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	**Angle-Independent (Non-iridescent)**	Weevil scales, *Parides* 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 Evolutionary Paradox

- **Convergent Evolution:** Blue color ($\lambda_{max} \approx 450$ nm) evolved independently at least 8 times in tarantulas.
- **Divergent Mechanisms:** Despite the identical color, the underlying nanostructures vary wildly (some use ordered 1D multilayers, others use amorphous quasi-ordered sponges).
- **Implication:** This color is an evolutionary **"Attractor"** or optimum. Since tarantulas have poor color vision, this is likely driven by **Natural Selection** (camouflage or metabolic efficiency) rather than Sexual Selection.

The Mechanism of "Stable Blue"

How do tarantulas achieve non-iridescent (stable) blue using structures that should be iridescent?

1. **Quasi-Order:** Some species use "spongy" chitin/air arrays with short-range order but no long-range lattice. This scatters blue in all directions (Isotropic).
2. **Geometric Scrambling (The "Hairy Mirror"):**
    - Some species (e.g., *P. metallica*) use **1D Multilayer Reflectors**, which are normally highly iridescent (like a mirror).
    - **The Trick:** These stacks are located inside cylindrical, curved hairs.
    - **Result:** The curvature of the hair mixes reflections from all angles simultaneously. This averages out the iridescence, resulting in a static, pigment-like blue appearance despite the coherent mechanism.

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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.

$$\text{Green Phenotype} = \text{Blue Structural Scatter} + \text{Yellow Pigment Filter}$$

$$\text{Blue Phenotype} = \text{Blue Structural Scatter} + \text{No Filter}$$

Evolutionary Implications

- **Continuous Evolution (Wasik et al.):** Changing nanostructure dimensions moves the peak λ_{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 $\rightarrow$ Energy lost as heat.
- **Scattering:** Non-absorptive interaction. Photon energy does *not* match a transition $\rightarrow$ Virtual state $\rightarrow$ 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).

Concept	Physics Principle	Usage in Fiction
Sophons	**Entanglement**	Unfolded protons. *Scientific Error:* Liu uses entanglement for FTL communication (Signal Velocity $> c$), which violates the "Gold Paradox" rules.

References Cited

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