

# Biological Optics, The DCU, and Scattering Physics

## Research Session Notes

2025-11-20

### 1. Physical Mechanisms of Color

#### Mechanisms Overview

Based on *Hsiung et al. (2015)* and *Bagnara (2007)*, color is produced via:

1. **Pigments (Absorption):** Selective absorption (e.g., Carotenoids, Melanin). Rare for blue.
2. **Structural (Scattering):** Interaction of light with nanostructures.
  - **Incoherent:** Randomly distributed scatterers (e.g., Blue sky, Tyndall). *Note: Johnsen argues this is still coherent scattering by an incoherent ensemble.*
  - **Coherent:** Ordered structures producing interference.

#### Photonic Crystal Geometries

Based on *Umbers (2012)*:

Type	Structure	Appearance	Example
1D	Multilayer Reflectors	Iridescent (Angle-dependent)	Beetle shells, Fish platelets
2D	Diffraction Gratings	Iridescent	Bird feather barbules
3D	Inverse Opals / Lattices	<b>Angle-Independent</b> (Non-iridescent)	Weevil scales, <i>Parides</i> butterflies

**Key Insight:** Non-iridescent coherent blue can also be produced by **Quasi-Ordered Arrays** (short-range order, isotropic orientation), as seen in bird spongy keratin and tarantula hairs.

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## 2. Case Study: Tarantula Blue (*Hsiung et al. 2015*)

### The “Weird” Findings

The study of Theraphosidae (tarantulas) reveals a system that defies standard evolutionary logic regarding structural color. Unlike birds or butterflies, where structural color is often sexually selected and highly diverse, tarantula blue represents an evolutionary “singularity.”

#### 1. The Evolutionary Paradox (Convergence vs. Divergence)

- **Extreme Convergence:** Intense blue coloration ( $\lambda_{max} \approx 450 \pm 10$  nm) has evolved independently at least **8 separate times** across the tarantula phylogeny.
- **The “Attractor” Hypothesis:** Despite being separated by millions of years of evolution, these lineages did not drift into violet or green. They are tightly constrained to this specific 450 nm “Navy Blue.”
- **The Contradiction:** In most animals (e.g., hummingbirds), structural color evolves via *Sexual Selection*, leading to a “rainbow” of diversity. In tarantulas, the strict conservation of hue suggests **Natural Selection** or a strong biophysical constraint is the primary driver.

#### 2. The Optical Paradox: “Many Roads to Rome”

Perhaps the most surprising finding is that while the *color* is identical, the *mechanism* is not. Evolution solved the “How to make Blue” problem in two completely different ways, yet achieved the exact same spectral result.

- **Mechanism A: Spongy Quasi-Ordering:** Some species (e.g., *Annandaliella travancorica*) use a disordered, sponge-like array of chitin and air. This naturally produces diffuse, non-iridescent blue (like the sky).
- **Mechanism B: Ordered Multilayers:** Other species (e.g., *Poecilotheria metallica*) use strict 1D multilayer stacks (alternating chitin/air). In a flat system (like a beetle shell), this *should* create a highly iridescent, mirror-like flash that changes color with angle. **But it doesn’t.**

### 3. Geometric Scrambling: The “Hairy Mirror”

How does *P. metallica* use a mirror-like structure (Mechanism B) to produce a pigment-like matte blue?

- **The Geometry:** The multilayer stacks are rolled inside cylindrical bristles (hairs).
- **The “Scrambling” Effect:** Because the hair is curved, any incoming beam of light hits the nanostructure at every possible angle simultaneously (from 0° to 90°).
- **Rotational Averaging:** The eye sees the *sum* of all these reflections. The iridescence is effectively “canceled out” or averaged into a stable, static blue.
- **Significance:** This is a rare biological example where **Gross Morphology** (hair shape) fundamentally alters the **Nanostructural Physics** (interference), converting a coherent signal into a quasi-incoherent appearance.

### 4. The Functional Enigma (Who is it for?)

The ecology of tarantulas makes this color deeply puzzling:

- **The Blind Observer:** Tarantulas have very poor color vision and likely lack the opsins to discriminate this specific blue.
- **The Dark Environment:** They are crepuscular/nocturnal.
- **The Courtship:** Mating is primarily tactile and vibratory, not visual. Sexual dimorphism is low regarding this color (females are often just as blue).
- **Conclusion:** The color is likely **NOT for mating** (Sexual Selection). It is likely for **Camouflage** (matching the scotopic spectrum of shadows/moonlight?) or **Aposematism** (warning signal) against predators who *can* see blue (birds/wasps), rather than conspecifics.

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## 3. The Dermal Chromatophore Unit (DCU)

### Definition

A functional vertical stacking of cells in the dermis that acts as a biological “pixel.” Defined formally by **Joseph Bagnara**.

- **Top Layer: Xanthophores** (Yellow Filter).

- **Middle Layer: Iridophores** (Blue/White Reflector).
- **Bottom Layer: Melanophores** (Light Absorber / Contrast Background).

## The Interaction Model (Phase Shifts)

Evolution does not necessarily shift wavelength continuously. It often acts via **Subtractive Mixing**, creating discrete “Phase Shifts” in color space.

Green Phenotype = Blue Structural Scatter + Yellow Pigment Filter

Blue Phenotype = Blue Structural Scatter + No Filter

## Evolutionary Implications

- **Continuous Evolution (Wasik et al.):** Changing nanostructure dimensions moves the peak  $\lambda_{max}$  (e.g., UV  $\rightarrow$  Violet). Best modeled by **Brownian Motion**.
- **Discontinuous Evolution (Bagnara):** Gaining/Losing the yellow filter causes instantaneous jumps between Blue and Green. Best modeled by **Discrete Markov Models (Mk)** or **Ornstein-Uhlenbeck (OU)** (stabilizing selection at specific optical optima).

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## 4. Experimental Protocol: Imaging the DCU

**Goal:** Correlate microscopic DCU architecture with macroscopic reflectance spectra (Ultris X50).

### The “Digital DCU” Analysis

#### 1. Image Acquisition (The Z-Stack Fix)

Do not use a single focal plane. The DCU has depth. \* **Shot 1 (Surface):** Focus on Xanthophores (Yellow). \* **Shot 2 (Deep):** Focus on Melanophores/Iridophores (Black/Reflective). \* *Sampling:* Take 3 snips per Ultris ROI to account for patchiness.

## 2. Quantification (Masking)

- **Yellow Filter Index** ( $I_{yellow}$ ): Area fraction of yellow pigment (from Shot 1).
- **Melanophore Masking** ( $I_{mask}$ ): Area fraction of melanin (from Shot 2).
- **Reflector Brightness**: Mean intensity of non-pigmented areas.

## 3. The Mathematical Model

Fit spectral data to the interaction equation:

$$S_{obs}(\lambda) \approx [(1 - I_{mask}) \cdot S_{irid}(\lambda)] \cdot (T_{yellow}(\lambda))^{I_{yellow}}$$

## Study Designs

### 1. Intraspecific (Plasticity):

- Focus on **Melanophore State** (Expanded vs. Contracted).
- *Requirement*: Fixation (Ep/MSH/PFA) to standardize state.

### 2. Interspecific (Divergence):

- Focus on **Reflector Brightness** and **Pigment Presence**.
- *Analysis*: PGLS to correct for phylogeny.

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## 5. Physics Deep Dive: The Sönke Johnsen Perspective

### Scattering vs. Absorption

- **Absorption**: Photon energy matches a real state transition → Energy lost as heat.
- **Scattering**: Non-absorptive interaction. Photon energy does *not* match a transition → Virtual state → Re-emission of a “new” photon of identical energy.
  - *Analogy*: “**The Penny in the Well.**” A penny falls in (incident photon), hits the bottom (no shelf/state), and the system immediately throws a *new* penny back up (scattered photon).

## The “Tyndall” Critique

Johnsen argues Prum’s dichotomy (Incoherent vs. Coherent) is semantically flawed. \* “Tyndall Scattering” is historically outdated; it is just Mie scattering. \* Rayleigh scattering is a **coherent** process (dipole oscillation). \* The “Incoherent” nature of the blue sky is due to the **random distribution** of molecules, not the scattering mechanism itself.

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## 6. Advanced Optics: Velocity & Refractive Index

### The Sommerfeld Precursor

How light interacts with matter (The “Maternity Ward” Analogy).

1. **Signal Velocity (The Runner):** The wavefront. Moves at  $c$ . The electrons (babies) haven’t woken up yet.
2. **Phase Velocity (The Wake):** The steady-state wave. Speed determined by refractive index ( $n$ ).
  - $n > 1$  (**Glass**): Electrons lag (Inertia)  $\rightarrow$  Wave drags backward  $\rightarrow v_p < c$ .
  - $0 < n < 1$  (**Gold/Plasma**): Electrons resonate (Spring-loaded)  $\rightarrow$  Wave shifts forward  $\rightarrow v_p > c$ .

### The Paradox: Faster Than Light?

- **Gold** ( $n = 0.25$ ): Phase velocity is  $4c$ .
- **Explanation:** The “Peaks” of the wave are geometric patterns (like the intersection of closing scissors). They race forward, but they **vanish** when they hit the “Front” (the Runner) because the amplitude there is zero.
- **Causality:** Information (Group/Signal Velocity) never exceeds  $c$ .

### Beam Attenuation Coefficient ( $c$ )

The “Total Loss” of the directional beam.

$$c = a + b$$

\*  $a$  (**Absorption**): Photon dies (Heating). \*  $b$  (**Scattering**): Photon is deflected (Blurring).

\* *Note:* Mathematically identical to the **Pure Death Model** in macroevolution (Exponential Decay).

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## 7. Sci-Fi Connections: Cixin Liu

### *The Three Body Problem & Ball Lightning*

Concept	Physics Principle	Usage in Fiction
Ball Lightning	Resonance	Macro-electrons tuned to the resonant frequency of specific matter (microchips, flesh) to destroy it selectively.
The Black Domain	Refractive Index	Modifying the vacuum ( $n$ ) to lower the speed of light ( $c$ ) to 16.7 km/s, trapping light via “Slow Fog.”
The Droplet	Strong Interaction	Material held together by the strong nuclear force (ignoring electromagnetic repulsion).
Sophons	Entanglement	Unfolded protons. <i>Scientific Error</i> : Liu uses entanglement for FTL communication (Signal Velocity $> c$ ), which violates the “Gold Paradox” rules.

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