LIVING LIGHT 2018

CONTENTS

INTRODUCTION

Dear Living Light 2018 Participant,

It is an honour for us to host such an exciting meeting in Cambridge and we thank you for joining us!

We designed the meeting with the intention of maximising interaction between the participants and with the hope that you will go back home with a new set of collaborators and friends which are as passionate as you are about working at the interface between biology, chemistry, physics, and engineering!

We truly hope that you will enjoy the conference and we ask for your collaboration to keep the meeting as informal and as constructive as possible: we would really like to build a collaborative community, which supports interdisciplinary and scientific fair play.

So have fun, do not be scared to ask questions and talk to as many people as possible!

On behalf of the organisers,

Silvia Vignolini
Living Light 2018, Conference Chair

SCIENTIFIC COMMITTEE

- Dr. Dimitri Deheyn, Scripps Institution of Oceanography, University of California, San Diego
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- Dr. Eng. Akira Saito, Dept. of Precision Science and Technology, Osaka University
- Prof. Doekele G Stavenga, Faculty of Science and Engineering, University of Groningen
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- Prof. Daniel Colaco Osorio, Osorio Lab, University of Sussex
- Dr. Bodo Wilts, Adolphe Merkle Institute, University of Fribourg
- Prof. Pete Vukusic, Biological Photonics, University of Exeter
- Prof. Beverley Glover, Department of Plant Sciences, University of Cambridge

LOCAL COMMITTEE

- Dr. Silvia Vignolini, Bio-Inspired Photonics, University of Cambridge
- Dr. Villads Egede Johansen, Bio-Inspired Photonics, University of Cambridge
- Olimpia D. Onelli, Bio-Inspired Photonics, University of Cambridge

GRAPHICS

- Nicolò Mingolini, ISIA Urbino, Italy
- Mélanie Bay, Bio-Inspired Photonics, University of Cambridge

HISTORY

1980s - 2000s
Physicists and engineers become increasingly interested in the study of bio-photonics. Collaborations with botanists and entomologists start to become more frequent,there is a real need for the creationof a collaborative network of scientists

2009
Jean-Pol Vigneron (Namur University) organises the first interdisciplinary meeting in San Sebastián (Spain)

2011
Following the success of the 2009 edition, the conference is held again in Shangai (China), under the leadership of Jian Zi (Fudan University)

2013
Following the premature loss of Jean-Pol Vigneron, it is decided to perpetuate the conference cycle in honour of his legacy

2014
A memorial meeting is held in Namur (Belgium), chaired by Philippe Lambin. The name "Living Light" is adopted for the first time.

2016
Dimitri Deheyn hosts Living Light in San Diego (US) at the Scripps Institute for Oceanography

2018
This year's edition takes place in Cambridge (UK), a thriving university city

TIMETABLE

10 Tuesday April 10th, 2018

18:00 Registration at the Møller Centre
21:00

11 Wednesday April 11st, 2018

07:30 | Registration
08:20 | Opening remarks

Vision / Development

Chair: ***Villads Johansen***

08:30 | Justin Marshall

09:10 | Nico Michiels
09:30 | Trevor Wardill

09:50 *Coffee break*

Chair: ***Dan Morse***

10:20 | Kathryn Feller
10:40 | Olimpia Onelli
11:00 | Bodo Wilts
11:20 | Anthony McDougal
11:40 | Bram Vanthournout

12:00 *Lunch*

Plants / Art

Chair: ***Bodo Wilts***

13:30 | Heather Whitney

14:10 | Jordan Ferria
14:30 | Lisa M Steiner
14:50 | Rox Middleton

15:10 *Coffee break*

Chair: ***Beverly Glover***

15:40 | Nathan Masters
16:00 | Miranda Sinnott-Armstrong
16:20 | Martin Lopez-Garcia
16:40 | Franziska Schenk

17:00 *Short break and refreshments*

17:20 | Plenary discussions
18:00 |

12 Thursday April 12nd, 2018

Optics / Genetics

Chair: ***Silvia Vignolini***

08:30 | Dvir Gur

09:10 | Matthew Shawkey
09:30 | Sebastien Mouchet

09:50 *Coffee break*

Chair: ***Nico Michiels***

10:20 | Rachel Thayer
10:40 | Colin Ingham
11:00 | Nicola Nadeau
11:20 | Kenneth Järrendahl
11:40 | Jan Totz

12:00 *Lunch*

Optics / Function / Biomimetics

Chair: ***Mattew Shawkey***

13:30 | Marianne Elias
13:50 | Villads Johansen
14:10 | Alison Sweeney
14:30 | Maria Plyushcheva
14:50 | Daniel Wangpraseurt

15:10 *Coffee break*

Chair: ***Adriana Briscoe***

15:40 | Mathias Kolle
16:00 | Alon Gorodetsky
16:20 | Hendrik Hölscher
16:40 | Thomas Swift

17:00 *Short break and refreshments*

17:20 | Poster session
19:00

20:00 | *Dinner; Group photo*
23:00

13 Friday April 13rd, 2018

Fossils / Microstructures

08:20 | Poster winner announcement

Chair: ***Mathias Kolle***

08:30 | Maria McNamara

09:10 | Liliana D'Alba
09:30 | Luke McDonald

09:50 *Coffee break*

Chair: ***Alison Sweeney***

10:20 | Giliane Odin
10:40 | Bor-Kai Hsiung
11:00 | Andrew Parnell
11:20 | Siegfried Reipert
11:40 | Daniel Osorio

12:00 *Lunch*

Evolution / Function

Chair: ***Daniel Osorio***

13:30 | Mary Caswell Stoddard

14:10 | Doris Gomez
14:30 | Dan Morse
14:50 | Hugo Gruson

15:10 *Coffee break*

Chair: ***Maria McNamara***

15:40 | Michael Kühl
16:00 | Adriana Briscoe
16:20 | Johannes Groessling
16:40 | Amanda Holt

17:00 *Short break and refreshments*

17:20 | Plenary discussions
18:00

14 Saturday April 14th, 2018

10:00 Meet at the Chemistry Department (drop bags)

11:00 Punting on the river Cam

13:00 Lunch at the Botanic Garden Café

14:30 Visit of the Botanic Garden

16:30 Collect bags from Chemistry Department

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- On Twitter: https://twitter.com/LivingLightConf
- Haghtag #LivingLight2018

... and offline

The Møller Centre
Churchill College
Storey's Way
CB3 0DE

St John's College
St John's Steet
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Chemistry Department
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Botanic Garden
1 Brookside
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ABSTRACTS

Invited lectures

Stomatopod crustaceans and how they Stoke up Newton

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Stomatopods love light. These shy, violent shrimps detect more of the spectrum than any other animal and manipulate light through pigments, molecules, optical elements and cuticular nanostructures in ways that have biologists reaching for physics text books. As well as their neatly spaced twelve spectral sensitivities (300-720 nm), several species also sample polarised light comprehensively with receptors arrayed at 0, 45, 90, 135° and with both left and right handed circular polarisation receptors.

Instead of a desire (through evolution) to construct a dodecahedral colour space or a Poincaré sphere to fully describe light, we hypothesise that mantis shrimps are more interested in the examination of signals and surfaces, particularly those from their own bodies. Are they nature's little spectrophotometers and ellipsometers? Do they encode Stokes parameters and present spectra, not chromatic ratios, to a brain-based look-up table?

This presentation will summarise our knowledge of stomatopod vision and describe some of the coloured and polarised light reflection elements that stomatopods apparently use to 'talk' to each other. Structural reflections mechanisms, including scatter and selective e-vector reflection or transmission, as well as pigmentary mechanisms, construct this language.

Three bio-inspired spin-off directions from this research include: early cancer detection, optical data storage for computing and satellite design.

The birds and bees and bright blue leaves: investigating the functions of leaf iridescence

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As photosynthetic organisms, plants have developed a diverse range of mechanisms to manipulate the light they rely on to provide both energy and information. One of these mechanisms is by the production of cellular structures that directly influence the reflection or transmission of light at specific wavelengths. A phylogenetically diverse range of plants produce such structures in their photosynthetic tissue, (predominantly the leaves). As well as this phenomena being phylogenetically diverse, there is also a diversity in the mechanism by which this light manipulation is achieved. Due to the prominence of these structures in the photosynthetic tissue, our initial enquires have focused on the impacts of iridescence on light harvesting, and this presentation will summarise our current findings as to the impact of leaf iridescence on photosynthesis.

However, as sessile organisms, plants can also use light to manipulate the biotic aspects of their of their environment, such as pollinators and herbivores. We have also been investigating the hypothesis that leaf iridescence might be multifunctional, and have roles in detering or confusing potential herbivores. The results from this investigation suggest that the visual impacts of iridescence can be complex, and may have implications for how biomimetic materials should be used.

Structural colors in zebrafish: vision and pattern formation

Dvir Gur[1,2], Jan-David Nicolas[3], Vlad Brumfeld[4],
Tim Salditt[3], Dan Oron[1], Gil Levkowitz[2]

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Colors in nature are obtained by either pigmentation, structural colors or by a combination of the two. Structural colors are produced by the interaction of light with structured materials which are often transparent. The colors are used for a variety of functions, including camouflage, vision, communication, and mate recognition. In adult zebrafish, both the skin and the eye contain reflecting iridophores (specialized guanine crystals forming cells). The beautiful skin pattern of alternating dark and light stripes across the zebrafish body is obtained by a complex combination of both pigment cells and iridophores, which are thought to play a key role in intra-species communication. The eye of the zebrafish is remarkable and contains two silvery reflecting layers; located in the iris, and just behind the retina, these layers highly affect both the eye sensitivity and the visual acuity of the fish. We have used a combination of synchrotron-based, state of the art diffraction imaging, together with micro CT, cryo-SEM, optical studies and mathematical simulations, to obtain a mechanistic understanding of how these reflecting layers function, and to elucidate how this functionality is enabled by their structures.

Biophotonic structures in insects through deep time: insights from fossils and taphonomic experiments

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Many modern insects possess intricate tissue architectures ordered on the nanoscale that can produce striking structural colours and other visual effects with important functions in signaling. Recent studies have begun to illuminate the evolutionary history of photonic structures in insects through deep time by analyzing fossils and by simulating aspects of the fossilization process through controlled (taphonomic) laboratory experiments. Currently in its infancy, the field of fossil photonics is dominated by several studies of multilayer reflectors in fossil beetles, of various photonic structures in fossil moths and a single study that uses taphonomic experiments to elucidate how such structures are preserved. Here I review research to date and present data on new specimens of structurally colored insects and from new taphonomic experiments that shed light on previously unexplored aspects of fossil photonics. Future studies should focus on the identification and ultrastructural and optical characterization of fossil 3D photonic crystals and structures responsible for producing specific optical effects that may contribute to signalling, e.g. polarization, 'true' black, etc. Data from taphonomic experiments allow testing of evolutionary hypotheses and are critical components of models for the preservation and evolution of specific photonic structures in insects through deep time.

The Ecology and Evolution of Avian Color

Mary Caswell Stoddard [1]

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Birds are the most colorful terrestrial vertebrates, equipped with tetrachromatic vision. They provide an especially vibrant system in which to investigate animal communication and signaling. How does a bird's visual experience affect its behavior and evolution? My lab uses an integrative approach, using tools from computer vision, optics and psychophysics, to investigate avian coloration from mechanistic and functional perspectives. We combine studies of museum specimens with experiments in the lab and field. Using diverse examples from the avian world – including plumage evolution, egg mimicry and coevolution between cuckoos and hosts, shorebird egg camouflage and hummingbird iridescence – I will show how investigating color can uncover surprising insights into avian ecology, evolution and sensory biology.

ABSTRACTS

Talks

Active photolocation in diurnal fishes: challenging the counterintuitive

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Diurnal active photolocation (DAP) is the process by which diurnal fish re-direct downwelling light into the horizontal visual plane using their own irides to generate reflections in cryptic target organisms, facilitating their detection. Although nocturnal active photolocation is known from chemiluminescent fishes, *diurnal* active photolocation is a controversial hypothesis. This debate follows from the obviously less favourable conditions during the day (bright backgrounds), but is also hampered by a lack of relevant data. Our research focuses on quantifying all the key elements involved in this process, and testing predictions experimentally. This allows us to narrow down the morphological, perceptual, and ecological niche in which DAP may function. Important properties that will affect the contribution DAP can make to target detection are (1) the presence of highly reflective eyes in targets, (2) iris radiance and modulation in the observer, (3) distance between sender and target, (4) small-scale light gradients, and (5) the receiver's visual system.

The key question is whether real-world combinations of these properties can result in functional DAP. Our work focuses on a single species, the triplefin *T. delaisi*, a small (3-5 cm), crypto-benthic micro-predator [1]. We present unpublished data from visual modelling and manipulative experiments that support the idea that DAP can supplement visual detection of cryptic micro-prey and cryptic predators in an ecologically relevant part of the parameter space. Given the ubiquity of small benthic species with specialised forms of iris radiance and reflective eyes in many prey and predator species, this is likely to be a widespread phenomenon.

[1] Michiels, N., et al., Controlled Iris Radiance in a diurnal Fish looking at Prey. *bioRxiv*. 10.1101/206615, 2017

Squid dynamic iridescence provides polarized signals detectable by conspecifics

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Cephalopods have sophisticated adaptable skin, capable of presenting vibrant coloration and patterning that enables dynamic signaling or camouflage. Part of their dermal color repertoire is structural and provided by iridophores, groups of dynamic cells containing the protein reflectin. Neural excitation elicits changes in the color and reflectivity of an iridophore, but also its degree and angle of polarization. Here we have tested whether the light polarization changes which we have quantified from activated iridophores in the longfin squid (*Doryteuthis pealeii*) resulted in behavioral changes when replayed to conspecifics. We found that stimulated iridophores increased their degree of polarization from 13% to 18±3% and changed their angle of polarization by 11±6 degrees. Behaviorally, squids responded robustly to polarization contrast-only looming stimuli that differed from the background in angle of polarization by 15-17 degrees, when the percent polarization was ≥10%. Some continued to respond at 10% even when the stimulus differed from the background by as little as 3 degrees, which rivals the highest known light polarization sensitivity of any animal. Clearly, squids boast the necessary adaptations for sending rapid polarized skin signals and such changes can be detected by their visual systems. Thus, squids have the necessary sensory and motor abilities to perform intraspecific communication through neurally controlled polarized skin reflections. How they perceive the visual dimensions of polarization, color and brightness and whether polarization acts as a signal amplifier in the low-contrast environments of turbid or poorly illuminated waters remain for future investigation.

A twinkle in the eye: description of a novel photonic tapetum for improving bioluminescence detection

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A common way to improve visual sensitivity in dim-light environments is to use a reflecting mirror, called a tapetum, behind the photoreceptors of an eye. Unlike the majority of taxa, which have a tapetum *behind* their retinas, we observed that certain species of crustacean larvae in the order Stomatopoda possess a reflective structure *within* their photoreceptors. These intrarhabdomal photonic structures (IRPSs) bisect the retinular cells of each light-sensing rhabdom into a proximal and distal tier. The IRPS itself is composed of four cells packed with a highly-ordered, 3-dimensional arrangement of ~150 nm diameter vesicles that produce a narrow reflection band between 500-600 nm when illuminated on-axis *in vivo*. Visual and optical modelling supports the hypothesis that IRPSs contribute to a novel solution for increasing long-wavelength light sensitivity in the distal photoreceptive tier. The only known sources of long-wavelength light in nocturnal, pelagic environment occupied by IRPS-containing larvae are the emission spectra from coastal bioluminescent species [1]. This suggests that IRPS-containing larvae may detect bioluminescence as a cue for predation, anti-predation, or location of the adult settlement habitat. Further, we have currently identified IRPS structures in five stomatopod species, all from the same family, Nannosquillidae. IRPS-containing retinas are absent in all investigated species outside of this taxon, suggesting that nannosquillids may have a different visual ecology relative to other stomatopod and crustacean larvae.

[1] Widder, E. A. *Science* **328,** 704–708 (2010).

Development of structural colour in green leaf beetles

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Structural colours have been observed and analysed in a large number of species, however the study of how the micro- and nano-scopic natural structures responsible of these colourations develop has been largely neglected. Understanding the interplay between chemical composition, structural morphology on multiple length scales, and mechanical constraints requires a range of investigation tools able to capture the different aspects of natural hierarchical architectures.

In my talk I will present our developmental study of the most widespread strategy for structural colouration in nature: the cuticular multilayer. In particular, our work focuses on the exoskeletal growth of the dock leaf beetle *Gastrophysa viridula*, capturing all aspects of its formation: the macroscopic growth is tracked *via* synchrotron microtomography, while the submicron features are revealed by electron microscopy and light spectroscopy combined with numerical modelling.

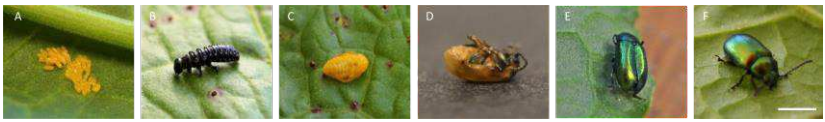

Figure 1 The life cycle of the beetle *G. viridula* spans about 1 month. Scale bar: 1cm.

[1] O.D. Onelli et al. Development of structural colour in leaf beetles. *Scientific Reports* (2017), **7**, 1373.

Butterfly gyroid nanostructures as a time-frozen glimpse of intracellular membrane development

Bodo D. Wilts[1] , Benjamin Apeleo Zubiri[2], Michael A. Klatt[3], Benjamin Butz[2], Michael G. Fischer[1], Stephen T. Kelly[4], Erdmann Spiecker[2], Ullrich Steiner[1], Gerd E. Schröder-Turk[5]

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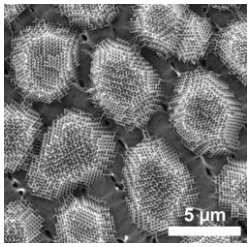
The formation of the biophotonic gyroid material in butterfly wing scales is an exceptional feat of evolutionary engineering of functional nanostructures. Previous work hypothesized that this nanostructure forms by chitin polymerization inside a convoluted membrane of corresponding shape in the endoplasmic reticulum. *In vivo* imaging of e.g. developing butterflies however cannot yet elucidate this dynamic formation process, including whether membrane folding and chitin expression are simultaneous or subsequent processes. We report an unusual hierarchical ultrastructure in the Hairstreak butterfly, *Thecla opisena*, which as a solid materials allows high-resolution 3D microscopy. Rather than the conventional polycrystalline space-filling arrangement observed in other butterflies [1], the gyroid of *T. opisena* occurs in isolated facetted crystallites with a pronounced size-gradient. When interpreted as a sequence of time-frozen snapshots of the morphogenesis, this arrangement provides insight into the formation mechanisms of the nanoporous gyroid material as well as of the intracellular organelle membrane that acts as the template [2].



[1] S. Yoshioka, H. Fujita, S. Kinoshita, B. Matsuhana. *Journal of The Royal Society Interface* (2014), **11**, 20131029
[2] B.D. Wilts, et al. *Science Advances* (2017), **3**, e1603119.

Growth of lepidopteran scales

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The scales on the wings of lepidopterans are effectively single-cell exoskeletons which form during the pupal stage of the organism. The micro- and nano-architecture of these scales confer many functional properties, such as structural coloration, thermal regulation, directional wettability, and aerodynamic benefits. Although lepidopteran wing scales are well-studied as a biological product, we know relatively little about the processes that produce them.

In order to better define the behavior of these processes, we use a combination of traditional and novel imaging techniques to characterize the growth of key components of the cell. Lepidopteran scales appear to exhibit processes that have analogues with human fabrication strategies, such as extrusion, thin-sheet deformation, templated deposition, and subtraction of support structures. This characterization gives us a framework to understand both the growth rates of the individual cellular components as well as the total deformation that occurs during scale development.

Understanding the time-course of structural development is essential to begin deciphering the physical mechanisms driving the morphological development of scale cells. Visualization of the live scale during development will help evaluate various models of micro- and nano-structural formation in butterflies.

Colourful Collembola: multilevel organisation of iridescence.

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Springtails (Collembola) are small, soil-dwelling arthropods that are characterized by a tail-like appendage (furcula) that allows them to jump and evade predators. Besides this remarkable anti-predator adaptation, collembola species exhibit a wide colour variation, including striking iridescence. This iridescence originates from scales that are distributed across the surface of the entire body. In this research project we aim to elucidate the mechanistic basis of collembola colouration and focus on two species, one with golden/silver bands and one with purple iridescence. Using SEM, TEM and microspectrophotography, our results indicate that an interplay of diverse factors contributes to the intricate iridescence pattern. This includes the structuring of ridges on the scale surface, individual scale thickness, stacking of multiple scales, pigmented scale areas, and a multilayer in the cuticle. Function of the iridescence is currently unknown, but limited eyesight and living in low light conditions indicates a negligible role in sexual selection. We explore the hypothesis that the iridescence plays a role in thermoregulation.

Figure 1 Iridescence in *Tomocerus vulgaris* (left) with golden bands and *Lepidocyrtus* sp. (right).

How do petals build nanoscale ridges that scatter light and influence bee behaviour?

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Flowers and the animals that pollinate them interact at a key point – the petal epidermis. It is this single layer of tissue that often provides the visual surface that advertises nectar and pollen rewards. We take an integrated evo-devo approach to understanding the petal epidermis, and our recent research has focused on its optical and tactile properties. In particular, we have been exploring the function and development of cuticular ridges present on the petal surface of a range of flowering plant species that scatter light, generating a "blue halo" effect which improves foraging efficiency of bumblebee pollinators. We will present recent work on these nanoscale ridges, describing a combination of developmental genetic, evolutionary and pollinator behavioural perspectives.

Margaritaria nobilis – helicoidal cell wall disentangled

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The fruit *Margaritaria nobilis* displays beautiful iridescent blue colouration. This structural colour is caused by the helicoidal arrangement of cellulose fibres in its secondary cell wall.[1]
In this talk I will discuss what building blocks this cell wall is made up of and what properties they have. Firstly, the cellulose fibres were isolated via chemical purifications, and their morphology and crystallinity were assessed via electron and atomic force microscopy, and nuclear magnetic resonance spectroscopy and X-ray crystallography, respectively. The fibres were found to be exceptionally short and relatively highly crystalline. Secondly, xylan was analysed via enzyme digestions, gel electrophoresis and mass spectrometry. Xylan is a type of hemicellulose, found in high amounts in this cell wall, and is found to be fairly short as well, and regular. It is speculated that xylan may play a role in the helicoidal arrangement of the cellulose fibres. Finally, all the cell wall components were quantified to build up a cell wall model for this amazing fruit endocarp. All these findings shine light on the complex unit that is a secondary plant cell wall, and help to understand how a plant can produce such a vibrant optical response from simple organic building blocks.

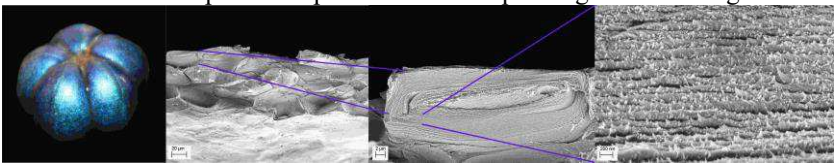

Figure 1 *M. nobilis* observed at different length scales: photo and electron micrographs

[1] S. Vignolini et al. Structural colour from helicoidal cell-wall architecture in fruits of *Margaritaria nobilis*. *J. R. Soc. Interface* (2016), **13**; DOI: 10.1098/rsif.2016.0645.

Direct observation of cell wall growth

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Pollia condensata has an extraordinary blue fruit known for its high intensity reflectivity, and glittery appearance. [1] The colours of the fruit are reflected by helicoidal cellulose stacks that form its overgrown cell walls.

It is also the only reported structural coloured material with both left and right handed chiroptical structures present in the same tissue, distinguishing it from other species, and from its artificial material analogue, iridescent Cellulose Nanocrystal film. This 'structural pigment' material is formed from dehydration of a self-assembled left-handed cholesteric crystallite suspension.

Helicoidal architecture in cellulose cell walls is extremely common but the exact mechanisms by which cell walls are laid down and their morphology controlled has been the subject of significant debate. Unpicking the respective roles of active biological control and passive entropy-driven self-assembly remains a contentious issue, and a debate we hope to contribute to.

Figure 1 The unusual reflection from *P. condensata* cell walls allows for the direct imaging of growing cell walls in a living plant without the use of genetic markers, stains or destructive techniques. We report direct measurement of growth in *P. condensata* and a related species with insight into understanding general cell wall growth mechanisms, and production of artificial structurally coloured cellulose pigments.

[1] S. Vignolini et al. Pointillist Structural Colour in *Pollia* fruit *PNAS* (2012), **109**

Dynamic living opals in brown algae

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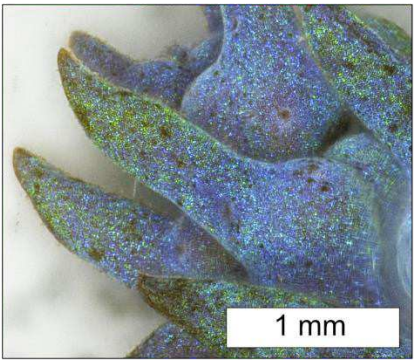
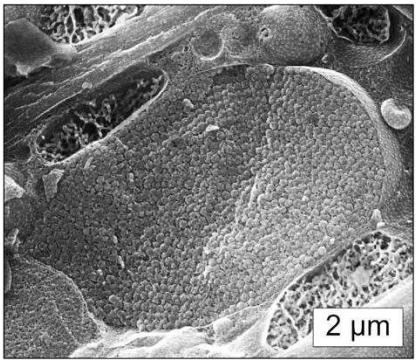
We present a naturally occurring 3D photonic crystal found in the brown algae, *Cystoseira tamariscifolia*. We have characterised and demonstrated the origin of the strong blue colouration of the algae: the intracellular opal-like arrangement of lipid nanospheres. These lipid opals are also dynamic with the structural colour responding to the environmental illumination.

The position of these "living opals" near the surface and in close proximity to chloroplasts suggests a role in which these vesicles can reactively modulate the light experienced by the chloroplasts for light harvesting.





Structural color occurs along a gradient in *Viburnum* fruits

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Structural color is common in some groups of organisms (such as birds, beetles, and butterflies), but rare in others (including most plant tissues, but especially fruits). To better understand how and why structural color has evolved in *Viburnum*, we characterized the traits underlying structural color in *V. tinus* (a thick cell wall and many layers of cellulose fibers) across 20 species of *Viburnum*, including blue-, black-, purple-, and red-fruited species. We quantified the structural component to several species' fruit color by comparing the reflectance of cells with and without pigments; the difference represents the color generated by the cell wall. We find that the bluest species (*V. davidii* and *V. tinus*) have a large structural component to their color, in addition to thick cell walls and many cellulose layers. *V. dentatum* is intermediate, with a small structural effect, blue-ish color, intermediate cell wall thickness, some layering, and some helicoidal cellulose fibers. The remaining species have nearly no measurable structural effect, and thin cell walls with few layers. Structural color in *Viburnum* fruits has evolved along a gradient between a large structural component to nearly pure pigmented color. Furthermore, the traits that underlie structural color in *V. tinus* are present across the entire clade, suggesting that the building blocks for structural color are widely available. Because pigments play a functional role in fruits, it may be extremely rare for a fruit to evolve a nearly pure structural color, but there may be many more fruits that combine structures and pigments.

Goblin's gold moss: structural color and light management in the dark

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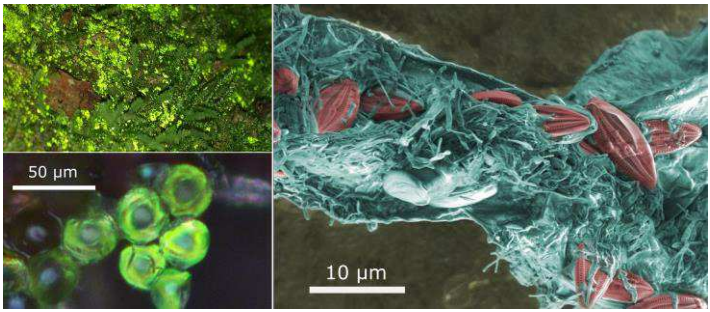
Mosses are one of the most resilient photosynthetic organisms in nature what allow them to live in extreme environments. *Schistostega pennata* (also known as Goblins gold) is a unique moss living in an extremely dark environment where no other plant can survive such as caves. It was believed that part of this adaptation consist on developing lens-shaped cells thought to act as light concentrators towards the chloroplast [1], but this assumption was never proofed. We will present a rigorous study of the optical properties of the organic microlenses and their expected effect on chloroplast absorption. Moreover, a unique feature of *S. pennata* is the strongly angular dependent green iridescence observable during the juvenile stage. We will discuss the origin of this structural color. Interestingly, we observed the presence of unicellular algae diatom type that could be related with the exclusive and unique optical features of the Goblin´s moss.



[1] M.I.S.I Gnatov *et al.,* Additional Observations on protonema of Schistostega pennata. *Arctoa* (2012) 21: 1-20

From mimesis to biomimetics: towards ‘smarter’ art

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Located at the interface of art and science, and drawing on relevant findings from material science, optical physics and evolutionary biology, this paper argues that the scientific field of biomimetics has the potential to lead to, and enable, ‘smarter’ art. Tracing the origin of biomimetics back to the ancient concept of mimesis (defined by Aristotle as ‘imitation of nature’ both via form and material), the emphasis is on latest bio-mimetic colour-technology and its potential via novel colour-shift to introduce ‘the dynamic’ into painting - historically a decidedly static medium. Until now, iridescent hues such as those found on the wings of certain butterflies have never been encountered in the art world. However, here the author illustrates how, facilitated by concerted scientific study of nature’s millennia-old colour optics, she arrives at vital clues on how to adapt and adopt these challenging new nano-materials for painting. And indeed, the resulting artwork, like iridescent creatures, fluctuates in perceived colour and pattern, depending on the light and vantage – thereby extending the canon of art by adding new colour spectra, novel visual realms and modes of expression. Tracing the author’s unique biomimetic approach, this visual, vividly illustrated, account affords an insight into the new colour technology’s evolution. Together with innovative artistic possibilities, the paper advocates that – both for scientists and artists – there remains much to be garnered from nature’s ingenuity.

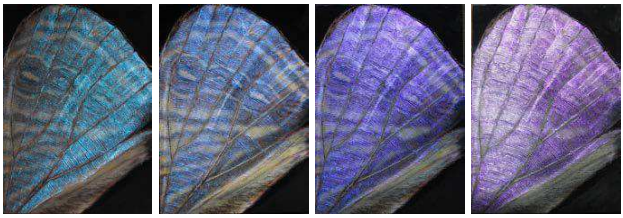

Figure 1 Franziska Schenk, ‘Morpho’ painting (2015). The piece shifts in colour.

Re-visiting the optical bases of hummingbird (Aves:Trochilidae) coloration.

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Hummingbirds have some of the brightest and most iridescent colors among animals. Their feathers contain stacks of hollow, platelet-like, melanin-filled organelles called melanosomes, but how these produce colors has only been addressed in a single paper [1] that, through modeling of color in two hummingbird species, suggested multilayer interference as a cause. Here, we attempt to replicate this study using feathers from 35 hummingbird species. While the models used in [1] predict (in some species) the location of peak reflectance, they do not match the overall shape. We thus modified these models and considered additional factors including the outer cortex surrounding the melanosomes and obtained better results. Macroscale features such as the shape of the barbule may also contribute to color and will be considered. We will also describe recent efforts to replicate hummingbird-like structures using synthetic melanosomes and the discovery of similar nanostructures in fossil dinosaur feathers.

[1] C.H. Greenewalt, W. Brandt, D.D. Friel. THe iridescent colors of hummingbird feathers. *Proceedings of the American Philosophical Society* **3,** 249-253, 1960.

Controlled fluorescence in beetles' photonic structures

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Fluorescence emission occurs in the integuments of many living species including but not limited to insects, arachnids, mammals, anthozoans (e.g., sea anemones and corals) and scyphozoans (i.e., true jellyfish). In insects, fluorophores, such as papiliochrome II and biopterin, are at the origin of such emission. In some cases, they are naturally embedded in photonic structures, which influence the light emission in terms of spectral intensity and spatial distribution [1, 2].

Using linear and non-linear optical techniques, single-photon and multi-photon excitation fluorescence analyses as well as liquid chromatography-mass spectrometry, we investigated the cases of fluorescent beetles with different types of photonic structures (ordered photonic crystals and randomly-disordered structures). These structures control both the beetles' colourations and emissions of embedded fluorophores. In addition to optical simulations, the combination of these techniques helps in understanding the influence of the photonic structures on the fluorescence emission, identifying the related pigments, unveiling their multi-excited states character and highlighting the role of the photonic structures' anisotropy in the fluorescence.

[1] P. Vukusic, I. Hooper. Directionally Controlled Fluorescence Emission in Butterflies, *Science* (2005), **310**, 1151.

[2] S. R. Mouchet, M. Lobet, B. Kolaric, A. M. Kaczmarek, R. Van Deun, P. Vukusic, O. Deparis, E. Van Hooijdonk. Controlled fluorescence in a beetle's photonic structure and its sensitivity to environmentally induced changes, *Proc. R. Soc. B* (2016), **283**, 20162334.

Genetic basis and evolutionary context for structural color shift in the Buckeye butterfly

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Structural color is caused by interference of light as it encounters nanoscale physical structures near the surface of an organism. Although structural color is a pervasive phenomenon, the biological production of the nanostructures remains poorly understood. I am using *Junonia coenia,* a lab-tractable butterfly with extreme intraspecific structural color variation, to overcome two significant challenges inherent to interrogating biological structural color. I show that *J. coenia* responded to artificial selection on color by a 50% thickness increase of each scale lamina, thus shifting color from brown to blue. There was no associated change in pigmentation, providing a rare opportunity to genetically parse loci that regulate specifically the structural component of overall wing color. A second advantage is that *J. coenia* utilizes thin film reflectors, a very simple type of structural color, with only one variable dimension. I can therefore compute reliable measurements of the nanostructure from spectra, making it feasible to phenotype large sample sizes quantitatively without electron microscopy. I exploit these advantages to genetically map quantitative trait loci that control nanostructural dimensions. Lastly, I show that this mode of color evolution (i.e. altering the thickness of scale laminae) recapitulates naturally evolved wing color variation throughout the genus *Junonia.*

Flavobacterium IR1 as a model organism for the genetic manipulation of structural colour

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Despite the frequency and diversity of structural colour in living organisms there is little knowledge of the underlying genes and biochemical pathways. *Flavobacterium* IR1 is able to rapidly self-assemble into a 2D photonic crystal on hydrated surfaces. Consequently, colonies of IR1 are able to display intense, angle-dependent colours when illuminated with white light. A program of transposon mutagenesis was used to identify genes that modulate structural colour. Genes involved in gliding motility, a key stress response, sugar metabolism and genes with no previously known role were identified. This work supports a more widespread genomics effort and commercial strategies in terms of biosensors, the incorporation of structural colour into hybrid living/non-living devices and the use of microbial templates for biomimetics.

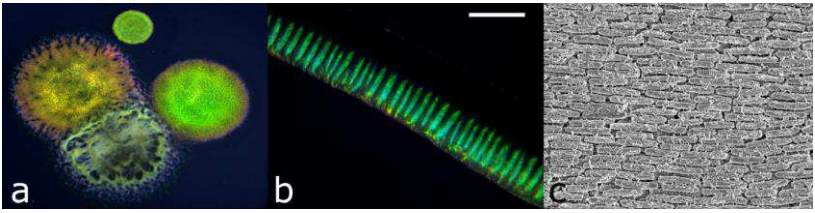

Figure 1 Structural Colour in *Flavobacterium* IR1**. A.** Examples of wild-type (right hand colony) and mutants (other colonies) with altered structural colouration. **B.** Example of patterning within a streak of WT IR1 on an agar plate, caused by different domains of aligned cells interacting with incident light. **C.** Scanning electron microscopy showing highly ordered IR1(M16) cells. Scale bar = 1 cm (Panel A), 1 mm (Panel B) and 2.5 microns (Panel C).

V.E. Johansen/L. Caton *et al.* Living colours: Genetic manipulation of structural colour in bacterial colonies. *PNAS* (2018) *DOI: 10.1073/pnas.1716214115*

The genetics and development of structural colour formation in the *Heliconius* butterflies

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Iridescent optical structures are fairly common in nature, but relatively little is known about their production or evolution. Here we describe the structures responsible for producing blue-green iridescent colour in *Heliconius* butterflies. Iridescent scales have ridges composed of layered lamellae, which act as multilayer reflectors. Differences in brightness between species can be explained by the extent of overlap of the lamellae and their curvature as well as the density of ridges on the scale. *Heliconius* are well known for their Müllerian mimicry as well as extensive within-species colour variation. We find that iridescent structural colour is not very well matched between co-mimetic species. Differences appear less pronounced in models of *Heliconius* vision than models of avian vision, suggesting that they are not driven by selection to avoid heterospecific courtship by co-mimics. Ridge profiles appear to evolve relatively slowly, being similar between closely related taxa, while ridge density evolves faster and is well matched between distantly related co-mimics.

These fast-evolving structures, in addition to excellent genomic resources make *Heliconius* the ideal system to identify understand how the genetic code of butterflies acts to control the assembly of colour-producing structures found on their wing scales. We have used crosses between iridescent and non-iridescent subspecies, as well as variation found in naturally occurring hybrid zones, to identify several genetic loci that control iridescent structural colour variation.

A detailed analysis of the Bouligand structure with examples from beetles of the scarabaeidae family

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Bouligand structured [1] cuticle play an important role for the mechanical and optical properties of many arthropods. From an optical point of view the twisted-layer arrangement in the Bouligand structures has analogies with human-made polarization components such as fanned Šolc filters. Further studies of the rich variations of the natural structures are likely to give both a deeper understanding of the biological phenomena as well as biomimetical inspiration for novel optical components.

In our research we describe the optical polarization response from structures of Bouligand type. Here, we use Berreman-based calculations to obtain Mueller-matrix descriptions of specular reflection at oblique incidence. We compare features in the optical spectra with expressions for circular Bragg resonances and determine pitch distributions from spectral oscillations. Basic model structures are described beginning with single- and double-pitch structures after which we include unidirectional spacers. This is followed by introducing pitch distributions and other irregularities.

The calculated data are compared to experimental data obtained by Mueller-matrix spectroscopic ellipsometry from several scarab beetles of the Cetoniinae and Rutelinae subfamilies. Some beetles, e.g. *Cetoina aurata*, can be explained by a rather simple model structure whereas other beetles, e.g. *Chrysina argenteola*, require a much more advanced description.

[1] Y. Bouligand, Sur une architecture torsadée répandue dans de nombreuses cuticles d'Arthropodes, *C.R. Acad. Sc. Paris* (1965) **261**, 3665.

Fluorescent pattern formation in large arrays of photosensitive chemical oscillators

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In 2002, studying synchronization of nonlocally coupled oscillators, Kuramoto and coworkers made a remarkable observation: Although both the natural frequency of the individual oscillators as well as their coupling among each other were identical, for certain initial conditions some oscillators became phase-synchronized while others do not [1]. The discovery of this counterintuitive state, named chimera state, triggered an increasing number of studies on partial synchronization.

I will present a versatile setup based on optically coupled catalytic micro-particles [2], that allows for the experimental study of synchronization patterns in very large networks of relaxation oscillators under well-controlled laboratory conditions. In particular I will show our experimental observation of the spiral wave chimera, predicted by Kuramoto [1]. This pattern features a wave rotating around a spatially extended core that consists of phase-randomized oscillators [3]. The spiral wave chimera is likely to play a role in cortical cell ensembles, arrays of SQUIDS and carpets of cilia.

[1] Y. Kuramoto, et al. Coexistence of Coherence and Incoherence in Nonlocally Coupled Phase Oscillators. *Nonlin. Phenom. Complex Syst.* (2002).
[2] A. Taylor, et al. Insights into collective cell behaviour from populations of coupled chemical oscillators. *Phys. Chem. Chem. Phys.* (2015).
[3] J. F. Totz, et al. Spiral wave chimera states in large populations of coupled chemical oscillators. *Nature Physics* (2017).

The ecological puzzle of the evolution of transparency in aposematic butterflies

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Colors of butterflies are involved in anti-predator strategies such as deflection of predator attacks, camouflage, and aposematism, whereby chemically-defended prey advertise their distastefulness to predators by the means of conspicuous wing color patterns. Surprisingly, many aposematic butterfly species harbor transparent or translucent wings, a feature generally associated with camouflage. Why has transparency evolved in aposematic butterflies? Are those clearwing butterflies switching from aposematism to camouflage, and as such are they less distasteful? We explore these hypotheses using optical measurements, predator vision modelling and behavioral experiments on Ithomiini butterflies, a neotropical clade of nearly 400 aposematic species encompassing a large range of transparency, from fully opaque to almost fully transparent. Vision modelling and detection experiments involving avian and human predators show that transparency is associated with a lower detectability, suggesting that transparency might be part of a camouflage strategy. However, feeding experiments involving birds show that transparent species are at least as distasteful as opaque species, contradicting our hypothesis of a full switch of strategy. We discuss the potential benefits of being cryptic and aposematic (and unpalatable) at the same time. We also discuss alternative functions of transparency that our experiments may have overlooked, such as sexual signals via iridescent patterns produced by transparent wing.

Optical properties of self-organised bacterial colonies

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Bacteria can exhibit bright and brilliant colouration through the way they organise in colonies. One example is the recently isolated *Flavobacteria* IR1 that stack in a highly ordered fashion, with their 350-450 nm rod-shaped bodies forming a photonic crystal, exhibiting strong light interaction and giving colour to these otherwise transparent cells [1].

The study of light interaction in bacterial colonies dates a century back, with cell sizes being estimated by diffraction [2]. However, recent reports from Kientz and co-workers on structurally coloured bacterial colonies [3] have sparked new interest in this field, and a deeper understanding of the light interaction with bacterial colonies is therefore needed.

In this talk, I will therefore present a detailed optical analysis using colonies of IR1 as a model system. The purpose is to understand the features observed in angle-resolved reflection spectra - such as diffraction and peak wavelengths - and relate them back to the geometrical arrangement of bacterial colonies. Bandgap analysis, closed-form models and full-wave models will be used. I will furthermore describe the inherent disorder in the colonies and suggest methods for analysing its contribution to the reflectance spectra.

[1] Johansen et al., Living colours: Genetic manipulation of structural colour in bacterial colonies. *PNAS* (2018), 115 (11) 2652-2657
[2] A. Pijper, Diffraction in biological structures I, *S. Afr. Med. Rec*. (1923), **17,** 243-8
[3] B. Kientz et al. Glitter-Like Iridescence within the Bacteroidetes Especially *Cellulophaga spp.*: Optical Properties and Correlation with Gliding Motility. *PLOS ONE* (2012), **7**, 1-12

Eye patches: protein assembly of index-gradient squid lenses

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A parabolic relationship between lens radius and refractive index allows spherical lenses to avoid spherical aberration. We show that in squid, patchy colloidal physics resulted from an evolutionary radiation of globular S-crystallin proteins. Small angle x-ray scattering experiments on lens tissue show colloidal gels of S-crystallins at all radial positions. Sparse lens materials form via low-valence linkages between disordered loops protruding from the surface. The arms are polydisperse and bind via a set of hydrogen bonds between disordered side chains. Peripheral lens regions with low particle valence form stable, volume-spanning gels at low density, while central regions with higher average valence gel at higher densities. The proteins demonstrate an evolved set of linkers for self-assembly of nanoparticles into volumetric materials. This talk will also discuss possible physical analogies between the squid lens system, Chinese "century eggs", and reflectin-based systems also found in cephalopods that suggest common strategies for assembling optical materials from proteins.

Chromophore interactions in the strong coupling limit: the live system of scale worms *Lepidonotus squamatus*

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[2] *Universitat Pompeu Fabra (UPF), Barcelona, Spain.*
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The first theory of the transfer of the electronic excitation energy between donor and acceptor molecules was formulated assuming a coherent transfer mediated by dipole-dipole interactions [1]. Coherence implies constant phase relation during the energy transfer. The energy lost by the donor must be exactly equal to the energy gained by acceptor. The coherence assumption, i.e. the strong-coupling limit, is generally not met in practice. The weak-coupling limit which is called Förster resonance energy transfer (FRET), is a physical process whereby the excited-state energy of the donor molecule is incoherently transferred to a neighboring acceptor chromophore in the ground state [2]. For the pair the lifetime of the donor decreases as compared to the isolated donor case. The presence of two chromophores in Lepidonotus squamatus that might show FRET have been shown by Plyushcheva et al. [3]. Here we show results of fluorescence-excitation measurements performed with a tunable white laser. We observed a strong acceptor resonance for excitation wavelengths matching the donor emission. We further performed chromophore-lifetime measurements with two-photon and single-photon excitation. In both cases, we found that the donor lifetime is *longer* in the presence of acceptor than for the donor alone. This might indicate that the energy transfer proceeds coherently, as initially assumed [1].

[1] F. Perrin. La Fluorescence des Solutions. *Ann. de Phys.* (1929), **XII**, 169-275.
[2] T. Forster. Transfer mechanisms of electronic excitation. *Discuss. Faraday Soc.* (1959), **27**, 7-17.
[3] M. Plyushcheva et al. Two-color fluorescence in elytra of the scale-worm *Lepidonotus squamatus* (Polychaeta, Polynoidae): *in vivo* spectral characteristic. *Mater. Today: Proc.* (2017) **4/4/A**, 4998-5005.

3D bioprinted photosynthetic matter inspired by corals

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There is great interest in optimizing microalgal photosynthesis for the production of algal biomass and high value products, such as Omega-3 fatty acids[1]. Current cultivation techniques are either very costly or suffer from suboptimal light and nutrient delivery[2]. Aquatic photosynthetic tissues such as coral tissue are one of the most efficient photosynthetic communities on Earth, reaching photosynthetic quantum efficiencies that approach the theoretical maximum[3]. Here, we use a biomimetics approach to inspire the development of improved photonic materials for the optimization of photosynthetic quantum yields in microalgal cultivation. We study the photonic properties of coral tissues and develop 3D bioprinted photosynthetic living matter. Our coral inspired design is characterised by a fine-tuned physico-chemical microenvironment that allows for optimized algal growth. Our study provides a novel way to study the evolutionary optimization of light harvesting by coral tissues and seeks to inspire improved photobioreactor design solutions for microalgal cultivation.

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Stretchable optical fibers for extreme deformation sensing in biomechanics applications

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Quantitative assessment of pressure and extreme deformations is a formidable challenge in many biomedical applications, health monitoring, and human-machine interaction. Combining insights into biological light manipulation strategies with knowledge about current challenges in biomechanical sensing, we aim to design optomechanical sensors that can reliably indicate changes in mechanical parameters via an optical readout. This presentation will be focused on two exemplary synthetic material systems: (1) We demonstrate a simple strategy for measuring the pressure exerted on a patient's body using stretchable photonic fibers that are integrated into elastic bandages. The fibers were initially designed to capture the essential morphological components of a tropical fruit and since have been optimized to sustain repetitive strains of over 100%, responding to deformations with a predictable and reversible color variation. Integrated into bandages they could greatly improve the efficiency of compression therapy, leading to reduced treatment duration, improved patient outcomes, and significant savings in the healthcare system. (2) We report the design and scalable manufacture of highly stretchable and flexible optical fibers that can be fabricated in a one-step, continuous co-extrusion process at a scale of several 100m of fiber in one hour. The fibers guide light and can reversibly sustain over 300% strain. Stretching, bending, and indentation of the fibers results in predictable, repeatable, and reversible transmission losses. These stretchable optical fibers form a versatile material platform for the design of advanced sensing devices in health monitoring, rehabilitation, physical training, human-machine interaction, advanced functional textile design, and control of internet-of-things devices.

Dynamic materials inspired by cephalopods

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Cephalopods (e.g. squid, octopuses, and cuttlefish) have captivated the imagination of both the general public and scientists for more than a century due to their visually stunning camouflage displays, sophisticated nervous systems, and complex behavioral patterns. Given their unique capabilities and characteristics, it is not surprising that these marine invertebrates have recently emerged as exciting models for novel materials and systems. Within this context, our laboratory has developed various cephalopod-derived and cephalopod-inspired materials with unique functionalities. Our findings hold implications for next-generation adaptive camouflage devices, sensitive bioelectronic platforms, and advanced renewable energy technologies.

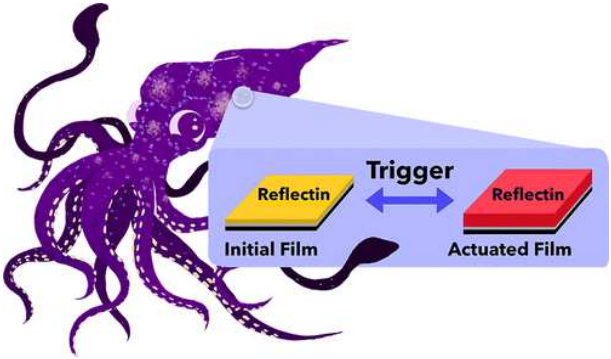

Figure 1 Illustration of a cephalopod, which can serve as inspiration for a stimuli-responsive camouflage device.

Multi-functionally of Colored Butterfly and Beetle Scales

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Many optical effects observed in nature originate from complex three-dimensional surface structures. Transferring these optical effects to technical applications often demands the development of new fabrication techniques [1-4]. However, in addition to that it is sometimes even puzzling to discover the underlying optical effect because the surface texture of plants and animals is multi-functional in most cases, i.e., it provides bright color and protection against environmental exposures at the same time. Therefore, two (or more) surfaces features have to be combined which might complicate the analysis. Butterflies for example developed many tricky structures embedded into their scales to obtain colorful wings. In addition to this coloring, the scales are superhydrophobic and provide a self-cleaning effect. This multi-functionality is of high interest for many technical applications where colorful and self-cleaning surfaces are demanded. In this talk, I will present several examples of butterfly and beetle scales featuring this multi-functionality and discuss possible mechanisms providing color and environmental protection at the same time.

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Functional nanomaterials as a route to enhanced crop productivity

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There are obvious demands on current food production and unless there is a dramatic increase in crop productivity beyond the current increase from techniques we will be unable to meet world needs in the near future. We describe the use of functional-nanomaterials to increase the productivity of bread wheat. This work utilizes fluorescent, non-toxic, water-soluble carbon nano-dots (CDs) synthesized from a cheap carbohydrate starting-material to interact with the photosystems of plants[1]. The CDs are formed of a 3nm crystalline sp^3-carbon core, coated in a 1.5nm aromatic shell where glycan functionalisation can provide a quasi-spherical corona that enhances cellular internalization and reduces toxicity[1,2]. These CDs show a significant increase in carbon assimilation and crop productivity[3,4]. These findings present an alternative to genetic modification to meet food demands.

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Complex structural color in a Cretaceous moth

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The reconstruction of fossil color has provided unprecedented insights into the evolution of animal coloration over the past few years. Animal colors can be produced by pigments and by the physical interaction of light with biological nanostructures varying in refractive index. Structural coloration is widespread in nature, but the fossil record of insects has thus far been limited to simple multilayer nanostructures, leading some authors to conclude that more complex nanostructures evolved more recently. However, these conclusions were based on compression fossils that may be limited by their preservation mode and potential [1]. For example, three-dimensional structures in fossils preserved in carbonate rocks are susceptible to deformation during burial of sediments. Such concerns are not relevant to amber specimens, which should largely preserve the true three-dimensional morphology. Here, we report on the color and optical mechanisms of a Micropterigidae-like moth specimen from Cretaceous (~99 mya) Burmese amber inclusions. We used optical and electron microscopy and finite-difference time-domain (FDTD) simulations to 1) understand the mechanism responsible for the golden coloration in two species of the genus Micropterix (*Lepidoptera: Micropterigidae*; *M. calthella* and *M. tunbergella,* the closest extant relatives of the fossil specimen) and 2) reconstruct the life color of the amber moth based on its nanostructure. Nearly identical 2D nanostructures are present on the wings and legs of both extant and fossil moths, demonstrating that complex color-producing mechanisms occurred in insects earlier than previously thought.

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Diverse 3D nanostructures in fossil insect scales

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Beetles represent the most speciose order amongst modern insects, with many species displaying vibrant structural colours. In beetles, as in most insects, these colours derive typically from 1D thin-film and multilayer reflectors in the cuticle ultrastructure; however, certain beetles (predominantly weevils and longhorns) have evolved complex 3D photonic nanostructures, housed within cuticular scales [1]. Despite their abundance in extant species, photonic structures are comparatively rare in the insect fossil record, partly due to the paucity of preserved scales. To date, 3D photonic nanostructures have been reported in only a single fossil weevil [2] and, thus, the evolutionary history of these tissue architectures, and the driving forces behind them, are unknown. Here, we report the discovery of diverse 3D nanostructures in fossilized scale structures. We used small-angle X-ray scattering (SAXS) in tandem with electron microscopy to characterize the fossil scales' ultrastructure, identifying photonic nanostructures akin to those reported in modern insects. These data provide novel insights into the evolution, development and functionality of scales in coleopteran species.

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Optical characterization of experimentally degraded circularly polarizing scarab beetles: testing the potential for fossilization

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Insect cuticles possess diverse structural colouration mechanisms that include helicoidal (Bouligand) structures formed by chitin fibrils in the exocuticle of some scarab beetles. With adequate spacing, these structures reflect light with a high degree of circular polarization, the biological function of which is unknown. While recent studies have illuminated the evolutionary history of other photonic structures in insects, the evolution of Bouligand structures in beetles remains enigmatic. To test the potential for helicoids to be fossilized, we conducted decay and maturation experiments on cuticles from four taxa exhibiting optical activity and one that does not. Changes were assessed using reflectance spectrometry and Mueller matrices analysis.

Reflectance spectra of untreated cuticles illustrate notably the variations of Bouligand structures implied in scarabs' cuticles. Original colour and polarization survive decay in *Ischiopsopha* and *Gymnopleurus*, but not in the two *Chrysina*; paradoxically, original colour and polarization survive maturation in *Chrysina*, but not in the two other genera. For *Torynorrhina,* original colours survive decay but not maturation. The origin of these discrepancies is uncertain but may be associated with unusual cusp-like arrangement of the exocuticular layers of *Chrysina*. These results reveal new detailed structural features in scarabs' cuticles and suggest that preservation of Bouligand structures is controlled by both taxonomy and taphonomic processes and, while complex, may be possible in fossils.

Modulating Iridescence in Structural Colors through Hierarchy, Micro-geometry, but Randomness

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Iridescence has long been considered as an intrinsic special feature in structural colors. But we have also learned, for around two decades, that iridescence in structural colors can be reduced by incorporating certain degrees of randomness, as demonstrate by the photonic glass and polycrystals.

By studying structural colors in two different groups of spiders – the large, non-iridescent blue tarantulas and the tiny iridescent peacock spiders – we have found examples shown iridescence in structural colors can be both reduced and enhanced through the interaction of sub-micrometer photonic structural features, micrometer-scale geometries, and hierarchies without the needs of randomization.

To fully understand how iridescence is affected by structures of specialized setae in these spiders, we use an interdisciplinary biomimetic approach and apply a myriad of characterization, simulation, and prototyping techniques during our investigations, including but not limited to, spectrophotometry, electron microscopy, imaging scatterometry, hyperspectral imaging, finite element analysis, and two-photon nanolithography.

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[3] B.-K. Hsiung, et al. Rainbow peacock spiders inspire miniature super-iridesent optics. *Nat. Comm.* (2017), **8**, 2278.

Ultra-white beetle scales are spatially isotropic

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The porous network structure of chitin filaments and air within the scales [1] of the *Cyphochilus* beetle is considered to be the strongest [1, 2] structural whites found in nature. Multiple studies have reported that the internal network is strongly anisotropic [2-4], with chitin filling fractions ~ 60 %. All previous morphology studies of this network structure were performed on sectioned or incomplete scales. We have performed structural characterization measurements on intact scales using, imaging ellipsometry, spin-echo small angle neutron scattering (SESANS) and X-ray tomography. In all instances we find isotropic structure with a much lower Chitin filling fraction nearer 30 %, consistent with a lightweight optical structure.

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[3] Cortese, L. et al. Anisotropic Light Transport in White Beetle Scales. Adv. Optical Mater. 3, 1337–1341 (2015).
[4] Wilts, B. D. et al. Evolutionary-Optimized Photonic Network Structure in White Beetle Wing Scales. Adv. Mat. 7, 1702057 (2017).

Optical active intracellular mesostructures preserved by cryopreparation

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Cryopreparation extends our capability to preserve optical active intracellular inclusions. Accordingly, we found novel grating-like mesostructures in cryofixed, rapidly freeze-substituted epidermal cells of the ovisac of brine shrimps, *Artemia franciscana* [1]. As indicated by confocal reflection microscopy (CRM) they seem to act as light-dispersing ´umbrellas´ for protection of eggs inside the ovisac during embryogenesis.
Although the cryopreserved ´zebra-striped´ flakes (Figure 1) are reminiscent of mesocrystals assembled from inorganic crystalline subunits and biopolymers (e.g. during biomineralization), we did not find any crystallized inorganic components. Therefore, we suggest the assembly of (liquid) mesocrystals under participation of proteinaceous subunits as an interesting new mechanism for the generation of optical active cellular inclusions.

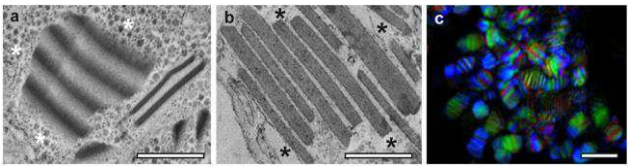

Figure 1 Optical active mesostructures in *A. franciscana*. TEM: a) cryofixed and rapidly freeze substituted; asterisks: glycogen-rich cytoplasm. b) Chemically fixed and processed at room temperature; asterisks: washing out of cytoplasmic material. c) CRM. Scale bars in a and b: 1 µm; in c: 5 µm.

[1] Hollergschwandtner et al.. Novel mesostructured inclusions in the epidermal lining of *Artemia franciscana* ovisacs show optical activity. PeerJ (2017).5:e3923.

The meaning of colour

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Why are animals colourful, and why are they colourful to the human eye despite being directed at species with different colour vision from ours? The answer to the second of these question lies in the geometry of colour spaces, and leads to an answer to the longstanding evolutionary puzzle posed by the first.

Consideration of the geometry of colour spaces leads us to define a measure of colour, which we term "vividness", which we demonstrate to have a high degree of consistency between different observers. Vividness is minimal for greys, and maximal for more intense colours, including black and white. In including achromatic colours vividness is distinct from standard measures of colourfulness.

The projective, convex structure of colour spaces responsible for its between-species consistency also endows vividness with a physical meaning, because mixing reduces vividness compared to (at least one of) the constituents. We argue that this endows vividness with semiotic meaning, offering a simple and general explanation of why animals are colourful.

Transparency in butterflies: how structures shape optical properties

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Although apparently simple, transparency is a highly complex coloration strategy. While abundant in water, transparency is nearly absent on land, with the exception of insect wings. Research effort concentrated on water transparency has left transparency on land – with specific requirements and solutions - virtually unstudied. Lepidoptera (butterflies and moths) represent an outstanding group to investigate transparency on land, as species harbor wings covered with scales, a key multifunctional innovation. This innovation, however, has been abandoned by many Lepidoptera species, which have evolved clear wings. We here present a study on clearwing butterflies and moths at a broad interspecific level, encompassing a large number of families. At the interface between physics and biology, we characterize wing structural diversity using electronic microscopy and photonic imaging. Using goniospectrometry and vision modelling, we measure wing optical properties and assess their perception by butterflies and their main predators, birds. Using a phylogenetic comparative approach, we establish that transparency has evolved multiple times independently in butterflies, and we reveal interesting links between optics and wing nano/microstructure. We discuss the diversity of strategies for transparency, and their potential value for camouflage, to provide a better understanding of the processes that drive the evolution of transparency.

Recent evolution of reflectin metastability enables tunable control of structural color

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Genetic engineering and biophysical analyses have recently revealed the mechanism by which the reflectin proteins function as a signal-controlled molecular machine, regulating an osmotic motor that reversibly controls the thickness, spacing and refractive index of the membrane-bound intracellular Bragg lamellae unique to the iridocytes of Loliginid squids. Initially disordered, these reflectins are block copolymers with canonical domains interspersed with cationic linkers. A neurotransmitter-triggered signal transduction cascade culminates in catalytic phosphorylation of the reflectins' linkers, activating and tuning reflectance. The resulting charge neutralization overcomes the linkers' Coulombic repulsion of inter- and intra-chain contacts, progressively driving condensation and secondary folding of the canonical repeat segments to form amphiphilic, bifacially phase-segregated alpha and beta structures, with the progressive emergence of hydrophobic faces mediating hierarchical assembly. These reflectins are metastable, with phase-segregation providing the entropic drive to folding and assembly, stored in the protein like a stretched spring, while the Coulombic repulsion of the linkers provides an opposing "stretch." Once released by neutralization, the resulting condensation, folding and hierarchical assembly trigger Gibbs-Donnan dehydration, shrinking the thickness and spacing of the Bragg lamellae while increasing their refractive index, progressively changing the color of reflected light from red to blue while increasing its intensity. The process is fully cyclable. Mutational analyses show that the "switch" is delocalized along the reflectins' length. Computational analyses suggest that the recent evolution of tunability in the loliginid reflectins is the result of sequence changes enhancing the cationic character of the linkers, poising the Loliginid reflectins as metastable oligomers prior to phosphorylation, as opposed to the non-tunable multimers of the ancestral reflectins.

Diversity and evolution of structures producing iridescence in hummingbirds

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Iridescent colours are colours that change depending on the angle of illumination or observation. They are produced when light is reflected by multilayer structures or diffracted by gratings. While this phenomenon is well understood for simple optical systems, it remains unclear how complex biological structures interact with light to produce iridescence. There are very few comparative studies at interspecific level (often focusing on a single patch), resulting in an underestimation of structures diversity. Through an interdisciplinary approach combining physics and biology, we here investigated 36 hummingbirds species, evenly distributed across the phylogeny. We explored at least 2 patches per species that we suspected were submitted to different selective regimes. For each patch, we analysed structures using electronic microscopy and measured colour with a novel approach we developed to encompass the full complexity of iridescence. We discovered an unsuspected diversity in structures producing iridescence in hummingbirds, with high rates of novel structures acquisition or reversion. We also identified the effect of several structures features (number of layers, layers width, irregularity, spacing, chemical composition) on iridescence. Using optical simulation methods and vision models, we show however that, in spite of the unexpected structural diversity, structural colours can produce highly convergent visual signals. Our findings demonstrate the need to take into account multiple patches per species and call for more research to understand the evolutive pressures causing the convergence patterns.

Ultraviolet and yellow reflectance but not fluorescence is important for visual discrimination of conspecifics by *Heliconius*

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Toxic *Heliconius* butterflies have yellow hindwing bars that – unlike those of their closest relatives – reflect ultraviolet (UV) and long wavelength light, and also fluoresce. The pigment in the yellow scales is 3-hydroxy-DL-kynurenine (3-OHK), which is found in the hair and scales of a variety of animals. In other butterflies like pierids with color schemes characterized by independent sources of variation in UV and human-visible yellow/orange, behavioral experiments have generally implicated the UV component as most relevant to mate choice. This has not been addressed in *Heliconius* butterflies, where variation exists in analogous color components, but moreover where fluorescence due to 3-OHK could also contribute to yellow wing coloration. In addition, the potential cost due to predator visibility is largely unknown for the analogous well-studied pierid butterfly species. In field studies with butterfly paper models, we show that both UV and 3-OHK yellow act as signals for *H. erato* when compared with models lacking UV or resembling ancestral *Eueides* yellow, respectively, but attack rates by birds do not differ significantly between the models. Furthermore, measurement of the quantum yield and reflectance spectra of 3-OHK indicates that fluorescence does not contribute to the visual signal under broad-spectrum illumination. Our results suggest that the use of 3-OHK pigmentation instead of ancestral yellow was driven by sexual selection rather than predation.

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Manipulation of the *in vivo* light field by nanostructured frustules: implications for photosynthesis and niche differentiation of diatoms

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The intricate micro- and nano-structures of the silicate frustules of diatoms mediate nutrient exchange and provide an enormous mechanical strength. Such structures also interact with incident sunlight in the photosynthetically productive wavelength range. In the large centric diatom *Coscinodiscus granii,* we found that photosynthesis was induced in chloroplasts distant from a localized laser illumination, explainable by waveguiding inside the frustule and coupling of chloroplasts to the evanescent field [1]. Transmitted white light into the cell was spectrally filtered in favor of photosynthetically more effective shorter wavelengths, by forward scattering on the valve structure or diffraction on the array of pores on the interior side of the frustule. This phenomenon was conserved in diatoms from pelagic and benthic habitats, but differed as a function of the angle of incident light between species [2]. In a benthic diatom community, enhanced scattering in the frustule compensated for high attenuation of blue light in the sediment. We speculate that the photonic structures of frustules alter the cellular light field to promote photobiological processes, facilitating niche differentiation of diatoms in various aquatic environments.

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Seeing the giant clam for the leaves

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'Giant' clams grow giant in nutrient-poor tropical waters in part because of photosymbiosis with algae residing in their mantle tissue. Their mantle tissue resembles a large leaf - flat, smooth and slightly curved at the edges. However, we previously described a high degree of structure within the clam mantle tissue, with algae organized in micropillars. Iridocytes produced by the clam then cover these pillars that reach to distances of millimeters down in the tissue.

We discovered that the layer of iridocytes serve to transform—with little loss—the intense ambient flux to a lower intensity flux that evenly coats these pillars, such that algae experience irradiances consistent with efficient photosynthesis [1]. Here we report a more detailed experimental characterization of this system including photosynthetic efficiencies of algae throughout the tissue depth of the clam system. With this more complete characterization, we estimate the amount of biomass generated over time by the clam, or the gross primary productivity, at around 200 gC/m^2day, or comparable to a temperate forest. This system of scatterers and absorbers specific to the giant clam displays a unique optical method for obtaining high GPP which could be useful in the development of photobioreactors and production of algae biofuels.

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ABSTRACTS

Posters

Bioinspired non-iridescent structural colors from ternary polymer blend films

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Structural colors, have gained lot of prominence in the recent years, owing to their vibrancy, durability, environment friendliness, choice of materials, stimuli responsiveness and long-lasting performance with special emphasis on angle-independent colors due to their applicability in LCD displays, coatings, and paints. Numerous studies on using colloids[1] and block copolymers[2] for fabricating angle-independent colors have been reported in literature. However, there is still need for a system that mimics colors in nature from porous materials, which are lightweight. Here, we demonstrate a facile two-step temperature-induced phase-separation in polymer blend films as a strategy to achieve angle-independent colors spanning entire visible spectrum, wherein, the resultant structures have close resemblance to multilayer structures in beetles, quasi-ordered structures in feather barbs of Eastern bluebird and white color of beetle scales. We have employed PS/PMMA blend system as a model system of study. The polymer blend films were thermally annealed above the glass-transition temperature of the polymer blend components and then the PS is selectively removed in order to enhance refractive-index contrast. Tuning the composition of the polymer blend film selectively controls the morphology and associated structural length scales. Characterization of the films using SEM, USAXS and UV-Visible spectroscopy revealed that the color of the films stems from disordered, quasi-ordered and multi-layer structures based on incoherent, coherent scattering and multi-layer interference respectively. The strategy employed is thus compatible via a roll-to-roll assembly enabling us to fabricate these colors on a large-scale.

Broadband optical properties of single setae from the Saharan silver ant

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The Saharan silver ant *Cataglyphis bombycina* is adapted to the extremely hot environment of the Sahara Desert [1]. The ant's body is densely covered by setae with triangular shaped cross sections [2]. These setae not only reflect the incoming solar radiation by total internal reflection in the visible range [3], but also enhance the radiative cooling in the MIR range [2].
To understand how the morphology of the single seta influences the solar radiation perceived by the ant body, we investigated the relationship between structure and optical properties of single setae over a broad spectral range.
We simulated the scattering behaviour of single setae using the FDTD method focussing on the optical impact of size, shape and surface structure of single setae on their hemispherical back reflection. We show that simple ray optics is not sufficient to understand the optical properties of a single seta, which are strongly influenced by the combined effects of all structural parameters. We experimentally measured the orientation dependent Mie resonances in the MIR range. The chemical absorption bands of the materials constituting the setae are measured separately to help the interpretation of the optical properties in this range. We show that the single seta can indeed be regarded as an effective medium to enhance the radiative cooling in this range. Therefore, we speculate that the size of the seta is optimized for the scattering properties over a broad spectral range to facilitate the cooling of the ant body.

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Thin film coloration in archaic moths

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Micropterix and *Nemophora* are small archaic moths that display vivid metallic coloration. The wings of, for example, *M. aureatella* (Figure 1A) show a combination of purple, bronze and gold-colored wing scales that form a simple pattern [1].

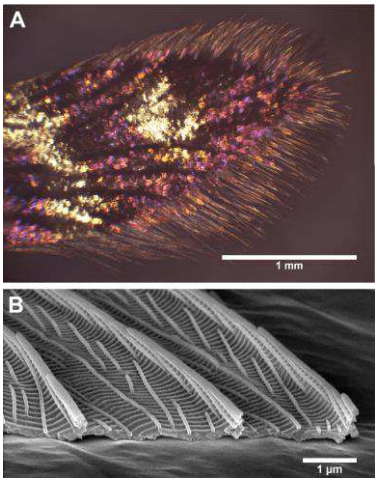

Figure 1 The archaic moth, *M. aureatella*. (**A**) Close-up photograph of a dorsal forewing. (**B**) SEM image of the cross-section of a single wing scale.

We have investigated the origin of scale coloration. Spectroscopic optical measurements and electron microscopy of single wing scales show that the vivid, metallic coloration originates from classical thin film interference [2]. The wing scales form a simple thin film with thickness varying from 125-200, giving rise to the color of the scales (Figure 1B). Computational modelling of the reflection properties of these nanostructures confirm the optical thin film model, where minute variations in the scale thickness have a major impact on the coloration. The resulting large changes in hue indicate functional significance for the organism.

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Scarab beetle-inspired helicoidal multilayers

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Some scarab beetles (e.g. the *Chrysina* genus) exhibit the property of selectively reflecting visible light with left-handed circular polarization. This remarkable feature is due to a multilayer of chitin nanofibrils stacked in a helicoidal arrangement inside the beetle's cuticles [1]. From a technological point of view, it is highly desirable to develop artificial structures that can exhibit similar circular polarization dependent light-matter interactions, for example for applications in the sensing of chiral molecules.

Here, we implement a thin film self-assembly approach to fabricate on-chip multilayered optical devices, with a focus on helicoidally stacked nanoparticle arrays inspired on the circular polarization selective reflection of scarab beetles. The fabrication method exploits a stress driven self-rolling mechanism of a thin film when selectively released from an underlying substrate [2]. The result of this self-assembly is a microtubular structure with multilayered walls that can have custom designed nanoparticle configurations at each layer. In our case, we are exploring the stacking of gold nanoparticle arrays with varying angle orientations, and show preliminary results of the structural and optical characterization of these rolled-up multilayered structures. These devices can potentially be implemented as on-chip circular polarization filters or sensors, and furthermore are compatible with microfluidic sensing platforms due to their tubular structure.

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Multiresonant antennas for polarization control

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Nanostructured surfaces allow enhanced in- and out-coupling of light for targeted wavelengths, propagation directions and polarizations [1, 2].

Inspired by plasmonic bull's-eye structures that use concentric circular grooves to provide spectrally selective and directional transmission of light [3-5], we introduce a new class of concentric polygonal bull's eyes [6] that can accommodate multiple resonances and provide independent control over emission directionality for multiple wavelengths. Since each resonant wavelength is directly mapped to a specific polarization orientation, we use the central subwavelength aperture as a built-in nano-cuvette to decode the spectral information of colloidal quantum dot emitters. Extending this concept beyond the plasmonic antenna structure, we fabricate structures made entirely out of colloidal quantum-dots [7]. Our results will be discussed in the context of polarimetric applications that may generate new forms of the spectral information of colloidal quantum-dot emitters.

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Changes in structural and pigmentary colours in response to cold stress in *Polyommatus icarus* butterflies

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While numerous papers have investigated the effects of thermal stress on the pigmentary colours of butterfly wings, such studies regarding structural colours are mostly lacking. To gain insight into the possible differences between the responses of the two kinds of colouration, we investigated the effects of prolonged cold stress (cooling at 5°C for up to 62 days) on the pupae of *Polyommatus icarus* butterflies. The wing surfaces coloured by photonic crystal-type nanoarchitectures (dorsal) and by pigments (ventral) showed markedly different behaviours [1].

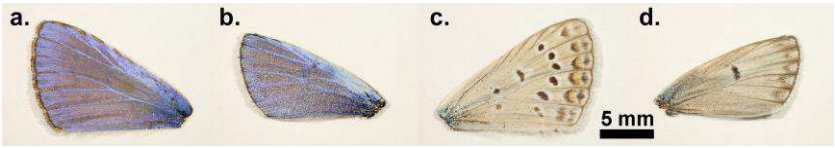

Figure 1 Wing of a wild butterfly (a, c) and of subjected to prolonged cooling (b, d).

It was found, that the dorsal blue colouration, used for sexual communication, is much more stress resistant than the pigment-generated pattern of the ventral wing surface used for camouflage. Significantly smaller magnitude changes were induced by the prolonged cooling in the blue colour of the males (Fig. 1a vs. 1b), as compared to the alteration of their ventral wing patterns (Fig. 1c vs. 1d), which exhibited aberrations proportional to the duration of cooling [1].

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Bacteria as a 2D photonic crystal

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Structural color is widespread in nature, from animal to plants there is a large variety of species and architecture producing brilliant iridescent colorations [1]. In contrast, structural color has been lees investigated on prokaryotes [2]. Here we report structural color in *Flavobacterium* IR1 colonies. The color of IR1 originates from the periodic organization of individual bacteria, which assemble into a 2D photonic crystal with hexagonal lattice, which is responsible for the structural coloration of the colony (Fig. 1a-c) [3]. The optical properties of the colony strongly rely on the interplay between order and disorder in the stacking of the bacteria (Fig. 1c,d). In this work we aim to unveil the relationship between morphology and optical response of the colony. We believe that a better understanding of such iridescent microorganisms could open new possible applications of structural color with living system such as biological pigments or living sensors.

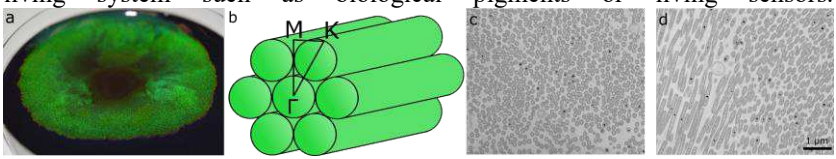

Figure 1 a) A colony of Flavobacterium IR1 shows bright green iridescence. b) The hexagonal backing of IR1 creates a 2D photonic crystal. c) Transmission Electron Microscopy on a cross section of an IR1 colony. a) Hexagonal packing. b) The boundary between two domains within the colony, each with a different orientation.

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The *Cyphochilus* beetle as an inspiration for sustainable white materials

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The brightness of a white material, that is the amount of incident light that it reflects, depends on the arrangement, the geometrical features, and the refractive index of its components. Optimizing the brightness of disordered structures represents an open challenge in the production of commercial white materials, where high refractive index particles are used to enhance their optical appearance.

Nature provides an important example of brightness optimization in a low refractive index medium. More in detail, the anisotropic chitin network inside the scales which cover the body of the *Cyphochilus* beetles outperforms all man-made low-refractive index materials known to date. [1,2,3]

Here, after quantifying the scattering efficiency of the chitin network *via* a coherent backscattering setup, we show a fast and scalable method to optimize the brightness of porous polymer films.

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Interactions of Light with Surfaces Mimicking the Skins of *Springtails*

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There is a great interest in unraveling the principles underlying colors in natural systems—plants and animals—and applying them to address practical challenges. We have recently microfabricated silica surfaces mimicking the skins of *Springtails*, soil-dwelling insects; those surfaces, regardless of their chemical makeup, exhibit repellence to a wide variety of polar and apolar liquids [1]. Herein, we report on the interactions of light with those textures as a function of feature sizes.

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Modern digital imaging for the study of biological coloration and pattern: utility and limitations.

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The recognition, interpretation, and response to color and pattern are fundamental aspects of visual systems in many organisms. When studying morphologies, natural histories, and evolution of traits and behaviors, the acquisition of accurate color data is paramount. Commonly, spectrophotometers are the standard for obtaining quantitative, objective data of biological specimens, but lack elements of visualization and interpretation (e.g., various lighting conditions and color spaces, receiver perception). For some applications and analyses, digital imaging can provide advantages that spectrophotometric data cannot, namely analysis of color and pattern landscapes and mosaics as opposed to individual, discrete data points (see R packages like *pavo*, *patternize*, *colorzapper*). Modern digital cameras, lenses, monitors, and software, however, possess their own series of actual and theoretical limitations that must be acknowledged and addressed. Here we present key points of consideration for effectively utilizing and standardizing accurate data capture, display, and interpretation, including camera sensors, color balance, color space, monitor calibration, and pixel analysis.

The many (sur)faces of *M. thailandicum*

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Microsorum thailandicum is a rainforest understorey fern exhibiting strong blue iridescence. The abaxial surface of the leaf is also structurally coloured, but it mostly reflects in the green and red part of the spectrum.
Investigating the ultrastructure of this leaf, we found that the first two layers of epidermal cells have a thickened cell wall, made of helicoidally arranged cellulose fibres. This helicoidal structure reflects left-handed circularly polarised light. The pitch measured from electron microscopy images was correlated to the optical response observed via microphoto- spectroscopy by modelling the helicoidal structures by analytical calculations.
We found that the reflected wavelengths vary significantly between cells, both on the adaxial and abaxial surface, in the same way as they vary within a single cell. Remarkably, the reflection from the abaxial epidermis is red-shifted with respect to the adaxial one, meaning the helicoidal cellulose structure has a bigger pitch, and the distribution of reflected wavelengths is much wider for the abaxial epidermis as well. This implies that more material has to be deposited between the cellulose fibres to obtain more spacing between the layers and thus a bigger pitch, and also that the cell wall deposition in the abaxial epidermal layer is less regular.
This study aims to inspire further studies on how the cell wall is laid down as well as on the function of structural colouration of leaves.

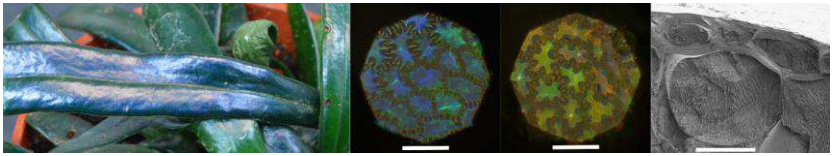

Figure 1 *Microsorum thalandicum*: photo, optical (adaxial and abaxial) and electron micrograph

Developing a linker to covalently bond silk proteins on polymers for optical materials

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Besides being used in medical applications, silk fibroin is very often used in optical devices. Silk offers remarkable optical properties[1,2] and various possibilities to chemically modify its structure[3]. Combining optical silk fibroin layers with polymeric materials allows creating composites with enhanced properties. However, an interface between a polymeric material and a modified protein does not allow strong intermolecular bonding[4]. It is of great interest to us to modify silk fibroin to make it attachable to a polymeric material. Hence, we report the synthesis of a heterogeneous bifunctionalized linker, which binds to tyrosine residues in silk fibroin by performing a diazonium coupling reaction and reacts with any organic polymer by C,H-insertion crosslinking chemistry. Being spin-coated on a polymer layer and crosslinked under UV light, multilayers of silk fibroin and polymers can be made.

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The French National Firefly Observatory, Flaugergues' bioluminescent earthworm & "Absence" of fluorescence in Arctic waters

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In 2015 we founded the French National Firefly and Glowworm Observatory, a citizen science project that asks the general public to help the scientific community to know in which regions of France these animals are thriving. The creation of this observatory through a novel approach and first results of the many thousands of observations will be presented. We are also trying to use a similar approach in Italy, Spain and Romania.

Amongst the about 7000 known earthworm species, thus far only 40 are reported to produce light. A short review will be presented about the current knowledge on these interesting animals and hypotheses concerning the function of producing underground light will be discussed and illustrated with some preliminary data obtained on Flaugergues' worm that we recently rediscovered in the French Loire valley after 250 years of absence from the scientific literature.

Recently the UTPIII expedition (https://www.underthepole.com) deep-dived down to -100m the waters of the North-Ouest Passage between Greenland via Canada to the south of Alaska. Organisms were collected and verified for natural fluorescence and bioluminescence. The hypothesis that these dark and cold waters are not favorable for fluorescent-signal-communication seems to be true. Preliminary results will be shown.

Understanding and reproducing structural colour in soft materials

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We aim to understand the mechanisms by which photonic nanostructures develop in living organisms and to apply this insight to the fabrication of synthetic soft materials with structural colour. To reveal the underlying biological mechanisms, we consider structural evolution in model species including butterflies and diatoms. Additionally we are designing structurally coloured fibres and films inspired by bird feathers [1], based on phase separation in an elastic matrix [2].

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Fluorescent art of the nature: universe of scale-worms (Polychaeta, Polynoidae).

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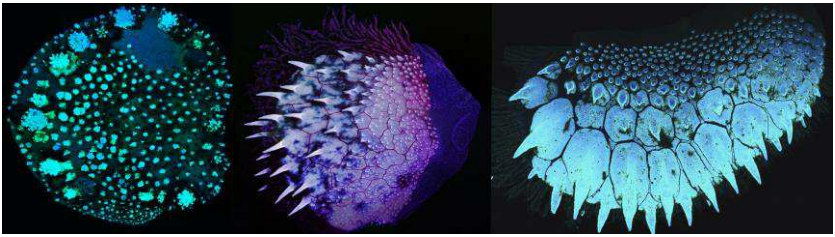
Fluorescence is found in an unaccountably diverse array of marine organisms, where its functions are largely unknown [1].

Among the segmented marine worms (Annelida, Polychaeta), the species of the order Polynoidae are commonly known as scale-worms because ornamented scales cover their dorsum. Polynoids are found worldwide from the tropics to the Antarctic and the Arctic. They occur from the intertidal to deep waters where they have been reported from abyssal depths and may be common on both soft and hard bottoms.

E. Newton Harvey in 1926 [2] mentioning that some species, like *Acholoe astericola*, show the yellowish fluorescence in ultra-violate light and other specie *Polynoe grubiana* shows only the bluish fluorescence of skeletal parts when its scales are examined from both, upper and lower sides. This information has been forgotten till the 2009, when Plyushcheva and Martin [3] described fluorescence for four more species. Here we would like to present all the variability of the fluorescent patterns that authors found up to the moment.



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Information coding and encryption using photonic crystals

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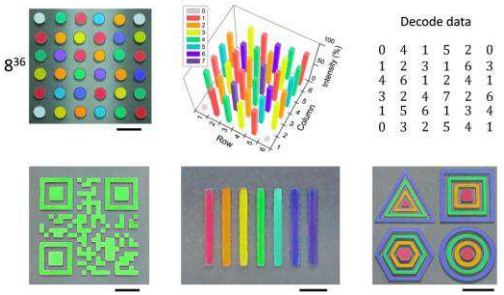
Photonic crystals (PC) provides an excellent candidate for coding and encryption. [1] The unique structure-caused photonic stopband and its angle-dependent property are attractive characters for coding and encryption. We developed a simple and efficient method to prepare high quality PC patterns as the coding sites for information storage and encryption. The prepared PC patterns of various geometries demonstrate excellent optical quality and the assembly process takes only a few minutes. By combining the easy-to-read nature of spectral coding and the large capacity of graphical coding, these high quality PC patterns show excellent capability for greater capacity coding and high security level encryption, which have great potential for information storage [2], anti-counterfeiting, displays[3], and sensors[4].



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Investigating iridoplast ultrastructure affecting *Begonia* leaf iridescence

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Iridoplasts have been proposed as the origin of blue leaf iridescence in the genus *Begonia*, however iridescence in some species is not visible. An understanding of the ultrastructure of iridoplasts in *Begonia* is a crucial initiating step to exploring this finding. Here, we elucidate iridoplast ultrastructure of phylogenetically selected *Begonia* by analysis of various microscopic techniques including transmission electron microscopy (TEM), confocal laser scanning microscopy (CLSM), and reflected light microscopy. Our study shows that there are two groups of *Begonia* categorized by iridescence; iridescent and non-iridescent *Begonia*. They are different in iridoplast ultrastructure, iridoplast distribution and iridoplast size per cell which affect their iridescent property. The iridoplasts of iridescent species had repetitively wide granal stacks and accumulated mostly at the centre of the cells while the non-iridescent species had typical thylakoid stacks and mostly distributed throughout cells, especially cell edge. The ratio of iridoplast size to epidermal cell size of iridescent *Begonia* tends to be higher than non-iridescent species. The further research on physiology, evolution and development of iridoplasts in both groups would be required to explore their functions and adaptive advantages.

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Structural Coloration of Blue Peacock Feathers

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The male peacock prides a magnificent array of feathers with a wide variety of structural colours originating from an interleaved lattice consisting of rodlet melanosomes and air tubes [1-2]. We here study the spectral properties of peacock feathers by applying various optical methods, e.g. microspectrophotometry, imaging scatterometry and angle-resolved polarisation-dependent reflectance measurements. The neck feathers show a consistent colour gradient between its proximal (green) and distal (blue) barbules (Fig. 1) with a brown colour in transmitted light, revealing the presence of melanin (Fig. 2). The measured spectra can be explained by applying finite-difference time-domain (FDTD) as well as effective-medium multilayer modelling.

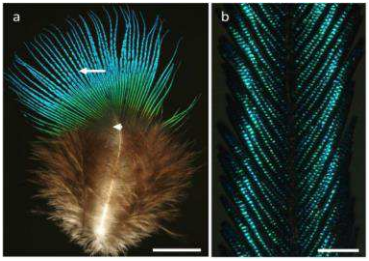

Figure 1 (a) A blue-green iridescent neck feather of the peacock. (b) A distal barb with barbules. Scale bars: 1 cm (a) and 200 µm (b).

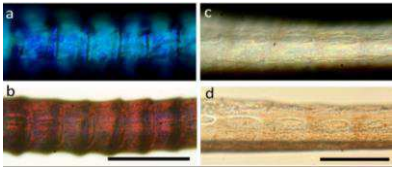

Figure 2 (a,b) Reflection and transmission light micrographs of a barbule of the distal part of the feather. (c,d) Reflection and transmission light micrographs of a barbule of the proximal part of the feather. Scale bars: 50 µm.

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Tunable Optical Functionality of Natural Micro grating Structures

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Natural photonic structures are fascinating templates for biomimetic designs for novel optical systems, components or devices to control and manipulate light such as blazed grating [1, 2]. Technically, it is very difficult to develop a transmission blazed micro-grating due to complicated fabrication process and other technical constraints on miniaturization. Seeing inspiration from nature, we have naturally found deeply grooved blazed micro-grating arrays on transparent insect wing (Rain-fly) surfaces. In this paper we demonstrate optical functionality of these blazed micro-grating probed using ultrashort laser pulses as well as monochromatic CW illumination. We experimentally and numerically study blazed micro-grating structures on surface of transparent insect wings, and demonstrate their coherent optical functionalities. We observe blazed diffraction properties which strongly depend on individual micro-gratings geometry. In order to support our experimental observation, we have considered Huaijun Wang's theoretical model for the diffraction of blazed transmission grating with moderate period [3]. Our observation may open up new opportunities in biomimetic device research for the design optical components for photonic integrated system.

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Bioinspired graphene-based nanocomposites

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With its extraordinary properties as the strongest and stiffest material ever measured and the best-known electrical conductor, graphene could have promising applications in many fields, especially in the area of nanocomposites. However, processing graphene-based nanocomposites is very difficult. So far, graphene-based nanocomposites exhibit rather poor properties. Nacre, the gold standard for biomimicry, provides an excellent example and guidelines for assembling two-dimensional nanosheets into high performance nanocomposites. The inspiration from nacre overcomes the bottleneck of traditional approaches for constructing nanocomposites, such as poor dispersion, low loading, and weak interface interactions. Herein, we summarizes recent research on graphene-based artificial nacre nanocomposites, [1-6] and focuses on the design of interface interactions and synergistic effects for constructing high performance nanocomposites.

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Pollia condensata: the plant with the shiniest fruits in the world

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Pollia condensata is a perennial understorey monocot from family *Commelinaceae*. It has the shiniest fruits in the world due to arrangement of the cell wall rather than pigmentation. The fruit is basically idehiscent and filled with hard seeds. Fruits collected in the 1800s and deposited at Kew have their color intact. Pollination is important for plant reproduction and maintaining healthy populations. However, there is no evidence or literature that pollination, reproduction dynamics and seed dispersal studies of P. *condensata* have been done or are well understood. We focused on abundance and diversity of pollinators and dispersers of Pollia in Kakamega forest; Time of flower anthesis was recorded, diversity of bees visiting the flowers and peak time of bee visits. Sweep netting was done to collect some of the bees. Main pollinators of *P.condensata* were found to be the common honey bee (*Apis mellifera*), *Ceratina* spp and stingless bees. Peak pollination times are 10.00 to 11.00 am with 47% of the visits, falling to 29.5% by noon. Between 1.00-4.00 pm, less than 10% of the pollinators visit the flowers. The most favorable weather condition for pollination is during wet warm days with record visitations of about 95%. After fruit set, the fruit undergoes colour changes from greenish, to clear, brown, pale purple to shiny deep blue within 3 months. Possible fruit dispersers of the plant are squirrels since some seeds were collected at the squirrel burrows. A monkey was also sighted picking the fruits.

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Structural colour in Diptera

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Structurally coloured living organisms exhibit complex optical devices leading to striking visual appearances. In insects, these devices are often made of biopolymers and comprise photonic crystals. A signature of the interference origin of such structural colours is iridescence, i.e. the displayed colours depend on the incidence and viewing angles. Many species have attracted much attention by the natural photonics scientific community since the XIXth century such as butterflies from the Nymphalidae family (e.g., *Morpho* genus), the Papilionidae family (e.g., *Papilio* genus) and the Lycaenidae family (e.g., *Polyommatus* genus) [1] or beetles from the Buprestidae family (e.g., *Chrysochroa* genus) and the Scarabaeidae family (e.g., *Chrysina* genus) [2].

However, species from some orders such as Diptera have not been extensively investigated. In this work, we analysed the structural colours from the abdomens of different but related dipteran species, each displaying various colours. Using electron microscopy, multilayers were found to be the mechanism for their colour appearance. Interestingly, they are located in different parts of the insects' cuticle, depending on the species. In addition to spectral measurements and optical simulations, we analysed the dipterans' colours in terms of chromaticity as well as with respect to the species' visual sensitivities and that of some of their predators.

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Toward understanding of the molecular mechanism of helicoidal formation of cellulose fibres: *in silico* study

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Magnificent structural colouration in some plants such as *Pollia condensata* and *Margaritaria nobilis* is caused by helicoidal arrangements of cellulose microfibrils. Although the helicoidal formation of cellulosic (cellulose and chitin) fibres are commonly observed in both plant and animal tissues, a very little is known about the underlying molecular mechanism that implements the helicoidal fibre formation. In this contribution, we report a molecular modelling study to understand such a mechanism using a system mimicking the cell wall structure of the endocarp of *M. nobilis*.

Coarse grain molecular dynamics simulation is applied to this study, which allows a scale-up of the system size due to its simplified molecular description. The system is composed of two main structural components, namely cellulose and hemicellulose. Molecular structures of hemicellulose and morphological features of cellulose fibres are implemented based on the experimental analyses of the endocarp of *M. nobilis*. A left-handed rotation of cellulose fibres was observed in a preliminary simulation of a small system, which implies the importance of physical interaction between cellulose and hemicellulose on the helicoidal fibre formation. Effects of molecular structures of hemicellulose and hydration levels, as well as the size effect of the system, will be discussed.

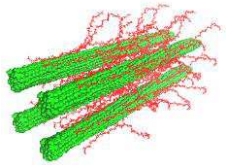

Figure 1 Schematic image of the simulation system. Green: cellulose. Red: hemicellulose

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