SENSING & SIGNALING

Structural Colour Without Pigment: Photonic Architecture for Durable Colourants

How biology generates vivid colour through light physics rather than chemistry

5	3	1–3	5
convergent strategies	principle clusters	TRL range	featured strategies

PROBLEM FRAMING

Pigment-based colour systems degrade under UV exposure and require chemical synthesis. Structural colour is permanent, substrate-integrated, and can produce spectral effects (iridescence, angle-independence) impossible with dyes. Implementation requires surface periodicity at the scale of visible wavelengths (200–700 nm).

Application domains: materials, aerospace, architecture

Principle cluster: optical interference, structural color, surface microstructure

Physics & Mechanism

Underlying physics

[DRAFT] Structural colour arises from coherent scattering or interference of light by periodic nanostructures whose feature size is comparable to visible wavelengths (200–700 nm). Three distinct mechanisms appear in biology: (1) Thin-film interference — parallel surfaces separated by λ/4 optical path length produce constructive interference for a specific wavelength; quarter-wave stacks of alternating materials multiply the effect (Morpho butterfly wing scales, 85 nm thin-film lamellae). (2) 3D photonic crystals — periodic dielectric structures with a photonic bandgap (weevil Lamprocyphus augustus, 3D opal structure). (3) Quasi-ordered arrays — short-range order without long-range periodicity produces angle-independent single-colour scattering (bluebird feather barbules, 180 nm air channels in β-keratin matrix). Key engineering challenge: feature sizes below 200 nm require either e-beam lithography, interference lithography, or self-assembly approaches (block copolymers, colloidal assembly). Self-assembly routes inspired by biological nanostructure formation are the most scalable. [END DRAFT]

Biological Strategies

Modify Light/Color Uniquely among · TRL 1/9 · 46 genera

In animals, iridescence is generated by the interaction of light with biological tissues that are nanostructured to produce thin films or diffraction gratings. Uniquely among animal visual signals, the study of iridescent coloration contributes to biological and physical sciences by enhancing our understanding of the evolution of communication strategies, and by providing insights into physical op…

Design principle: We then highlight unique properties of iridescent signals and review the proposed functions of iridescent coloration, focusing, in particular, on the ways in which iridescent colours allow animals to

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Modify Light/Color Polyphemus moth · TRL 3/9 · 46 genera

Photonic nanoarchitectures in the wing scales of butterflies and moths are capable of fast and chemically selective vapor sensing due to changing color when volatile vapors are introduced to the surrounding atmosphere. The detailed evaluation, using principal component analysis, showed that the butterfly-wing-based sensor material is capable of differentiating between vapor mixtures as the structu…

Design principle: This process is based on the capillary condensation of the vapors, which results in the conformal change of the chitin-air nanoarchitectures and leads to a vapor-specific optical response. Here, we in

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Modify Light/Color Ideopsis similis · TRL 3/9 · 46 genera

Nano-structured colorful zinc oxide (ZnO) replicas were produced using the wings of the Ideopsis similis butterfly as templates. Field emission scanning electron microscope analysis shows that all the microstructure details are maintained faithfully in the ZnO replica. A computer model was established to simulate the diffraction spectral results, which agreed well with the OM images.

Design principle: The ZnO replicas we obtained exhibit iridescence, which was clearly observed under an optical microscope (OM). Field emission scanning electron microscope analysis shows that all the microstructure de

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Modify Light/Color Cynandra opis butterfly wing · TRL 3/9 · 46 genera

Multilayer grating structures, such as those found on the wings of the butterfly Cynandra opis, are able to interact with light to generate structural coloration. When illuminated and viewed at defined angles, such structural color is characterized by exceptional purity and brightness. To provide further insight into the mechanism of structural coloration, two-photon laser lithography is used to f…

Design principle: Importantly, such tuneable bigrating structures are of significant utility in color filtering applications.

Modify Light/Color Rock pigeon

This iridescent neck feathers of rock pigeons contain a specialized microstructure composed of an outer keratin cortex surrounding an inner medullary layer. This thickness of the keratin cortex varies systematically between feather regions that appear green versus purple to the observer. When light enters the keratin layer, it undergoes interference effects owing to the precise thickness of this p…

Design principle: Engineers can apply this keratin-based interference principle to develop angle-dependent color-shifting materials for applications requiring dynamic visual properties without chemical pigments. The de

Combination Intelligence

Strategies that address different aspects of the same problem and are not redundant when combined.

Modify Light/Color + Modify Light/Color

Shared principles: optical interference, structural color, surface microstructure

These strategies share 3 underlying principles including optical interference and structural color and surface microstructure. They may not be alternatives — combining them could address different scale regimes of the same problem simultaneously.

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EXPLORE THE INTERACTIVE VERSION

This report is a static synthesis. The interactive version includes live strategy cards, the Design Brief generator, Combination Intelligence engine, and filtering by TRL, scale, and principle.

`https://atlasofnature.org/challenge/structural-colour-photonic`

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