata beetle

Chrysina aurigans beetle





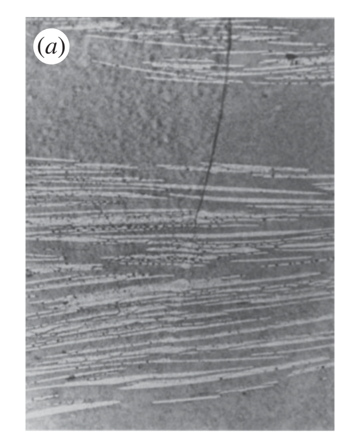
$1\mu\mathrm{m}$

thicker

thinner

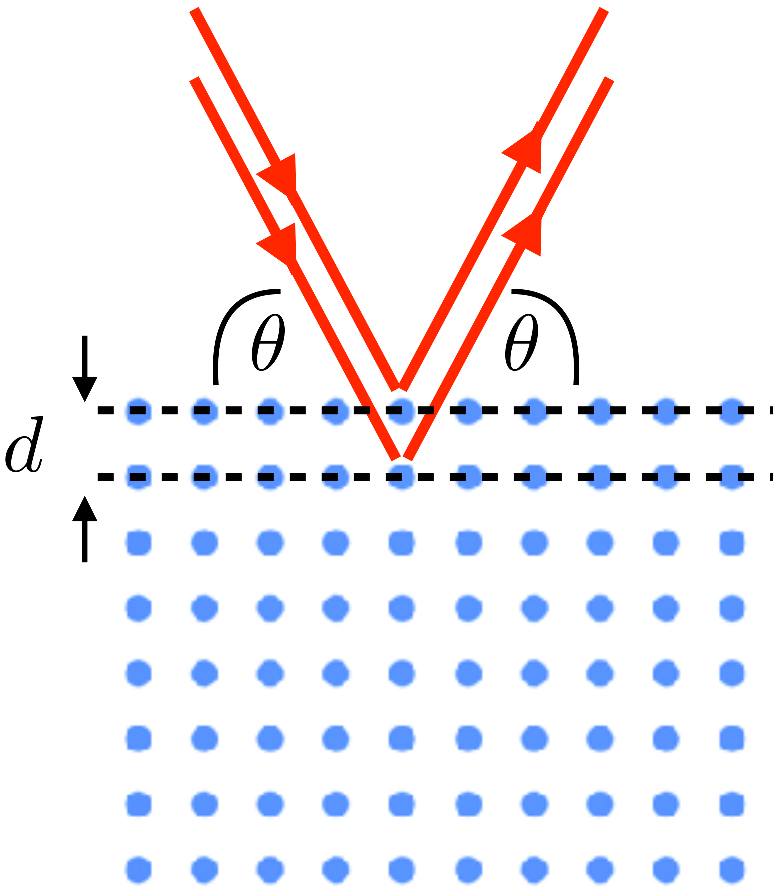
disordered layer spacing

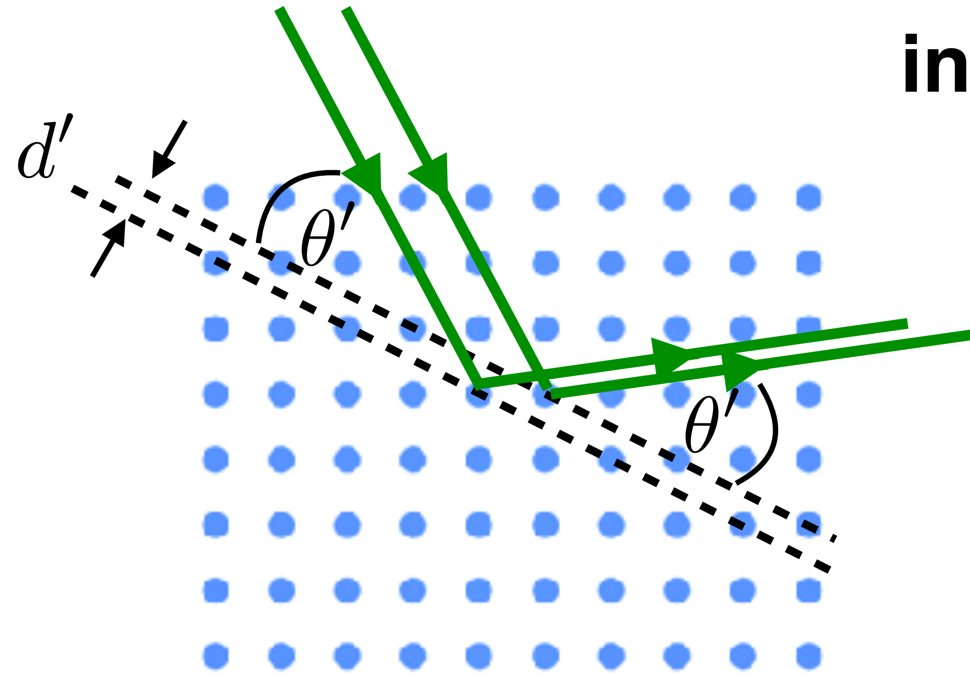
bleak fish



$1\mu\mathrm{m}$

Bragg scattering on crystal layers





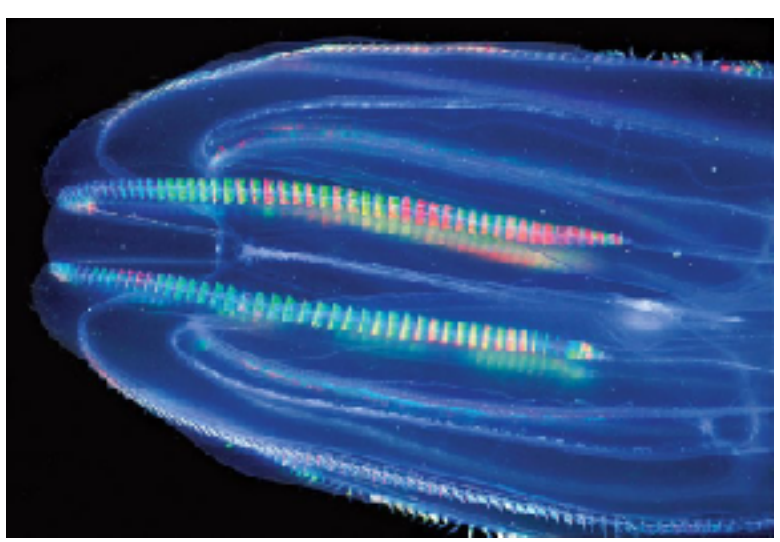
constructive interference condition

$$2d \sin\theta = m\lambda$$

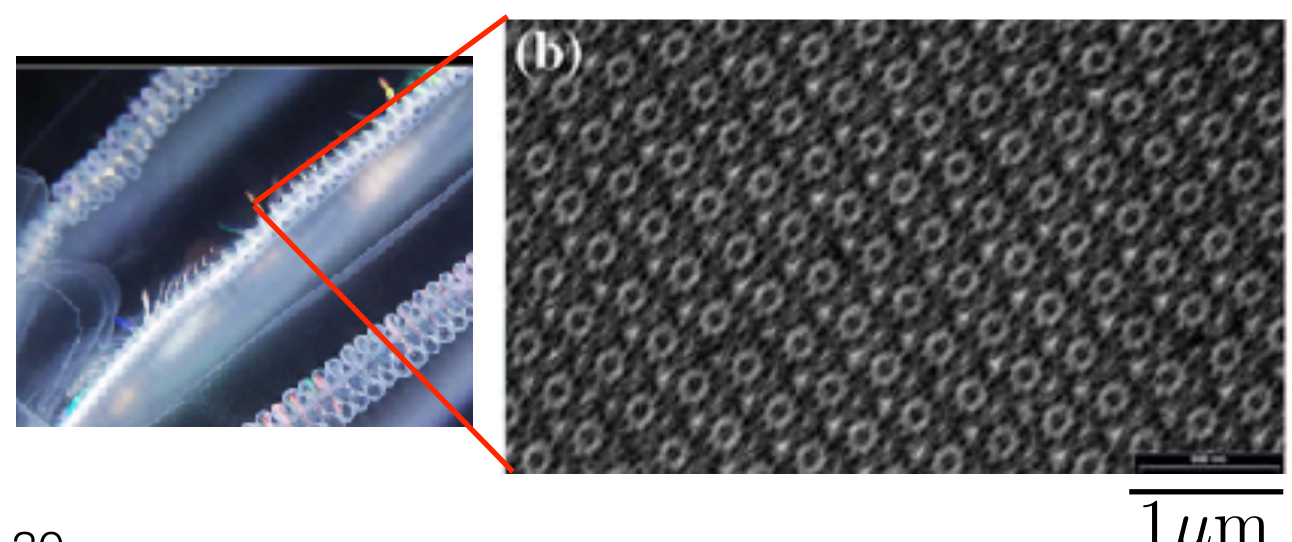
$$2d' \sin\theta' = m\lambda'$$

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

Comb jelly

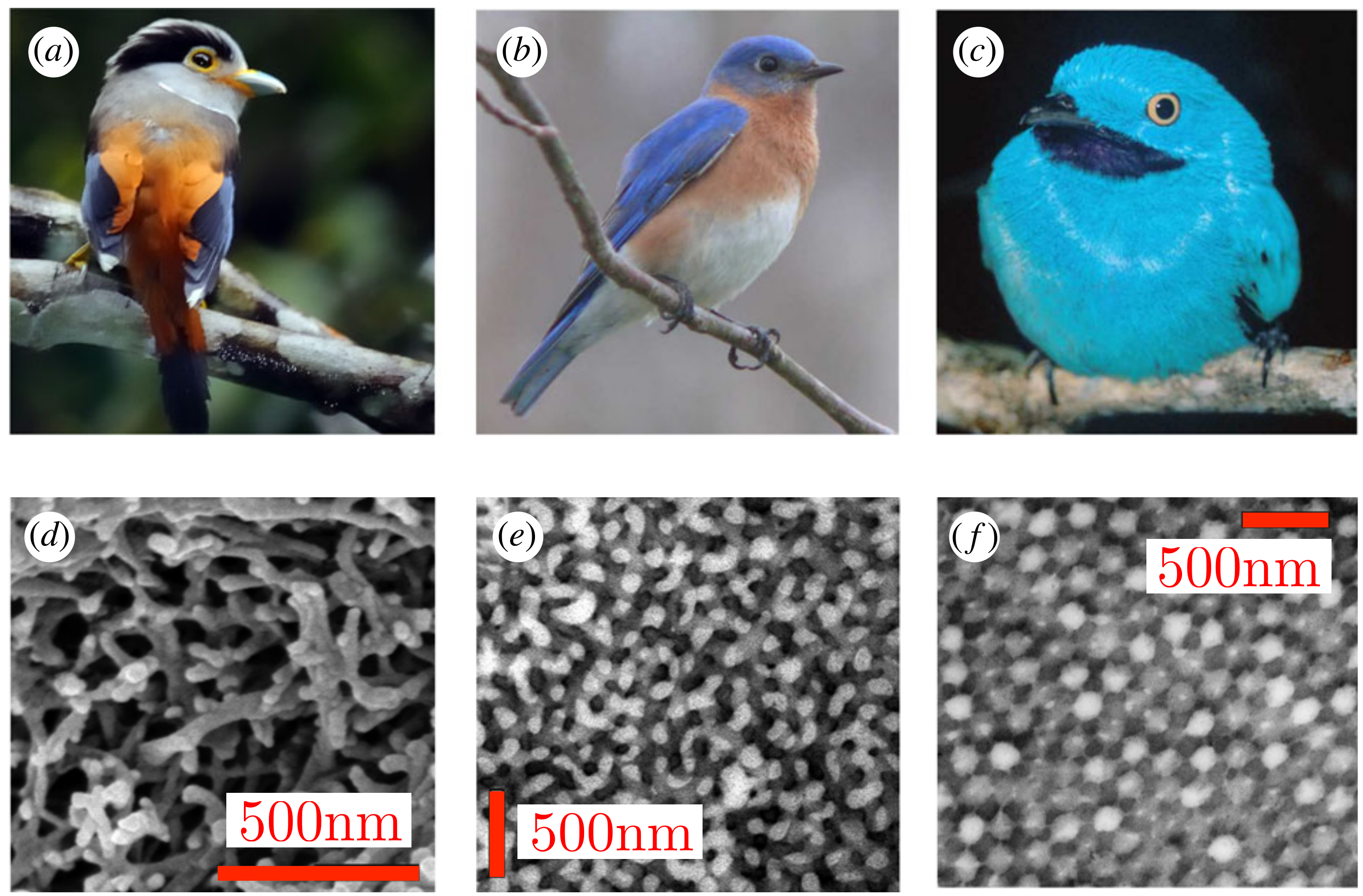


Beating cilia are changing crystal orientation



Scattering on disordered structures

Silver-breasted Broadbill | **Eastern bluebird** | **Plum-throated Cotinga**



Disordered structures with a characteristic length scale.

This length scale determines what light wavelengths are preferentially scattered.

This gives rise to blue colors in birds above.