Structure Colors

Photonic Structures: Discovery, Replication & Application

Photonics (ELEC-E3240)

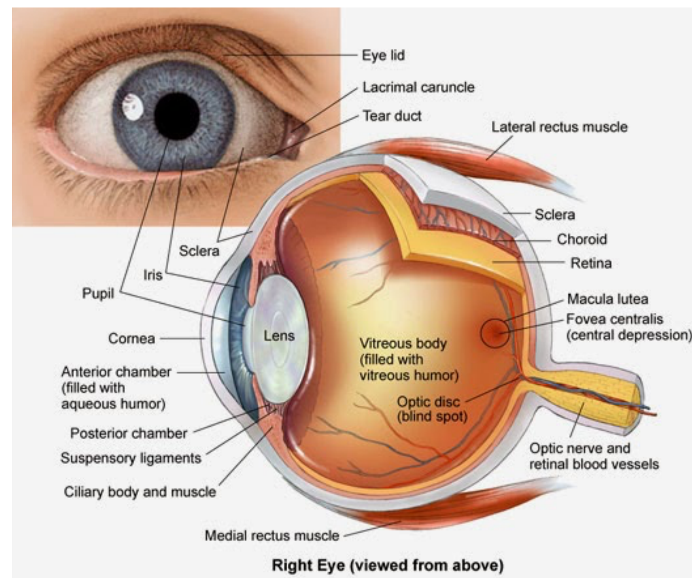
Zhipei Sun

Photonics Group
Department of Electronics and Nanoengineering
Aalto University

What is COLOR?

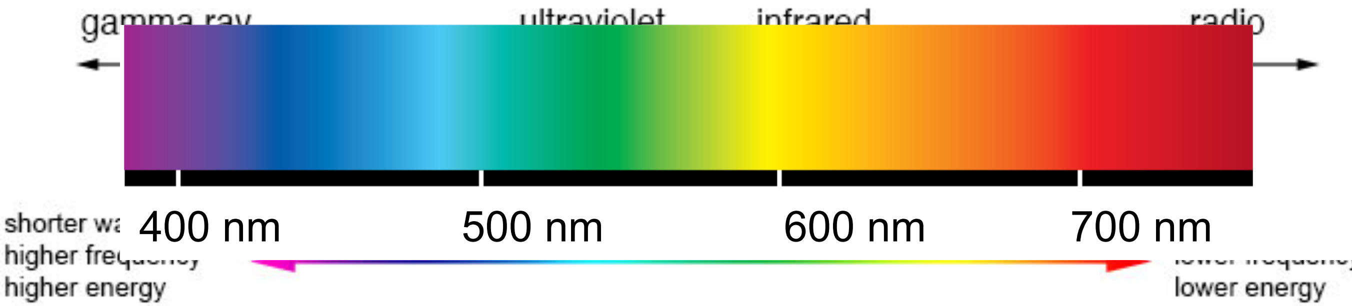
- **Color** is the characteristic of **human visual perception** described through color *categories*, such as red, yellow, green, blue, or purple. (From wikipedia)

- This perception of color derives from **cone cells** in the human eye when they are stimulated by the **reflected (or luminous) light** from objects.



Color generation

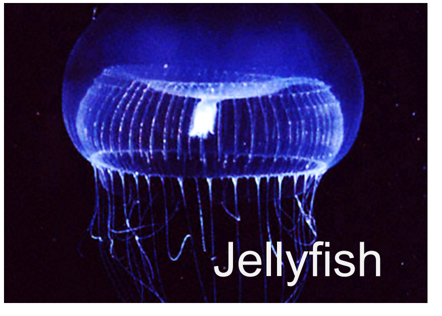
- Color and spectrum



- Color generation in nature

Pigment color

Bioluminescence



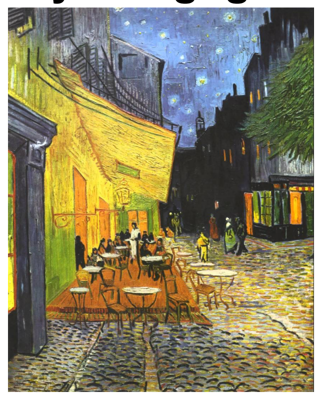
Structure color

parrot

Pigment color

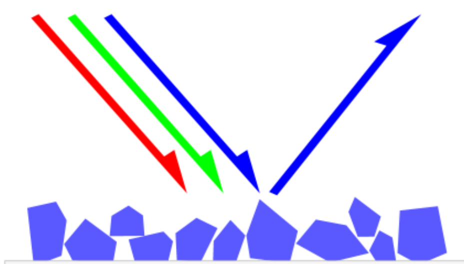
- Tulips from Holland

- Cafe terrace at night
  By van gogh

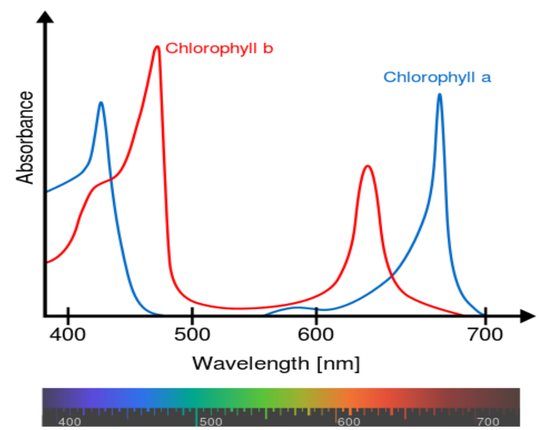


- Eyeshadow from NARS

Selective absorption



Chlorophyll



Transparent Fish (Leptocephalus)

Bioluminescence

Chemical reaction: A + B → C +

Firefly

Jellyfish

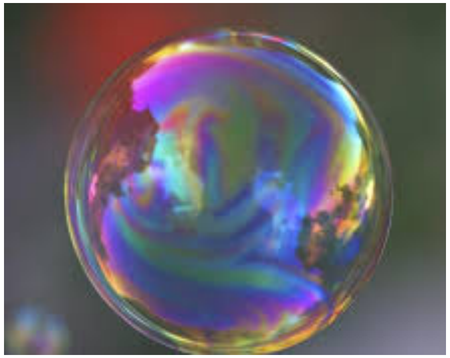
Structural color

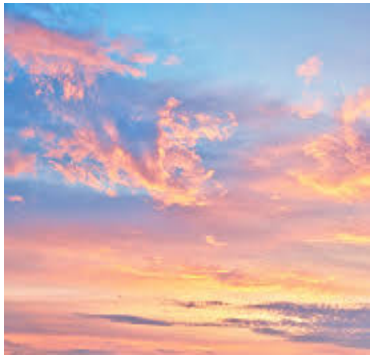
- Interactions between light and photonic structures

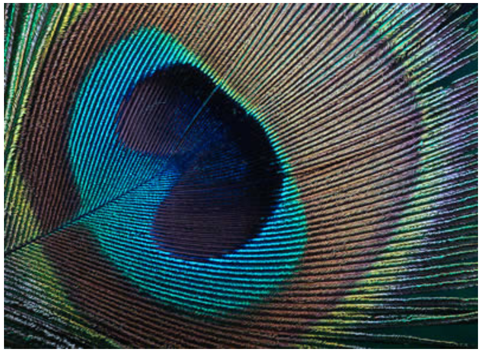
Interference

Diffraction

Scattering



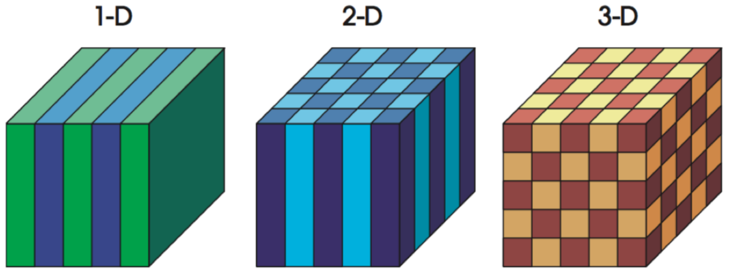




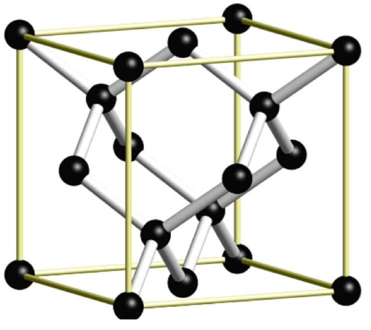
- Communication
- Courtship

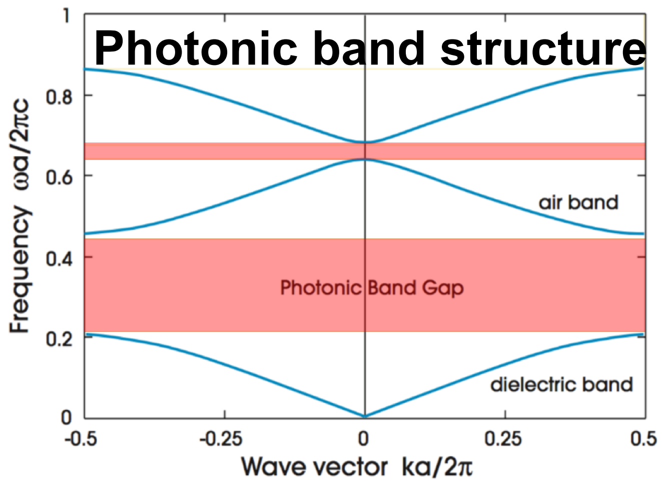
Photonic crystal structures

Photonic crystal:

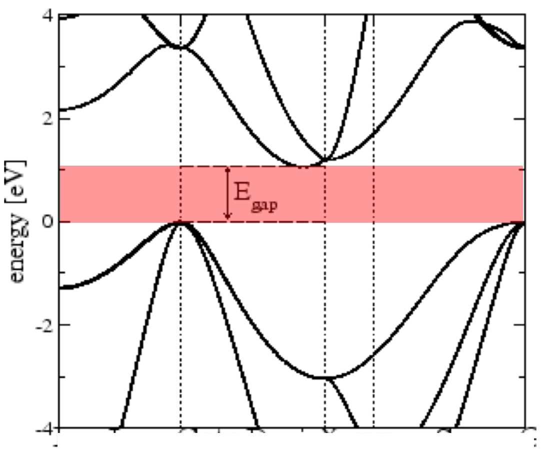


Si Diamond crystal structure





Electric band structure

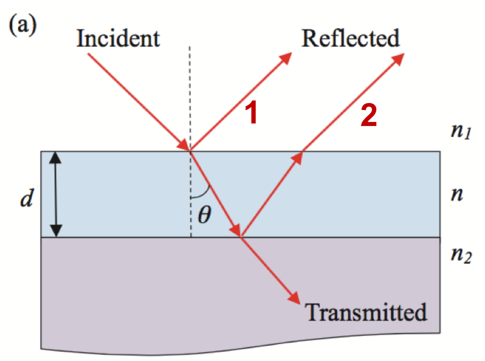


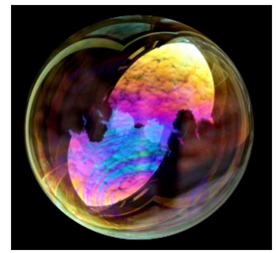
Wave vector k

Mechanism for structural coloration

interference

- Thin film





- **Constructive interference**

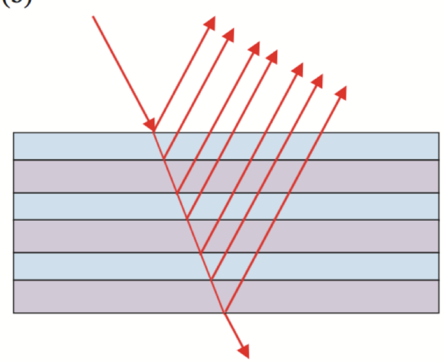
Optical path difference

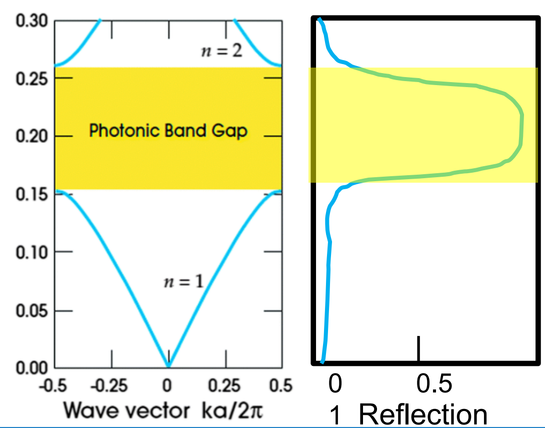
$$2nd\cos\theta = N\lambda$$

n: refractive index
N: order of the mode

- 1D photonic crystal

(b)





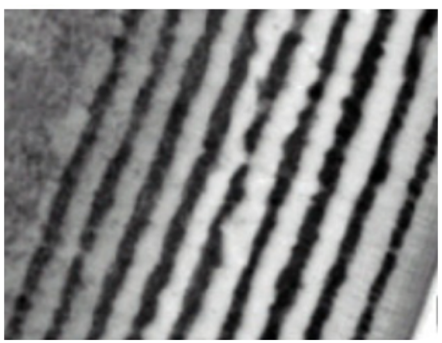
Parameters

- Refractive index
- Thickness
- Period (filling fraction)
- Incidence/Observation angles

Photonic crystals (PCs) in nature

1D PCs

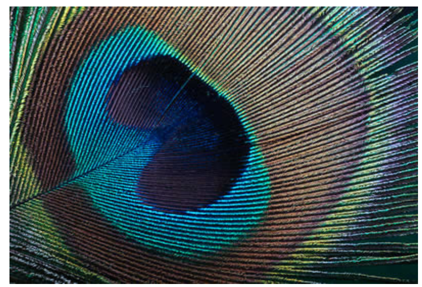
(beetle)

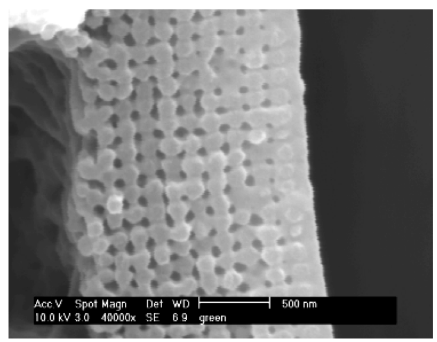


Parker *et al*., JEB 1998

2D PCs

(peacock)

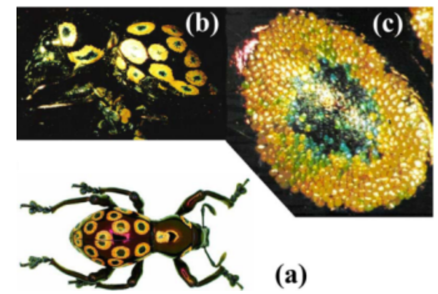


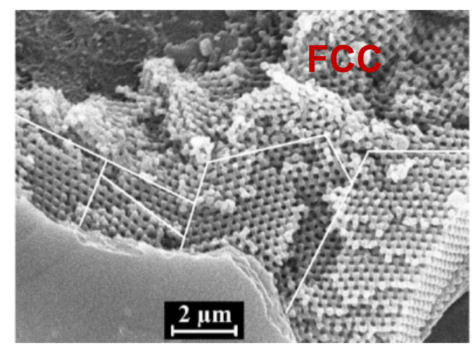


Zi *et al*., PNAS 2003

3D PCs

(weevil)





Welch *et al*., PRE 2007

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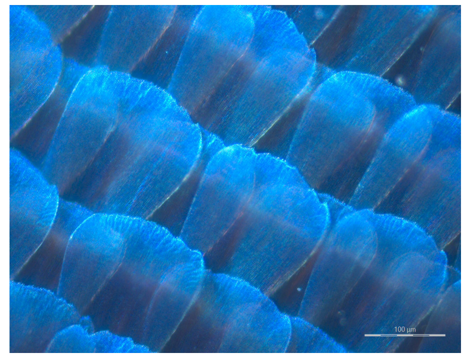
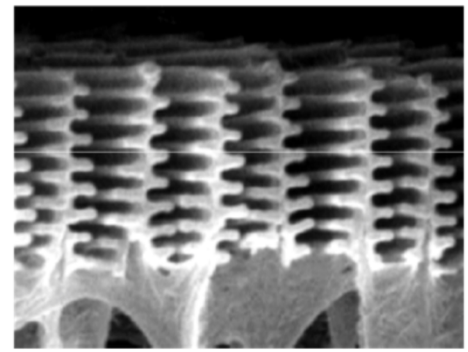
Photonic crystals (PCs) in nature

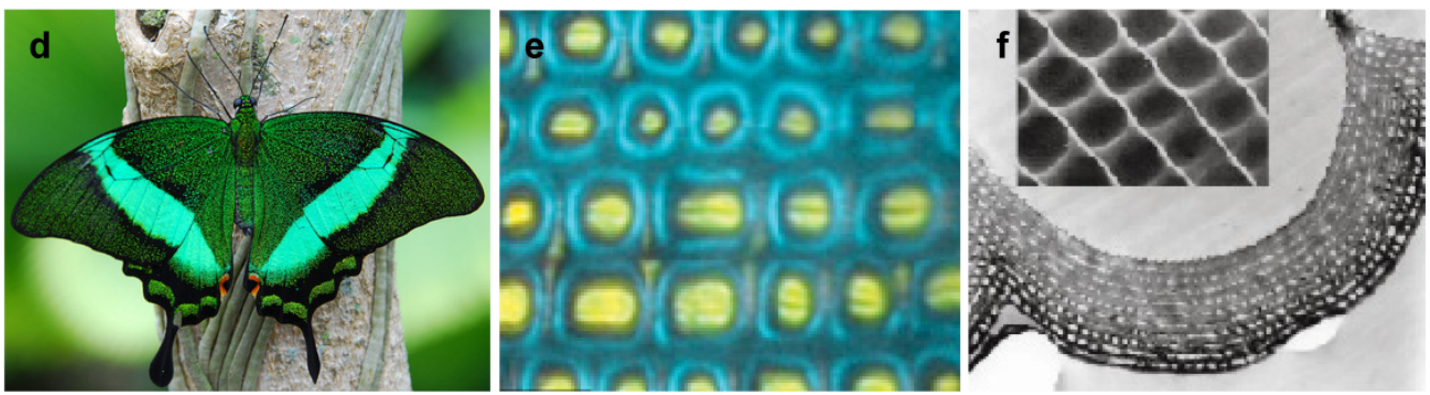
Hybrid

- Brazil morpho





- Indonesian butterfly



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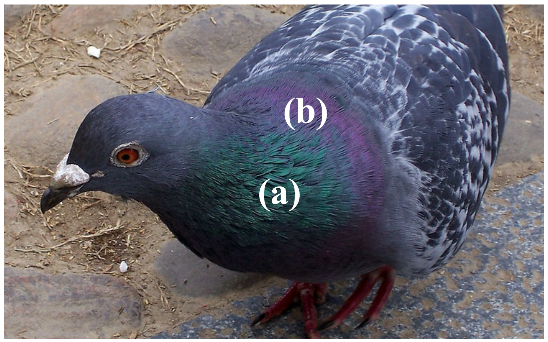
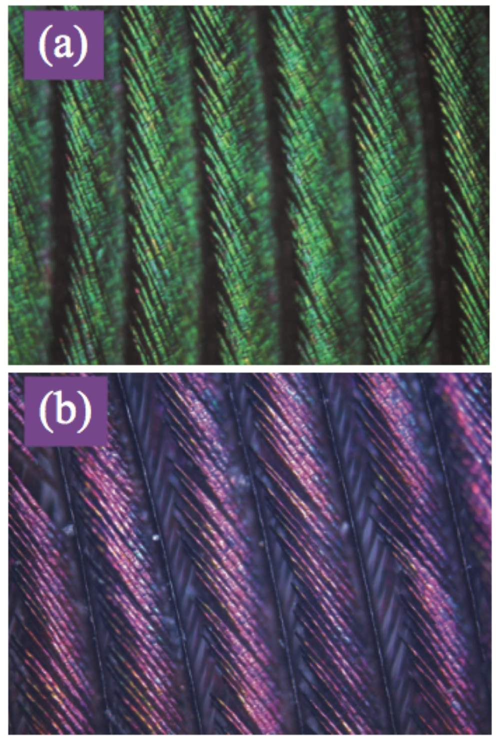
P. Vukusic, Proc. R. Soc. (1999) ;
P. Vukusic, Nature (2000)。

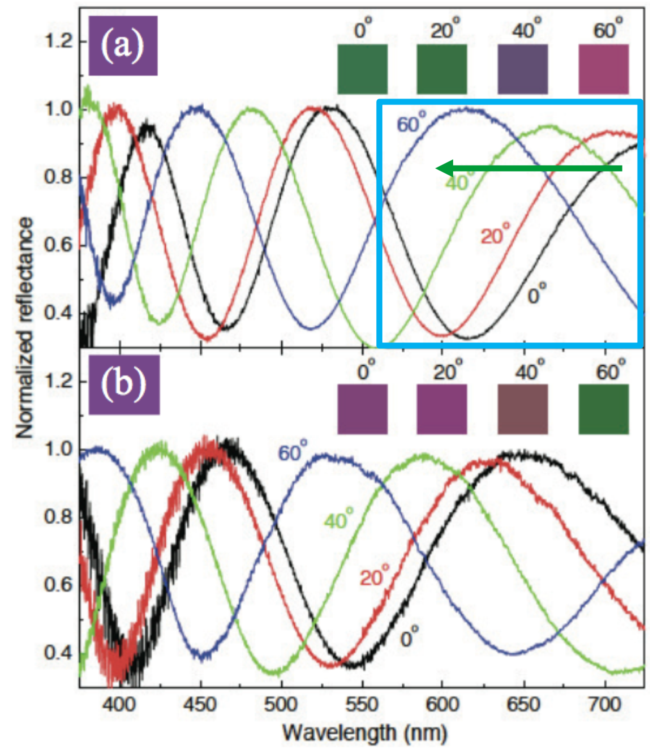
Properties of structural colors

Iridescence Color varies with different observation angles $2nd\cos\theta = N\lambda$



Pigeon





H.Yin, Phys. Rev. E (2006)

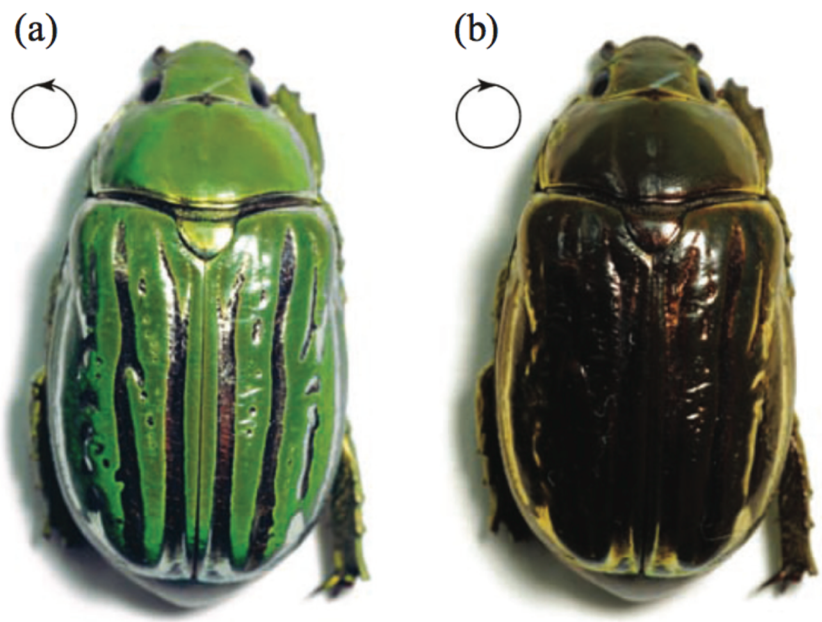
Properties of structural colors

Color changing with angle

Anna's Hummingbird /Calypte anna

Properties of structural colors

Polarization dependence



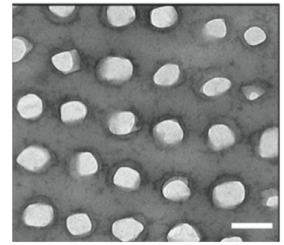
Jewel beetle

Brilliant green color

V.Sharma, Science (2009)

Properties of structural colors

Active color change



Parameters

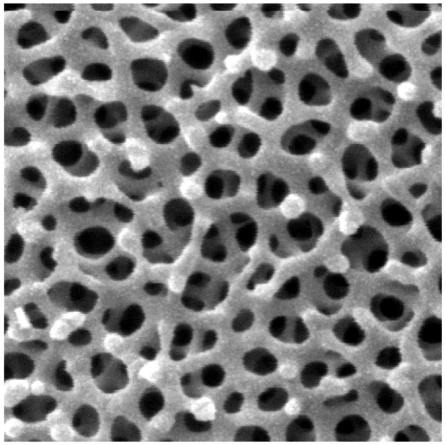
- Refractive index
- Period (thickness)
- Observation angle

Relaxed -------- Excited
Green Red Yellow

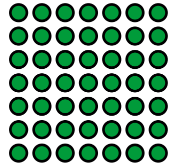
Excited -------- Relaxed
Red Yellow Green

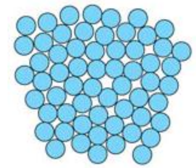
J. Teyssier, nature comm. (2015)

What about amorphous photonic structure colors?



Amorphous photonic crystals in nature

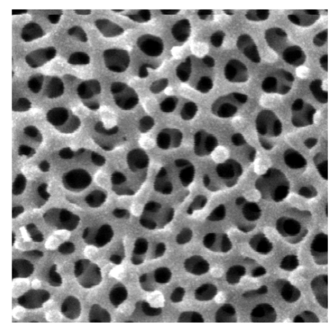




	Periodic	Amorphous
Long-range order	Yes	No
Short-range order	Yes	Yes
Iridescence	Yes	No

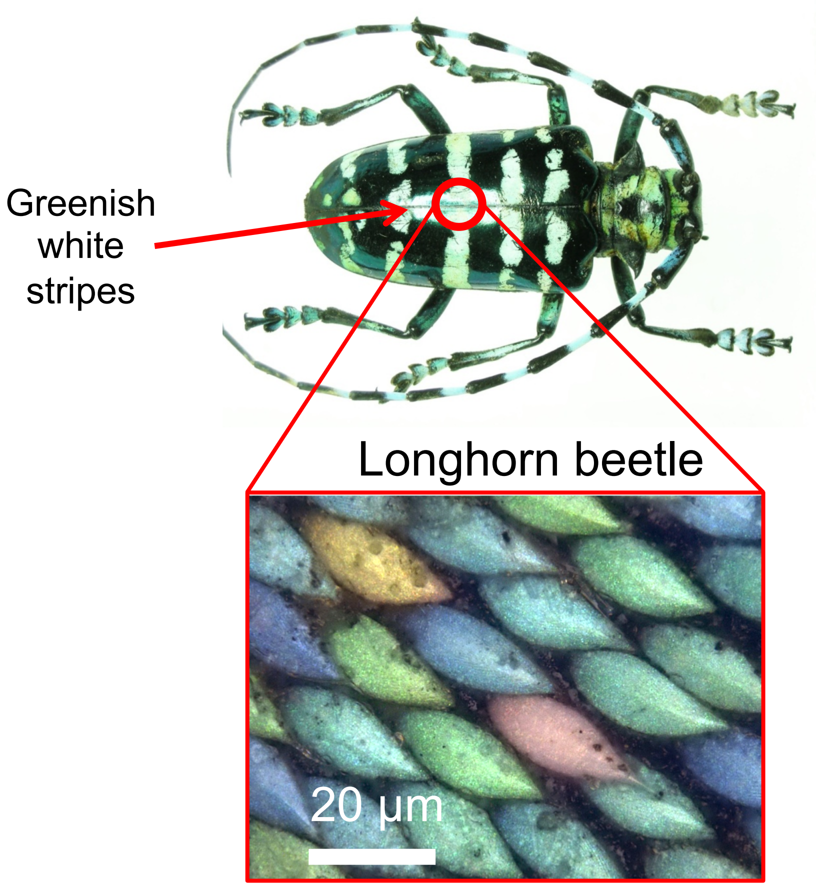
Parrot feather

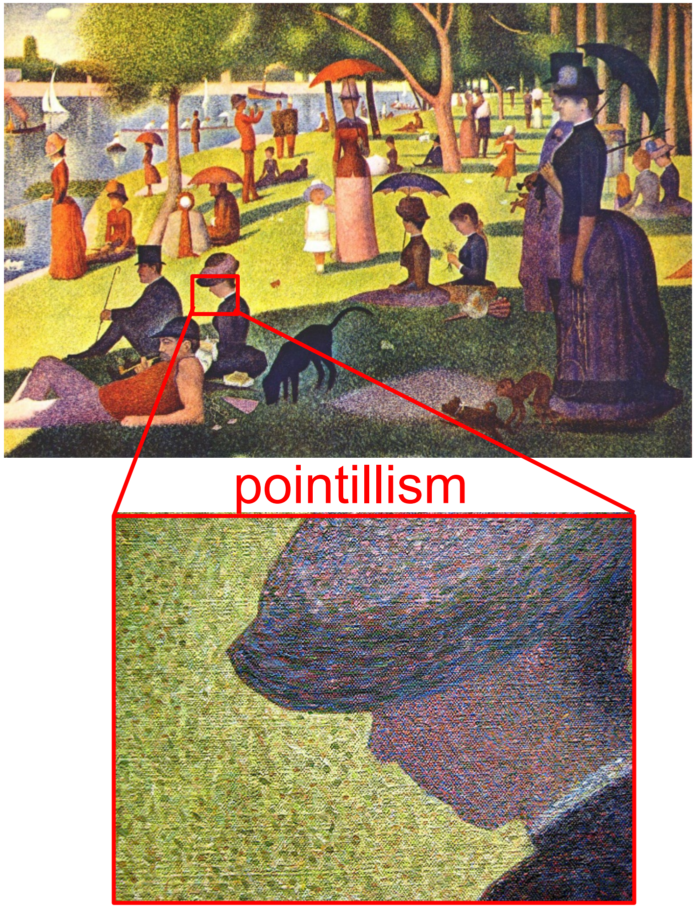
Amorphous diamond structure



Yin *et al*., PNAS **109**, 10798 (2012)

Amorphous photonic crystals in nature



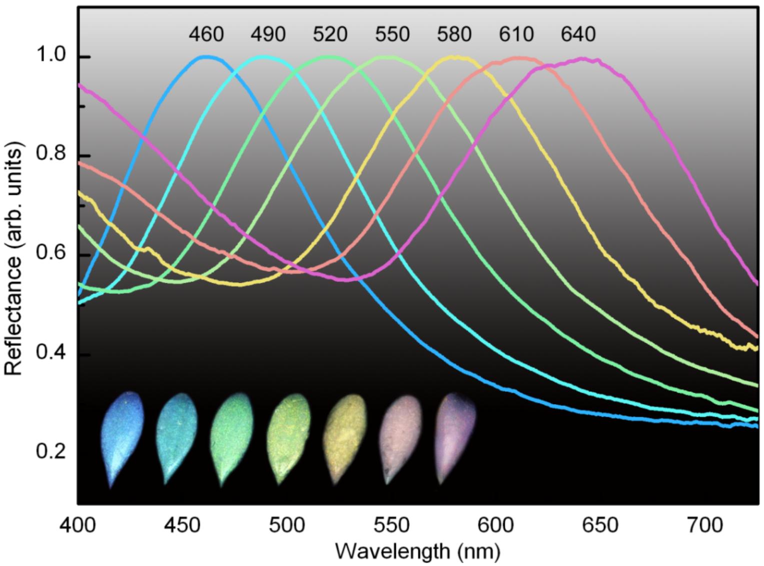


A Sunday Afternoon on the Island of La Grande Jatte
Georges Seurat (1859 - 1891)

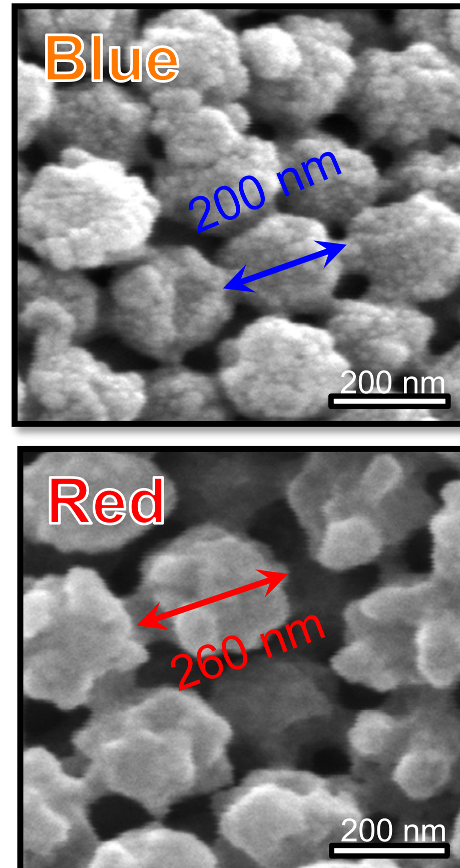
B.Q. Dong, Opt. Express (2010)

Longhorn beetles

Spectra and structure analysis of Colored Scales

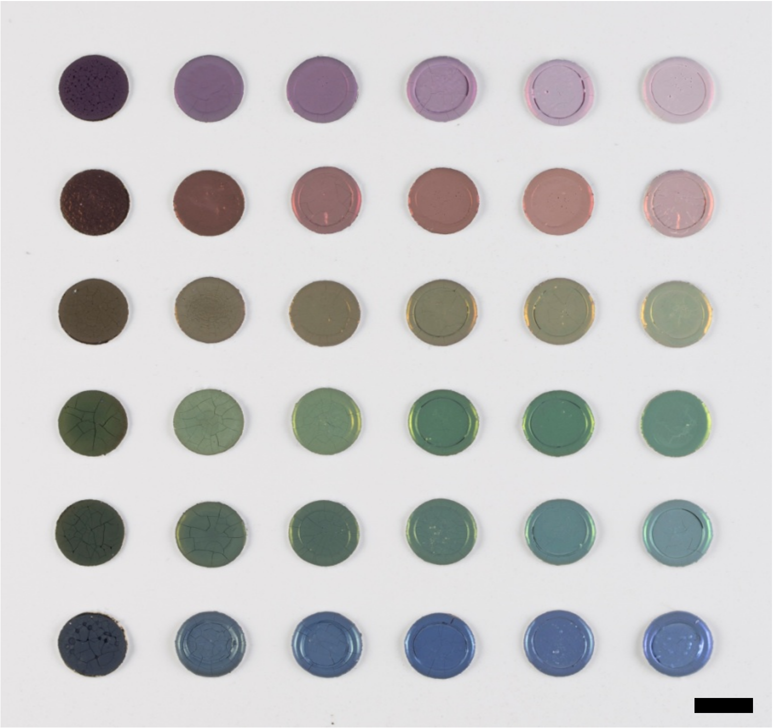


chitin nanoparticles



Diverse coloration due to size scaling

Artificial structure color



Fabrication methods

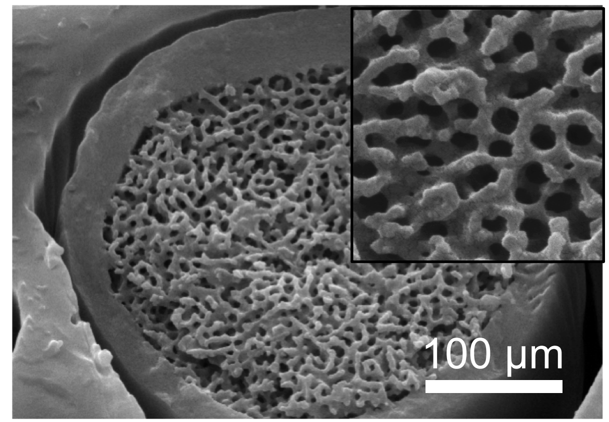
- Inversion from templates
  - ✓ Easy, low-cost
  - – limited by templates

- Self-assembly
  - ✓ Low-cost
  - – Limited kinds of materials

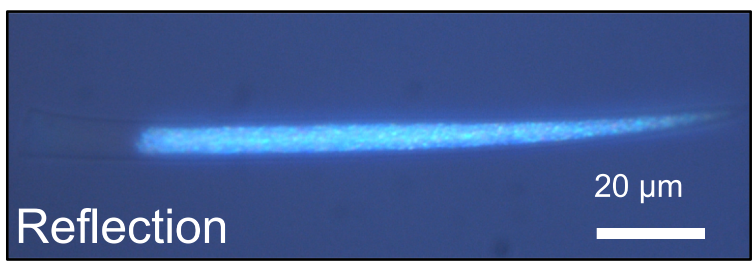
- Nanofabrication
  - ✓ Targeted, controllable, friendly for imaging processing
  - – Expensive, easy for 2D but difficult for 3D

Inversion from templates

Beetle *Sphingnotus mirabilis*



Spinodal decomposition structure

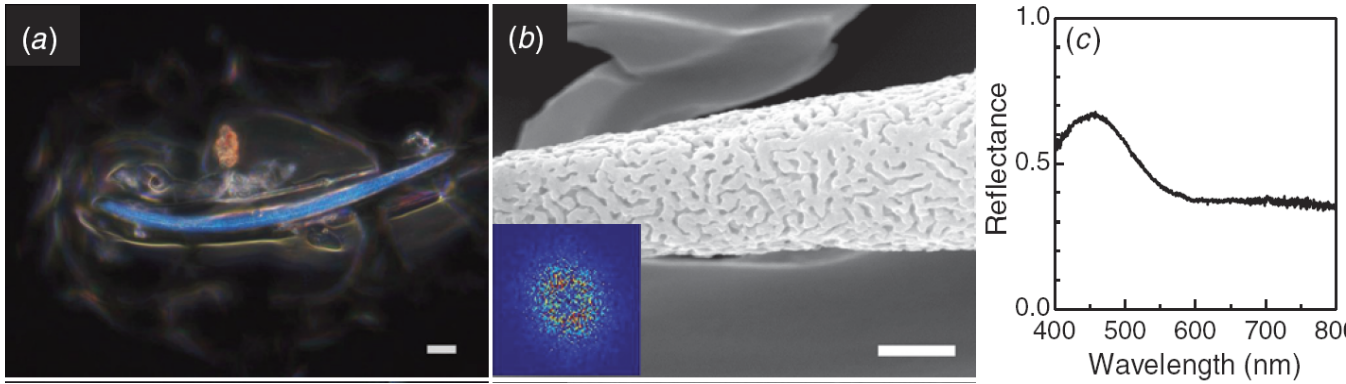


Y. F. Zhang *et al*., Bioinspir. Biomim (2013)

Inversion from templates

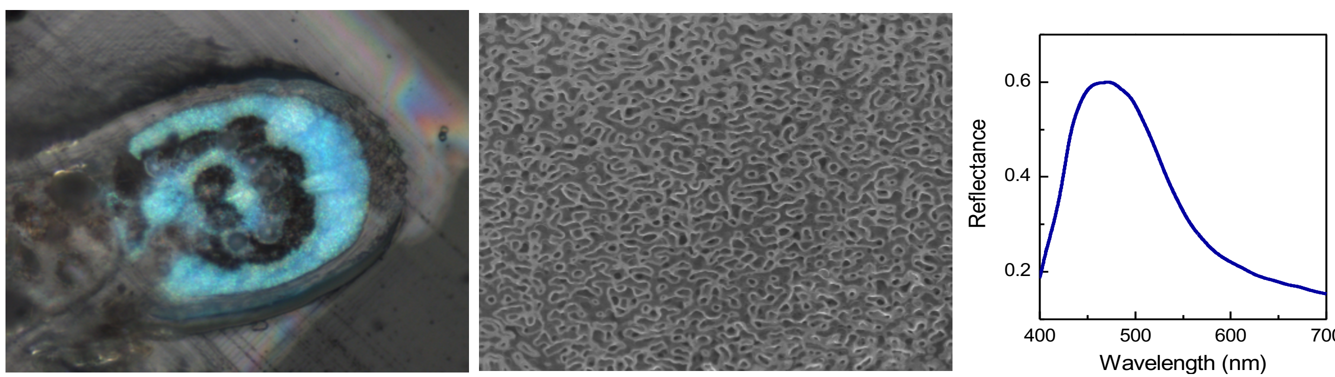
Inverted SiO_2

Atomic Layer Deposition



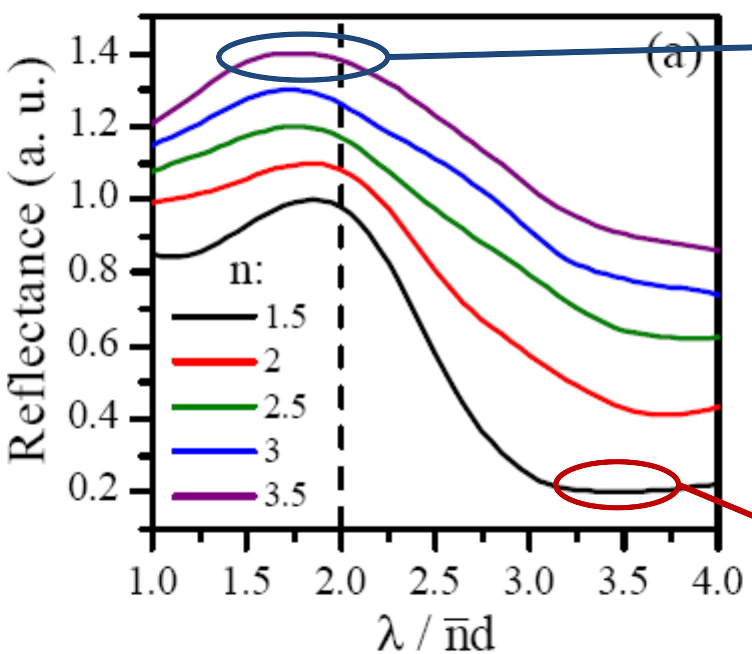
Inverted Al_3O_2

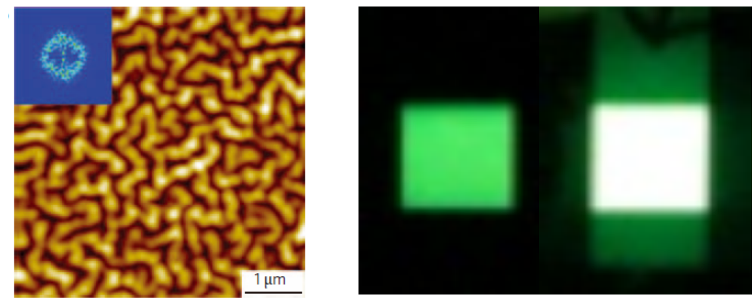
Sol-gel



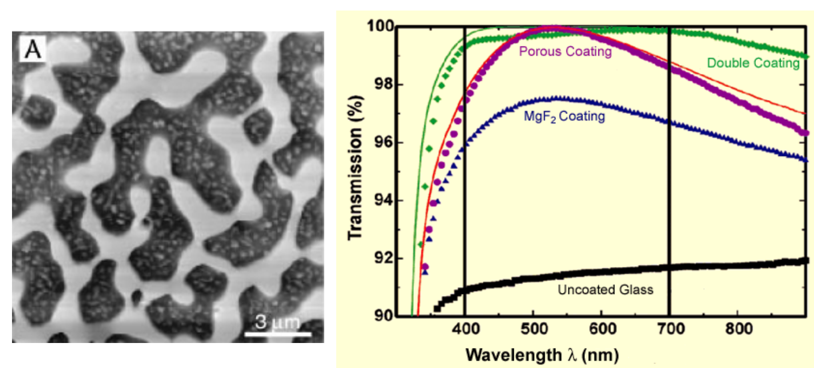
Potential applications in photonics

Inverted structure



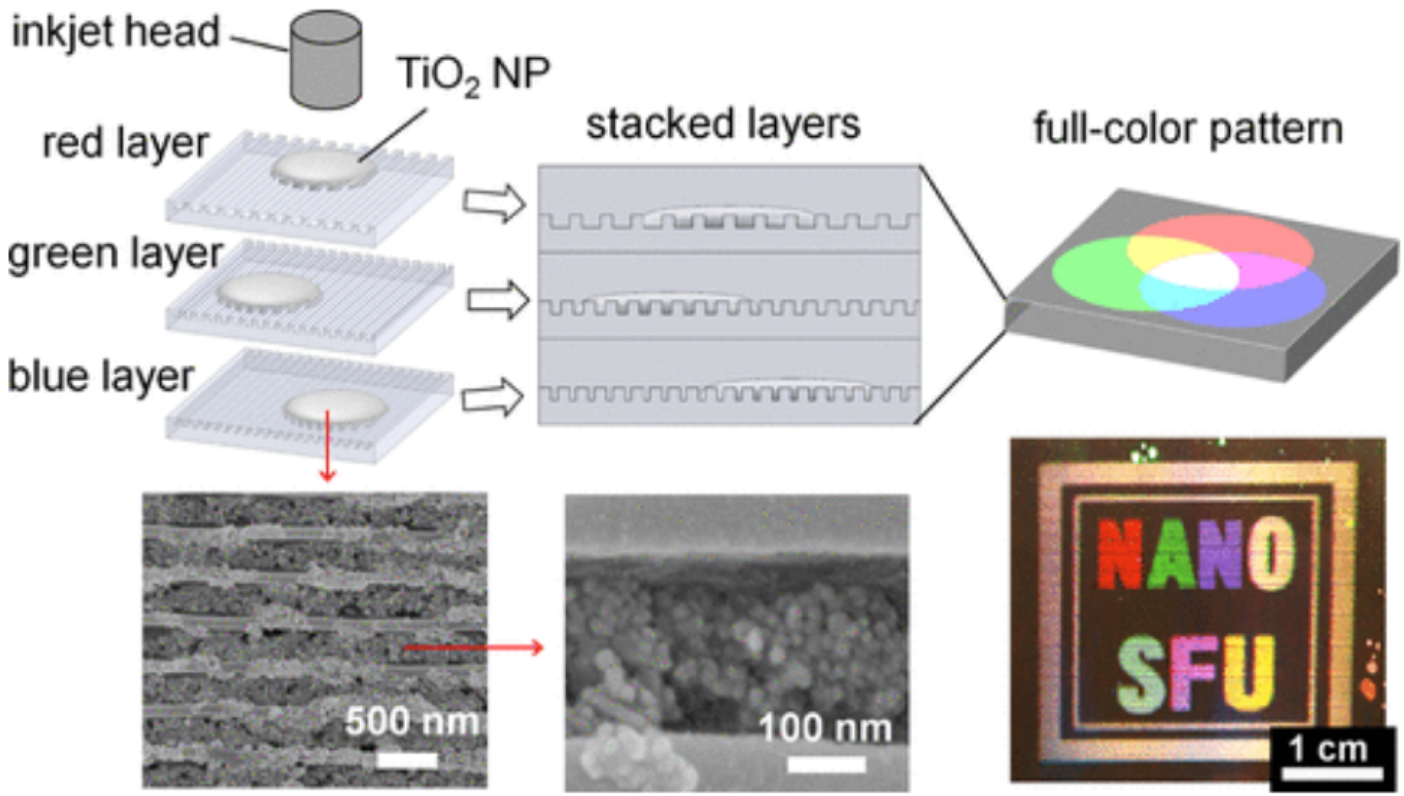


Enhance light extraction from OLED
Nature photonics **4,** 222 (2010)



Antireflection coatings
Science **283,** 520 (1999)

Scalable Inkjet-Based Structural Color Printing by Molding Transparent Gratings



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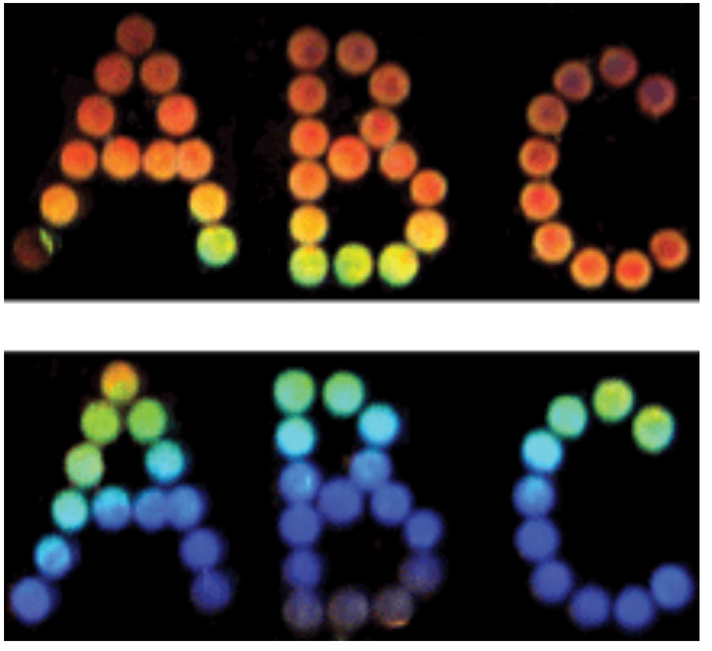
ACS Nano, *12* , 3112 (2018)

Self-Assembled Films Display structure color

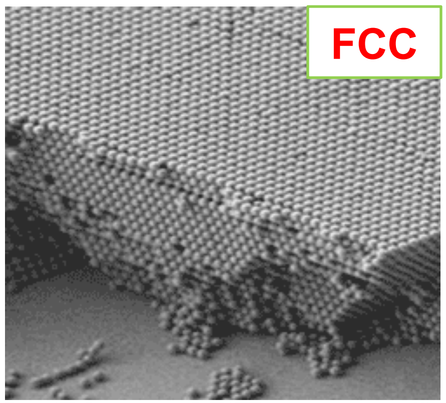


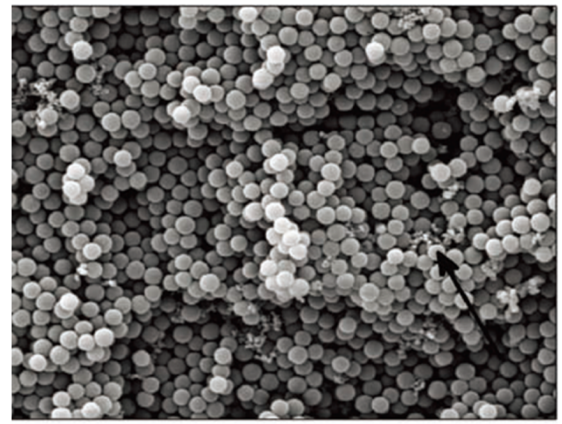
Courtesy of Haruma Kawaguchi, Keio University

Self-assembly

Single-size spheres

Dual-size spheres: 226 nm & 271 nm





Electrostatic repulsive force

Photonic crystal

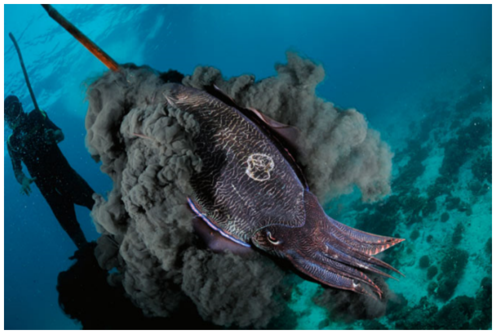
Amorphous photonic structure

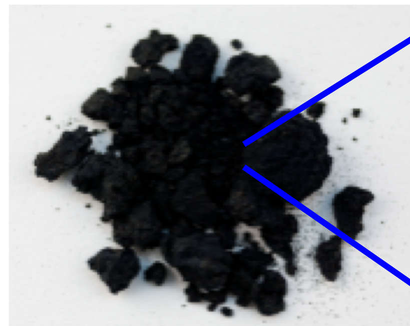
P. D. García *et al.*, Adv. Mater. 19, 2597 (2007)

J. D. Foster *et al.*, Adv Mater. 22, 2939 (2010)

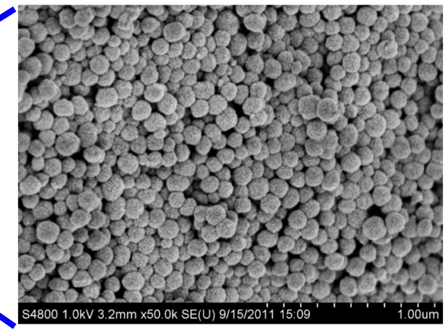
Self-assembly

- **Using PS spheres, and cuttlefish ink as an additive**





Dried cuttlefish ink



Ink particles ~ 110 nm

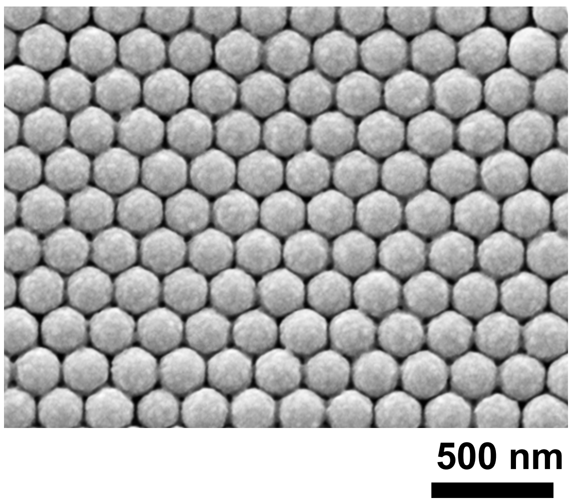
Advantages

- Non-spherical shape, **easy to attain amorphous structures**
- Broadband absorption, **enhancing color visibility**

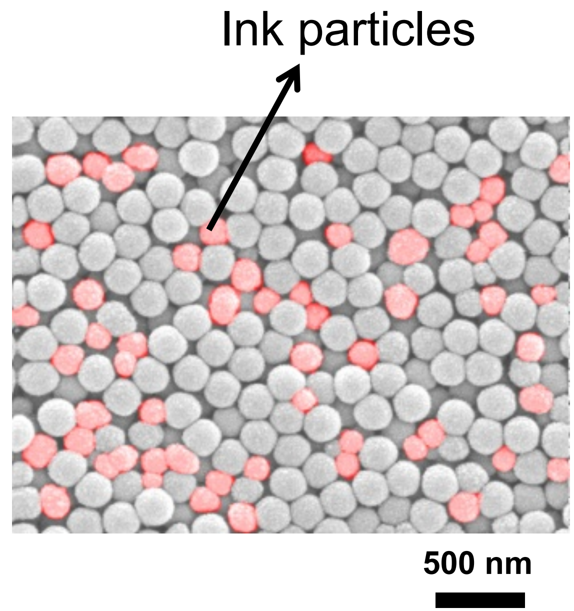
Self-assembly

Simple procedure:

- Mixing PS spheres and ink particles in water
- Drop onto a substrate
- Wait for drying



200-nm PS spheres alone



200-nm PS spheres + ink particles

Octopus is changing:

PATTERN
COLOR
BRIGHTNESS
TEXTURE