Framing structural colour – terminology, appearance, and relevance for design

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Research on structural colour tends to focus on understanding the nanostructure that generates the colour, rather than the appearance of the colour itself. The topic is generally covered from a technical perspective, where the visuality and aesthetics of the colour remain out of focus. As a result, a limited toolbox of unclear terminology limits both the description of the wide range of visual features of, and the design potential of structural colour. In the absence of established and widespread definitions, users of structural colours may encounter misunderstandings and misinterpretations of the appearance of structural colour. In essence, the visual features are usually oversimplified with too broad terms, such as "iridescent," "shiny and glittery," or "metallic". These function well as umbrella terms, but more specific descriptions of the visual qualities are needed. This work provides a coherent overview and explanation of the varied terminology used both in scientific and colloquial contexts. A major scrutiny is provided for 1) the visuality of iridescence, 2) the borderline between pigment colours and structural colours, as well as 3) the varied terminology used for effect pigments. In order to cover the technical perspective, a brief and easily available information package is provided on the classification of structural colour based on the structures and related mechanisms that bring about the colour. Finally, a table is introduced which proposes more detailed descriptions of the wide range of the visual qualities of structural colour. It is envisioned to advance the exchange of information between disciplines, to benefit both research on structural colour and end users of these colours, like designers and artists.

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Introduction

Structural colour is a colour formation mechanism. When nano-sized structures reflect light in a certain way, we perceive colour. Morpho butterfly wings, peacock feathers, and beetle elytra offer natural examples of structural colours (Figure 1a). Although usually the structural colour seen in nature is shimmering and iridescent, i.e., the perceived colour depends on the angle of view, there are also non-iridescent structural colours.

Figure 1: (a) Examples of structural colour in nature: Morpho butterfly, photo: Eeva Suorlahti, Jewell beetle, photo: authors, peacock feather, photo: Eeva Suorlahti; (b) Examples of naturally occurring structural colours used in art and crafts in history: Dress of cotton muslin, gilded metal thread and Indian jewel beetles (sternocera aeqisignata), Britain, 1868-69 Victoria and Albert Museum, London; Precious black opal set in a gold ring, Europe, 1800-69 Victoria and Albert Museum, London; Salver, mother-of-pearl and metal, Gujarat, early 17th century. Victoria and Albert Museum, London; Peacock-feather fan, Assam, 19th century. Victoria and Albert Museum; (c) Examples of man-made structural colour: Tiffany glass bowl, USA, New York (Long Island), designed by Louis Comfort Tiffany, for Tiffany Glass & Decorating Co. 1896 Victoria and Albert Museum, London; Ceramic vase, USA, New York (Long Island), designed by Louis Comfort Tiffany, for Tiffany Glass & Decorating Co., Stourbridge Glass Co. Corona glassworks, 190, Victoria and Albert Museum, London; Pearlescent paint [1]; Glitter nail polish (authors).

Structural colours have inspired both biologists and optical physicists to study their functionality in nature [2-3] as well as the underlying colour generation mechanisms [4-5]. These mechanisms, introduced in later section *Categorisation of structural colour in natural sciences* (on Page 31), include scattering, thin-film interference, multilayer reflectors as well as colours arising from diffraction gratings and photonic crystals. There has also been a growing interest in these colours in materials science owing to their aesthetical and technical properties [6-7]. Their visuality - referring to the features of the colours that are seen when the colour is perceived - have received little attention. What does structural colour look like? What different colours and visual features are related to this phenomenon?

Colours and visuals, like shapes, forms, patterns and textures, are central to art and design, but the literature on structural colour lacks the representation of the related visual fields. Many visual effects that rely on structural colour are widespread and desired by designers and artists (Figure 1b and 1c), where they are called e.g. metallic, iridescent, holographic, and pearlescent colours, to name a few. However, designers and artists may not be aware of the colour formation mechanisms underlying these colour effects, and this has led to the use of above-mentioned terms in a vague or even incorrect manner.

A shared understanding of the terminology regarding structural colour would benefit the exchange of knowledge between different fields. Painters need to describe the colours they require, and the manufacturer needs to be able to communicate the ways and practices of using a specific colourant. In contrast to pigment-based colourants, the operating principles of structural colours are not yet generally understood in art and design. Structural colours behave differently from pigments, particularly regarding mixing of colours, since additive colour theory needs to be adopted [8].

Some other features of structural colours also differ from those of pigmentary colours, and thereby affect their appearance. Some structural colours can, for example, be hygrochromic[1] and react to humidity [9], or form a rainbow-like rim colour[2] due to the coffee ring effect [10].

The increasing concern for environmental challenges in the field of design highlights the importance of this common language. For example, most textile dyeing processes are harmful to humans and the environment [11]. As a result, designers and artists have started to look for alternative dyeing methods, for example from the world of natural dyes (see [12], for example) as well as technological ones inspired by nanostructures in nature (examples: [13-15]).

Currently, structural colour technology is evolving at an ever-accelerating pace toward various practical applications. In addition to the striking visuality of structural colours, their functional properties make them potential alternatives for conventional colouring methods. They can create non-fading colours [16], and some nanostructures create hydrophobic surfaces [17]. However, many of today's artificial structural colours are made with materials such as plastics, metals, or toxic pigments that may be harmful to the environment [18]. Efforts have been made to develop sustainable structural colours without environmentally harmful compounds (e.g. [19]).

We aim to clarify the fundamental concepts of structural colour so that the discussion unfolds to a broader audience. To do this, we first discuss the current structural colour research and then try to provide useful definitions for the classification of structural colours. First, we briefly introduce the history and research of these colours in the context of art and design and point out some challenges in distinguishing structural colours from pigment colours. We suggest a general categorisation of structural colour mechanisms as a basis for identifying various visual features of structural colour. For this endeavour, we employ terminology used in the visual fields to describe structural colour. Finally, we propose how the visuality of structural colour, especially iridescence, could be described and communicated in a more comprehensive way. Table 6 in the *Discussion and Conclusions* section aims to address the visuality of structural colours from a wider perspective, by comprehensively describing the appearance in terms accessible to the general public, not just structural colour researchers.

Structural colour in design and art

Scientific research on structural colour

Little research has been done on structural colour in the context of design and art. However, various effect pigment colours [20], as well as iridescent and glittering surfaces, have been used in design and art throughout history. This includes examples such as Tiffany glass and Carnival glass [21], lusterware [22], peacock feathers used in ornaments and jewel beetle embroidery [23], ornaments with nacre (mother of pearl) [24], and different iridescent finishes in painted surfaces or plastics [25]. Today, we can identify several examples of structural colours in nature and in our built environment. While

[1] See *Hygrochromicity* under section *Certain other visual characteristics of structural colour* on Page 41.

[2] See *The Coffee-ring effect* under section *Certain other visual characteristics of structural colour* on Page 42.

nature's examples, such as the morpho butterfly wings, beetles, and mother of pearl, have received considerable attention in optical physics and biology [26-28], structural colour is not covered as a topic in itself in the field of design and art, but instead rather vague words are used to describe related visual effects.

Leddy [29] and others [30-32,2] have studied the aesthetics of glittering and shimmering colours, and the reason for their appeal to humans. These studies promote a comprehensive understanding of these colour effects, but the discussion is limited to a general level, using terms such as glitter, sparkle, and gloss. They do not, for example, discuss iridescence as a separate research subject. Therefore, it is impossible to draw precise conclusions about the aesthetics and visuality of a particular glittery, sparkly, or glossy colour effect.

Franziska Schenk and Andrew Parker [8,32-33] considered the possibilities of structural colour in fine art. However, they focused on effect pigment technology and its application in painting, not so much the visuality of structural colour itself in all its diversity. Another study by Schenk *et al.* [32] aims to accurately recreate the colours of the Japanese jewel beetle in a painting using effect pigment technology. Their research has revealed useful information on structural colours. For example, the human eye cannot conclude which nano-sized structure (after interacting with light) is responsible for a particular colour effect. In other words, several different colour formation mechanisms can produce a visual colour that looks the same to the human eye [32,8].

Zhao *et al.* [34] and Dushkina and Lakhtakia [35] studied the future potential of materials and colours that generate structural colour. However, these publications lack a thorough discussion about the appearance of the structural colour, and the design opportunities of the underlying colourants.

Structural colours can also be found in literature showcasing historical crafts and artwork. Iconic examples of structural colour created by nature, such as beetles, pearls, and the shimmering feathers of birds, have been used in various ornaments [36]. However, these studies focus on restoring various artefacts, like embroidery, rather than the structural colour itself [37].

Ceramics and glass artisanry are examples of design fields utilising structural colour. Part of the colours of lusterware glazes arise due to thin film interference, a common formation mechanism for structural colour. The creation of these colour effects has been known among Coptic glassmakers in Egypt and possibly in Syria since the sixth or seventh century [22].

Understanding structural colour

Literature on structural colour usually focusses on discussing the topic in a very technical way and putting less emphasis on the visuality and aesthetics [e.g., 2,4-5,9,38]. This overlooking of visuality may sometimes even complicate the discussion of structural colours in a scientific context. The lacking focus on visuality and the appearance of colours in publications may have limited the development of vocabulary to describe structural colours. For example, Seago *et al.* [9] point out that the underdeveloped terminology to describe different iridescences has, for example, made it difficult to identify some beetle species taxonomically. In 2008, Kinoshita *et al.* wrote in their article "Physics of Structural Colors" [38] that the scientific definition of structural colour is not yet fully established. Iridescence, a phenomenon closely related to structural colour, is associated with misconceptions that can lead to misleading or simplifying descriptions on its appearance and visuality [9]. Furthermore, there exists a misconception that all structural colours are glittering or iridescent.

There are some practical challenges that may hinder our ability to communicate the visuality and aesthetics of these colours. Photographs and most colour prints do not reproduce metallic colour effects as they are perceived in the environment [39]. Shiny, metallic colour effects are a common feature of structural colours. Perhaps even more so than in other fields of colour research, it is practically impossible to separate colour and material when discussing structural colour.

There has been research on rendering structural colours to include these in the material and colour ranges of 3D models, thus facilitating the use of these colours in design. Promising models for pearl colours [40], CD surfaces [41], and soap bubbles have already been suggested. Some studies focus on rendering the appearance of effect pigments (e.g., [42]). In these cases, it remains unclear whether they only consider effect pigments that rely on purely structural colour mechanisms or ones that also rely on other mechanisms. The latter would not provide the specific rendered appearance of structural colour. In the latter case, the images would not represent a pure structural colour rendering.

Most structural colours change depending on the angle of view. Static images therefore limit the visuality of the colour and the colour experience: the movement of the colour, and its spatiality. While all colour changes in relation to the surrounding space and illumination, the movement of light and the angle of view play a crucial role in the visuality of most structural colours.

To summarise the issues, scientific publications describe the appearance of structural colour using too general terms, which do not necessarily do justice to what is seen. This is problematic since vague terms increase the ambiguity of the reported scientific results and makes communication between fields challenging. A common language is needed, with concepts that are clear not only to physicists, biologists, and materials scientists, but also to users of colour, such as designers and artists. In order to achieve a holistic picture of the phenomenon, at least these three different aspects need to be understood:

1. *The type of nanostructure generating the structural colour.*
2. *The mechanism through which light interacts with the nanostructure.*
3. *The perception of the structural colour arising from the above interaction, and the associated experience.*

Pigment and structural colour

The word pigment is used in scientific literature to refer to many different things. For example, the word can be given two different definitions:

1. *A material (a non-soluble particle) that produces colour by absorption of light (so-called chemical colour).*
2. *A material (a non-soluble particle) that produces colour.*

Definition (2) includes definition (1) and is thus a broader definition. When defining structural colour, the phenomenon is often compared to colour generated through absorption. Therefore, several articles on structural colours use definition (1) for pigment colours [38,7,34,43].

As a robust summary, the difference between structural colour and pigments, according to Sun *et al.* [36] and Kinoshita *et al.* [38], is that structural colour is the result of selective reflection of light, whereas pigment colours originate from both absorption of light by electrons, and reflection[3]. In the animal kingdom, almost all colours emerge from pigments or structural colour. Colours based on pigments are formed when the electrons of a substance and light interact at the atomic level. Electrons absorb certain wavelengths of light, that is, part of the energy of light. An example of this are carotenoid pigments, which absorb shorter wavelengths of light (e.g., corresponding visually to hues of blue and green) and

[3] See section *Categorisation of structural colour in natural sciences* on Page 31.

reflect or possibly transmit longer wavelengths (corresponding visually to hues of red, orange, and yellow). In this way, the carotenoid produces variations of red, orange, and yellow in animals [2]. Structural colour, on the other hand, is created through a physical interaction between light and a nano-sized structures. In this case, the light interacts with a variety of mechanisms via the structure before it reaches the eye of the viewer. There is little loss of light energy in the process. The physical mechanisms behind structural colours include optical processes such as reflection, refraction, interference, diffraction, and light scattering [38].

Structural colour can be achieved with a material that is entirely colourless or transparent [4]. It can be characterised as "colour without pigment" [16], or perhaps an even more explicit expression would be "colour without absorption". While this definition is mostly correct, it is worth noting that in nature, some colours are created by a combination of structural colour and absorption pigments (e.g., the wings of many butterflies) [44]. Usually, in these cases, a dark background colour created with absorption pigments further enhances the colour generated by nanostructures, as in some morpho didius butterflies [8].

Articles related to the pigment industry may use definition (2) of the word pigment when referring to materials and dyes that generate structural colour. In this case, the word pigment is often used with quotation marks, i.e. “pigment”. Here, the colour resulting from the principles of structural colour may be referred to as pearl-like "pigment", iridescent "pigment", or pearlescent "pigment" [8]. These are structurally different to pigment particles according to definition (1). Schenk et al. [32] describe structural colourants with words like effect pigment, multilayer effect pigment, and metallic effect pigment, and omit quotation marks around the word pigment. In some of these “pigments”, (absorption) pigment mechanisms and structural colour reflections both contribute to the apparent colour. In these cases, the function of a dark pigmented background is usually to enhance the colour effect of the structural colour, just as in the examples of nature (e.g., the wings of the *morpho didius* butterfly presented earlier). Whether a particular effect pigment contains only a structural colourant or also an absorption pigment is sometimes extremely difficult to ascertain from the literature. This can confuse the reader, especially if the reader does not have an in-depth understanding of pigment technology.

For the reasons mentioned above, to avoid confusion, it would be ideal to be particularly careful about how the word pigment is used. Are we referring to particles generating colour through selective absorption (pigment), or do we extend the definition to comprise colour formed through physical interactions and nanostructures as well (“pigment”)? The pigment industry generally applies the latter definition.

According to Glover and Whitney [43] structural colours and chemical colourants, i.e., absorption colours (pigments), have slightly different visual properties. These differences are mainly related to colour intensity and stability. Chemical colours are often slightly dimmer compared to structural colours, and chemical colours usually look the same from every angle of view, meaning they are not iridescent.

Iridescence

Generally, iridescent colours can be defined as colours that change depending on the angle of view in respect to both the light source and the colour generating /reflecting surface [9,45,43]. Iridescence is one of the most-used keywords when describing structural colours [38]. The word originates from the Latin and Greek word iris, meaning rainbow, but also refers to the ancient Greek goddess Iris, who is the personification of the rainbow and a mediator of the gods' messages [2]. Meadows *et al.* [45] categorise iridescence as a colour created without pigments, although, according to them, pigments can in some cases act as structural elements (like melanin rods in peacock feathers [38]). Note that this categorisation would not mean that all non-iridescent colour is created with pigments. There are non-iridescent and pigment-free colours[4]. Meadows *et al.* [45] also point out the: "directionality and flashiness of these colours and the polarisation of light reflected from some iridescent objects" as unique properties of iridescent colours. The Oxford English Dictionary defines iridescence with the words "changing colours" and "glittering": "The quality of being iridescent; the intermingling and interchange of brilliant colours as in the rainbow, soap-bubbles, and mother-of-pearl; a play of glittering and changing colours." [46].

Defining iridescence is not entirely straightforward. Seago *et al.* [9] point out the scope and inaccuracy of the term, especially since it is sometimes described simply as the spectral (rainbow-like) reflection of light. Seago *et al.* [9] interpret iridescence as an umbrella term for several visual effects with a common denominator of angle-dependent colour. However, as the "iridescence" umbrella term contains various separate visual features, two dissimilar phenomena can both be described as "iridescent" as we lack more specific terms. These visual features require more precise definitions to convey to readers what type of iridescence is referred to in a specific context. Seago *et al.* [9] introduced a table, which we adopted (Table 1). The table proposes terminology of iridescence mechanisms [9] and it aims to help connect the different observed iridescences and their underlying structural colour mechanisms. As an example, it facilitates the taxonomic sorting of certain beetle species based on their iridescence.

Relationships between structural colours, optical mechanisms and visible reflectance in Coleoptera.		
Structural colour	**Mechanism**	**Wavelengths reflected**
simple metallic hues	multilayer reflector	discrete band of visible spectrum
silver or gold colour	variable thickness broadband multilayer reflector	all visible
circularly polarised colour	helically arranged multilayer reflector	yellow-green[a]
spectral iridescence	diffraction grating	all visible, as ordered spectra
opal or diamond effects	three-dimensional photonic crystal	all visible
UV and white reflectance	Tyndall scattering	all visible, plus ultraviolet
most non-metallic blues	quasi-ordered array	typically blues and purples[a]
[a] *Only these colours have been observed in nature; any colour is possible.*		

Table 1: The connections between the underlying structural colour mechanisms and the resulting visual effects. Adopted from [9].

Thus, while the table provides a basis for discussing the visuality of iridescence, it also generates questions, the greatest of which may be: Where to draw the line between iridescence and non-iridescence? Where does iridescence begin? Seago *et al.* [9] interpret mechanisms of structural colour and the mechanisms of iridescence as synonyms. However, structural colours caused by incoherent light scattering[5] are not iridescent.

The colour of the golden beetle chrysina chrysagyrea (Scarabaeidae: rutelinae) challenges the definition and scope of the term iridescence. Seago *et al.* [9] present it as an example of structural colour produced by broadband multilayer reflectors in the animal kingdom, and describe it as: "The broader

[4] As discussed later in sections *Incoherent light scattering and quasi-ordered light scattering* on Page 32.
[5] See section *Incoherent light scattering and quasi-ordered light scattering* on Page 32.

the range of bandwidths, the closer to pure gold or silver (mirror-like) the cuticle appears". This raises a question; to what level can iridescence be "reduced"? The appearance of the golden beetle changes when observed from different angles. But can it count as iridescent if the golden metallic-looking colour is retained throughout the change in appearance, where the colour does not, in fact, change? The change in appearance may thus not be caused by iridescence, but instead solely by the environment around the golden beetle.

In the context of design, metallic-looking colours are not usually described as iridescent. It is more common to associate iridescence with the changing and flickering nature of spectral colour. While metallic-looking hues often reflect light strongly and can therefore flicker like glitter, this would not make them iridescent. For instance, the golden colour produced by elementary gold (Au) is not iridescent[6].

All colour changes under the influence of light and space. This also applies to pigment colours, although with pigments, there is no clear change from one spectral colour to another. Sparkle, lustre, and metallicity are terms associated with the change of colour due to changes in light and space, and those same terms are usually also associated with iridescence. Many glossy and glittering colours are not iridescent, whereas various cast vinyls on the market can be used to create a "matte" iridescent colour, so removing gloss and glitter doesn't take away iridescence (see: [47]).

To conclude, it seems that the essence of iridescence points towards a change in colour hue and viewing angle rather than metallicity or sparkle, even though sparkle and metallicity are often found in these colours. Therefore, the definition of iridescence could more accurately include colours that either:

1. *Continuous change from one colour hue to another, as a function of the viewing angle, as in Japanese jewel beetle shells [32], prismatic flakes, or glitter particles (see: [48]), or*
2. *Reflect hues strongly only from a certain angle of view, while the colour intensity is drastically reduced from other angles of view, as in the Sapphirina copepod [49].*

In both cases (1 and 2), a change in colour would only count as iridescence if it depends on a periodic material structure. In the Discussion and Conclusions section, we suggest a list of answerable "questions" to help describe and clarify the nature of iridescence.

Categorisation of structural colour in natural sciences

This section proposes a clear classification of different types of structural colour to provide easily understandable information on the different colour types for readers in all fields. Structural colour can be roughly categorised into coherent and incoherent scattering. The coherent scattering part comprises what we generally think of when we consider structural colour. Effects such as iridescence can only be achieved through coherent scattering of light. However, there does not seem to be a consensus on this categorisation. Sometimes incoherent scattering is not considered to generate structural colour.

In this work, we roughly follow the definition and categorisation of structural colour put forth by Glover and Whitney [43], although this might not be the only way to categorise it. Several different terms are related to the optical mechanisms responsible for structural colours, and there are several ways to subdivide the mechanisms. However, we aim to introduce the most commonly used terms for the mechanisms.

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[6] See section *Metals and colour* on Page 39.

Incoherent light scattering

According to Glover and Whitney [43]: "Incoherent light scattering takes place when individual light scattering structures are randomly separated from one another by an average distance that is large compared to the wavelength of the light". The nature of the scattered light depends on the dimensions of the light-scattering structures, and the phase relationship of the scattered wavelengths of light is random. Although much of the structural colour in the animal kingdom is produced by coherent light scattering, the blue colour in many amphibians is caused by incoherent light scattering, as is the blueness of the sky or red and orange hues of the sunrise and sunset and blue colour in some spruces (Figure 2a-e) [43]. In the above examples, the reflected colour can be described by Rayleigh scattering, which is relevant for scattering objects smaller than the wavelength of light, and is a simplified version of the more general Mie scattering, which occurs with objects similarly sized or larger than the wavelength of light. The Tyndall effect can be used to describe the scattering of light from particles with sizes somewhere between these, and the resulting colour always appears light bluish.

White structural colour can arise from a variety of sources, but the whiteness in all beetles comes from structural colour related to incoherent light scattering, i.e., Mie scattering (Figure 2f) [9]. This also applies to light blue colours in beetles. These colour-inducing structures may have functional properties unrelated to visual effects, such as preventing water loss, reducing radiation absorption, and providing a protective colour for the beetles. Also, part of the light reflected by beetles may be ultraviolet [9].

Quasi-ordered scattering

Microstructures that are semi-organised in two or three dimensions can produce vibrant, non-iridescent, and mostly blue and green structural colours [9] (Figure 2g). These colours are generated from uniform nano-sized objects, i.e., light-scattering particles or apertures, immersed in a homogeneous and transparent or translucent material with a different refractive index. The reflected colour depends on the size and separation of the particles. While Mie (and Rayleigh) scattering generally applies to randomly organised particles, Quasi-ordered scattering describes the scattering from semi-organised particles. Table 2 summarises the visual examples of incoherent light scattering and quasi-ordered light scattering.

Mechanisms	Notes on the visuality	Examples
Incoherent light scattering: -Rayleigh scattering -Mie scattering -Tyndall effect	The resultant structural colour is not iridescent.	Blue sky, blue smoke, blue ice [36], colours of sunset and sunrise, blue coloration in blue spruce (*picea pungens*) [43], whites in beetles [9] (Figure 2a-f)
Quasi-ordered light scattering	Typically, most non-metallic blues and purples in nature are related to quasi-ordered scattering. In theory, any hue or colour could be generated with quasi-ordered light scattering [9]	In nature: blues and purples in amphibians [43] (Figure 2g)

Table 2: Examples of the colour and visuality of incoherent light scattering and quasi-ordered light scattering.

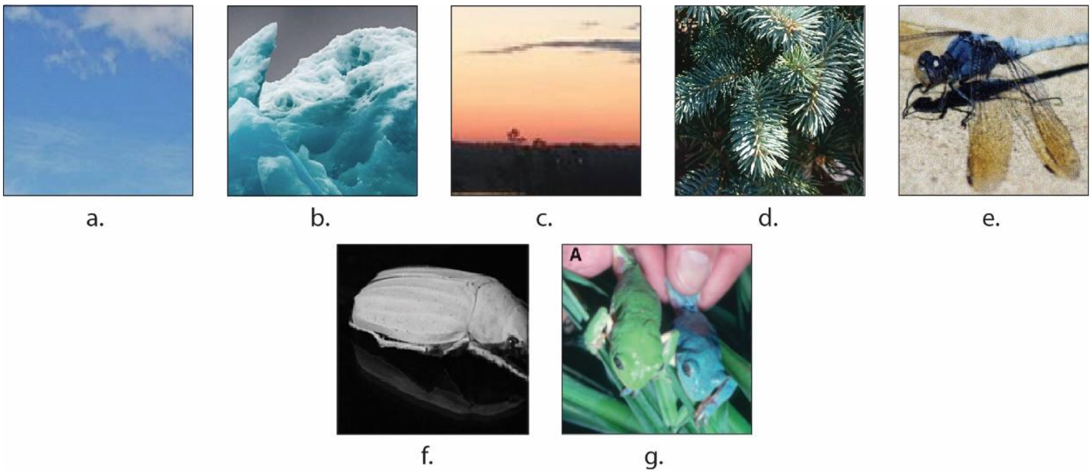

Figure 2: Examples of colours in nature created through incoherent light scattering and quasi-ordered light scattering. (a) blue sky (b) blue ice [50] (c) The colours of sunrise and sunset (d) blue spruce (picea pungens) (e) The blue colour of the dragonfly orthetrum caledonicum (libellulidae) [51] (f) Whites in beetles [9] (g) Blues and purples in amphibians result from quasi-ordered scattering [52].

Coherent light scattering

According to Glover and Whitney [43], most of the structural colours seen in the animal kingdom and all iridescent colours are due to *coherent light scattering*. In essence, coherent light-scatterers result in the interference of light. Coherent light scattering occurs when light interacts with an ordered distribution of light-scattering elements, with a constant phase difference among waves of a particular reflected wavelength. The ordered distribution of light-scatterers can cause either constructive or destructive interference (Figure 3). If the phase difference is a multiple of exactly one full wavelength, then constructive interference occurs, and light of that wavelength is strongly reflected. In contrast, if the phase differs by half a wavelength or an odd multiple of the half-wavelength, destructive interference occurs. In this case, the reflection of light of that wavelength is weak or non-existent.

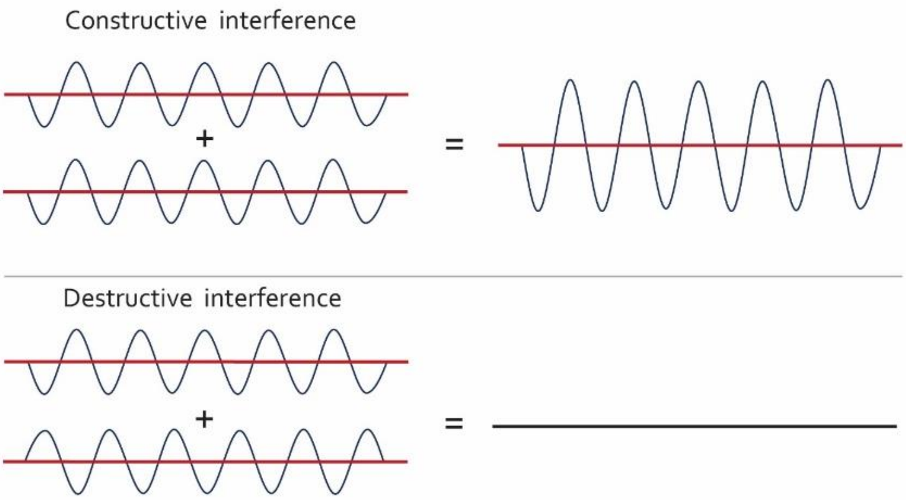

Figure 3: Illustrations explaining constructive and destructive interference in terms of the wave properties of the light beam.

Thin-film interference

Thin-film interference is the simplest form of coherent light scattering. Colours in soap bubbles and oil slicks are based on thin-film interference [43]. Thin-film interference occurs when light is reflected from two different surfaces or interfaces between materials, which are stacked on top of each other. Taking oil slicks as an example (see Figure 4), the first interface is the air-oil interface, and the second one is the oil-water interface. In the soap bubble example, the first one is the air-soap interface, the second one is the soap-air interface. For interference to occur, the interfaces need to very close to each other – in essence, the oil or soap layer needs to be very thin. Furthermore, the materials or substances involved need to be transparent, and the substances defining each interface need to have different refractive indices. As the ray of light from the sky meets the air-oil interface, some of the light passes through the interface, some of it is reflected back to the sky. The same occurs when the part of the original ray that passed through hits the oil-water interface. The ray of light is composed of a mixture of wavelengths, and some of these wavelengths will experience constructive interference when hitting the oil slick, while others will experience destructive interference. The refractive index difference, the thickness of the layer, and the incidence angle of the ray determine which wavelength experiences constructive interference. In essence, if waves reflected from the two interfaces are in phase with each other, then light with that wavelength experiences constructive interference, whereas if the waves of another wavelength are out of phase, then destructive interference occurs. For example, if parts of the oil slick appear monochromatically blue, then wavelengths that correspond to blue colour experience constructive interference in those parts of the slick [43]. Thin-film interference is the most common cause of iridescence in nature [32] (Figure 5a- c).

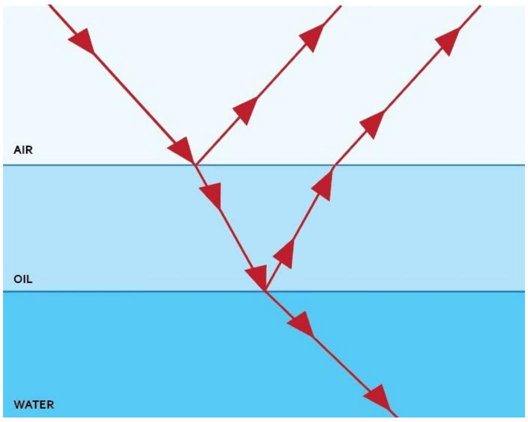

Figure 4: Schematic illustration of thin-film interference, where the red lines represent light rays of a wavelength that experiences constructive interference. Varying the direction of the incoming light beam changes which wavelengths of light experience constructive or destructive interference. This results in the change of colour (iridescence) perceived with the illumination/viewing angle.

Multilayer reflectors

Multilayer reflectors follow the principle of thin-film interference, the difference being that instead of two interfaces, there are several of them, where each layer of a certain substance has a strictly defined thickness. Here, each substance also has a different refractive index than the other. Multilayer reflectors produce even more intense structural disturbances at certain wavelengths and result in very pure, intense colours [43].

A classic example of a multi-layered structural colour in animals is the blue morpho rhetenor butterfly, whose multi-layered structure in its wing scales produces a bright and metallic-looking blue colour with an intensity that is said to be up to half a mile in visibility (Figure 5d) [43]. Due to its multilayered nanostructure, the iridescence in the morpho butterfly's wings can produce a very dramatic colour change; where one angle of observation reveals bright blues, while another shows the dark surface of the wing with its patterns.

Many examples of metallic-looking and iridescent colours produced by multilayer reflectors have been reported (Figure 5d-m). Hues from yellow to green as well as extremely metallic-looking, mirror-like golds and silvers [9] have been found in beetles (Figure 5g), but also in butterfly chrysalides [4].

According to Seago *et al.* [9], the thickness of the reflectors on the beetles may vary between different body areas, and for this reason, different colours may be reflected. The result might be a remarkably colourful collection of different colours of the spectrum (Figure 5h, 5i). Thus, in addition to the type of nanostructure, the shape of the surface on which the nanostructure is located also affects our perception of structural colour. Schenk *et al.* [32] created a chart that illustrates how the colours change from bluish turquoise to green and from red to orange and almost purple in Japanese jewel beetles (Figure 5j).

According to Ozaki *et al.* [40], the lustrous colours of mother of pearl are usually based on multilayer reflectors (Figure 5k), although sometimes their structural colour comes from a diffraction grating mechanism. Usually, natural pearl contains muted colours like white, pink, light blue, light yellow, and orange [53]. The observed colour arises from the interplay of structural colour, pigments (e.g. melanin and carotenoids), and metals [54].

Mother of pearl has inspired humans to create artificial structural colours, and the mechanisms of thin-film interference and multilayer reflectors have been utilised in pearlescent “pigment” technology, although some of the modern effect “pigments” might also rely on the presence of diffraction gratings[7] (Figure 5l).

Even though in nature, multilayer reflectors are often reported to create variations of blues and greens, in theory, any hue is possible to create with this colouring mechanism [9]. Table 3 summarises the visual examples of multilayer reflectors and thin-film interference.

<u>Additive-averaging or optical mixing process</u>

An additive-averaging or optical mixing process, also known as “pointillistic” colour mixing, has been reported in tiger beetles. Small pits or dots with multilayer reflectors reflect some narrow wavelength bands which differ from the surrounding field. These pixel-like pits optically mix and form a matte brown or green colour when viewed from a distance. The same mixing method has been reported to create a grey colour in some beetles described as a “structural black colour” (Figure 5m) [9] and blue colour in pollia condensate [55] (Figure 5n).

<u>Additive colour mixing</u>

Colours based on multilayer reflectors can be mixed via the additive mixing process, which is different from the way traditional fine-art paints are mixed [8]. When multilayer reflectors consist of several thin-film layers, each layer reflects light with a different wavelength (distribution) of the spectrum depending on the optical thickness of the layer. One layer reflects light with long wavelengths we perceive as red, another slightly thinner layer reflects orange, an even thinner one yellow, then green and blue, until all the colours of the rainbow are reflected, which are additively combined, and a bright white light is observed [8].

In additive colour mixing, the so-called primary colours are red, green, and blue. If these three colours have the same intensity, layering or mixing them will result in a perceived white colour. In theory, almost any colour (except for black) can be obtained by combining the right amount of these three colours [8].

[7] We will discuss pearlescent effect “pigments” in section *Man-made structural colours and related terminology* on Page 40.

Helicoidal reflectors

The structural colour arising from cellulose nanocrystals and the pollia condensata fruit (Figure 5n, 5o) is remarkably similar to the structural colour created by multilayer reflectors. The nanostructures found in pollia condensata have been defined as multilayer reflectors in some publications (e.g., [46]). In traditional multilayer interference, sharp periodic boundaries produce colour-dependent reflection, while the colours of cellulose nanocrystals (CNC) and pollia condensata arise from the presence of a continuous periodic structure, a helicoidal stacking of cellulose [56].

Mechanisms	**Notes on the visuality**	**Examples**
Thin-film interference, also known as thin-film reflectors (interference colours)	Iridescent, usually many colours visible at the same time	In nature: oil slicks, soap bubbles, mosquito wings [57] (Figure 5a-c)
Multilayer reflectors, also known as multilayer interference, interference colours, 1D photonic crystals	The structural colour is usually pure and intense with a narrow wavelength spectrum. Individual strong colours, such as the blue of the wings of the *morpho* butterfly, which are also often iridescent. May also appear metallic, silvery, mirror-like or pearl-like, with a corresponding broad wavelength range [4]. Some golden and silvery beetle colours [9] are metallic and possibly non-iridescent. The shape of the surface on which the nanostructure is located affects the number of hues observed. Additive and pointillistic colour mixing.	In nature: *Morpho* butterfly, blue *sapphirina* copepod, *selaginella*, peacock begonia, Japanese jewel beetle, mother of pearl (Figure 5d-k, 5m) Artificial examples: Most pearlescent effect "pigments" and goniochromatic colours (Figure 5l)

Table 3: Examples of the colour and visuality of multilayer reflectors and thin-film interference.

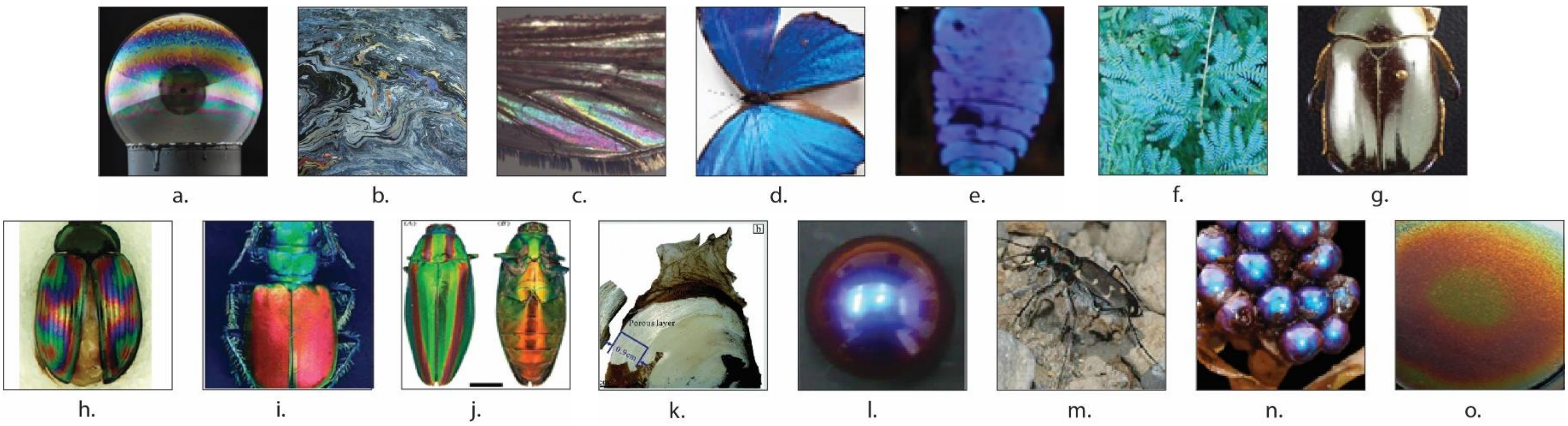

Figure 5: Examples of colours created through thin-film interference (a-c), multilayer reflectors (d-m), and helicoidal reflectors (n and o). (a) Soap bubble [58]; (b) Oil slicks [59]; (c) Mosquito wings [57]; (d) Morpho butterfly blue (photo: Eeva Suorlahti); (e) Sapphirina copepod [49]; (f) Selaginella [60]; (g) Beetle Chrysina chrysagyrea (scarabaeidae: rutelinae) [9]; (h) Beetle Amarygminae (tenebrionidae) [9]; (i) Beetle Cicindela scutellaris scutellaris (carabidae: cicindelinae) [9]; (j) Japanese jewel beetle [32]; (k) Mother of Pearl [62]; (l) Pearlescent colours [1]; (m) Cicindela repanda (additive colour mixing) [9]; (n) Pollia condensata [55]; (o) Cellulose nanocrystal film.

Diffraction grating

Seago *et al.* [9] define a diffraction grating as a group of nanoscale parallel ridges or slits regularly distributed on a two-dimensional surface. A beam of light that hits the grating is split into several smaller light beams (Figure 6), where the change of direction of each wavelength of light comprising the original beam is affected in a different way. Diffraction gratings may result in white light being split into the full visible colour spectrum. Perhaps the best-known example of structural colour generated by a diffraction grating is the rainbow effects observed on the surface of a CD (Figure 7e) [43].

According to Parker [4], diffraction gratings were believed to be very rare among invertebrates, but this was later revealed to be false. The mechanism has been found to produce iridescent colours in, for example, beetle (Figure 7c, 7d) and spider species, and on the setae or setules (hairs) of crustacea (Figure 7b) [4]. In these species, the part of the iridescence arising from a diffraction grating often has a rainbow-like appearance. Seago *et al.* [9] describe this structural colour as follows: "*Iridescence due to diffraction gratings is always the shape of one or more ordered spectra, i.e., the colors are in the same order as the colors of the visible light spectrum, red – orange – yellow – green – blue – purple.*"

Some mollusks also create structural colours produced by diffraction gratings. Possibly one of the most striking examples is the mollusk pinctada margaritifera, which can generate very strong iridescent colours [63]. Colour nuances like green, blue, aubergine, and pink can be found in the shell and pearls of this mollusk (Figure 7a) [53].

In plants, diffraction gratings have been reported in flower petals, but often the resulting diffracted light wavelengths are in the UV region of the spectrum and visible to bees but not to humans [43].

Diffraction gratings produce the metallic-like coloured holograms found in credit cards, stamps and banknotes, where they act as anti-counterfeiting features (Figure 7f). Diffraction grating structures can be synthetically produced on various reflective surfaces such as wrapping paper (see Figure 7, example 7g). Recently even iridescent chocolate with diffraction gratings has appeared in social media channels (Figure 7h) [64]. Table 4 and Figure 7 show a summary of examples of materials with structural colours produced by diffraction gratings.

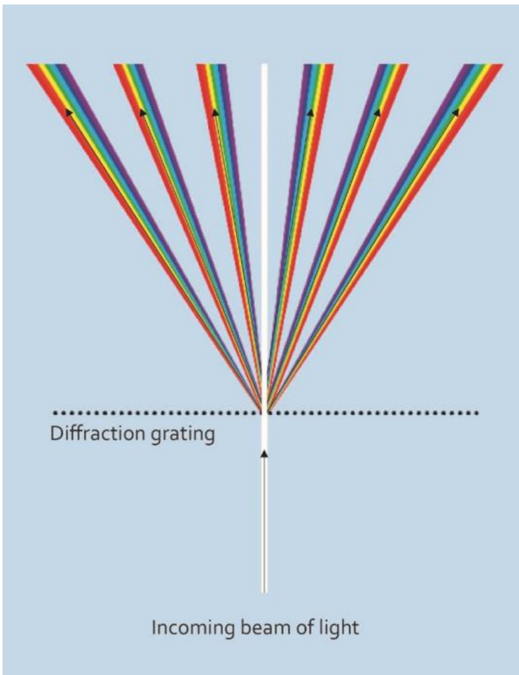

Figure 6: Schematic illustration showing how a diffraction grating splits an incoming light ray (white) into several rays having gradients of wavelengths (colours).

Mechanism	Notes of the visuality	Examples
Diffraction grating	Rainbow effect and spectral iridescence: The colours appear in the same order as the colours of the visible light spectrum (rainbow), i.e., red – orange – yellow – green – blue – violet.	In nature: Pinctada margaritifera [63], hairs of crustacea [4], rainbow-like effects in beetles [9] (Figure 7a-d) Artificial examples: Compact Discs (CD), Metallic- like coloured holograms found in credit cards, foil-type wrapping paper, and stamps and banknotes [36]. (Figure 7e-g) Diffraction grating sheets can now be purchased from retailers, which allows applying iridescent colour to chocolate and other crafts. (Figure 7h)

Table 4: Examples of the colour and visuality of diffraction gratings.

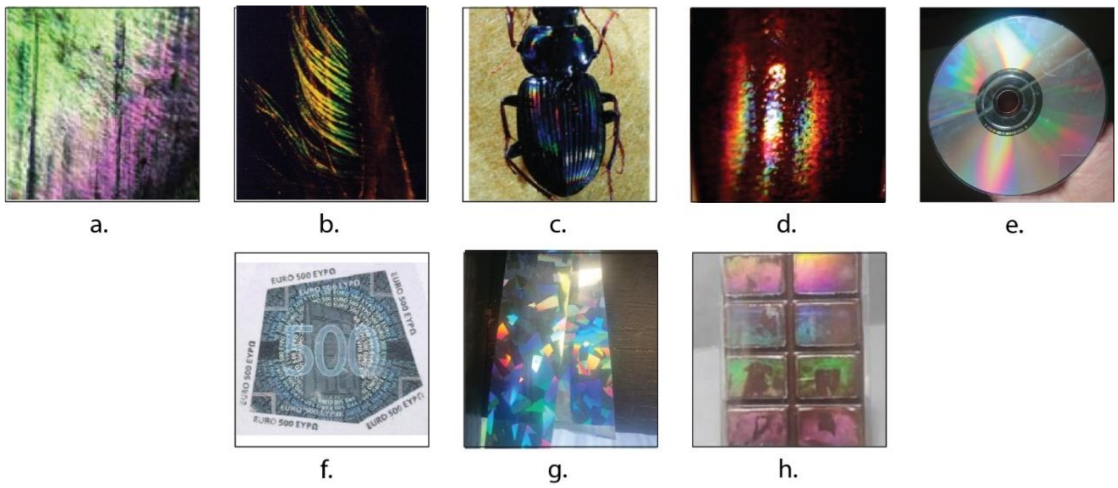

Figure 7: Examples of colours created through diffraction gratings: (a) Pinctada margaritifera [63]; (b) Halophores (hairs) on the first antenna of azygocypridina lowryi (ostracoda) [51]; (c) Beetle loxandrus rectus (carabidae: harpalinae) [9]; (d) Beetle pallodes (nitidulidae) [9]; (e) Compact Disc; (f) Hologram in paper money [65]; (g) Wrapping paper described as "holographic"; (h) Diffraction grating pattern in chocolate [66].

Photonic crystals

Structural colour can also be caused by photonic crystals [43]. The scientific definition of photonic crystals comprises structures which have a periodicity in either one, two or three dimensions, where the periodic structure interacts with light, resulting in structural colour (Figure 8). To this end, multilayer reflectors fit within the umbrella term of photonic crystals, because they are, in essence, photonic crystals with a periodicity in one dimension (1D). However, here, and in several related publications, photonic crystals refer to organised three-dimensional structures (Table 5). Natural opal is a classic example of a photonic crystal. Opal contains small spheres of silica packed together (Figure 9a). The diffraction of light through the opal is determined by the size and regularity, and spacing of the spheres, which in turn determines the perceptible colours. Photonic crystals have been found in many animals, including comb-jelly, many butterfly species, feathers from several bird species like peacocks and magpies (Figure 9b, 9c) [36] and seamice (*annelida aphrodita*) (Figure 9d) [4].

In beetles, photonic crystals have been described to create "opal or diamond effects" [9] (Figure 9e). However, due to limited picture examples, the description of the appearance of these colours remains rather vague. Due to having periodicities in three dimensions, rather than a single one as for multilayer reflectors, the iridescence of 3D photonic crystals is also reduced. The angle-induced shift in colour appears less dramatic and intense [9]. This also applies to 2D photonic crystals, with an iridescence intensity at an intermediate between 1D (multilayer reflectors) and 3D photonic crystals.

The edelweiss flower presents an example of three-dimensional photonic crystals in plants. The whiteness of the flower comes from photonic crystals (Figure 9f) [43].

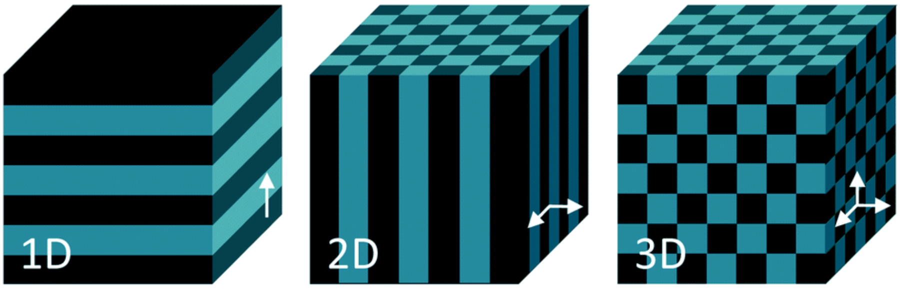

Figure 8: Schematic illustration of photonic crystals with periodicity in 1, 2 or 3 dimensions. Adopted from [67].

Mechanism	Notes of the visuality	Examples
Photonic crystals (more specifically, 2D photonic crystals and 3D photonic crystals)	Sparkling, gemstone-like reflections and metallic, opaque colours, as well as dimmed metallic colours and whites. The iridescence is less dramatic visually in 2D, and even less so, in 3D photonic crystals.	In nature: opals, peacock feathers, magpie feathers, aphrodita, beetles, edelweiss (Figure 9a-f)

Table 5: Examples of the colour and visuality of photonic crystals.

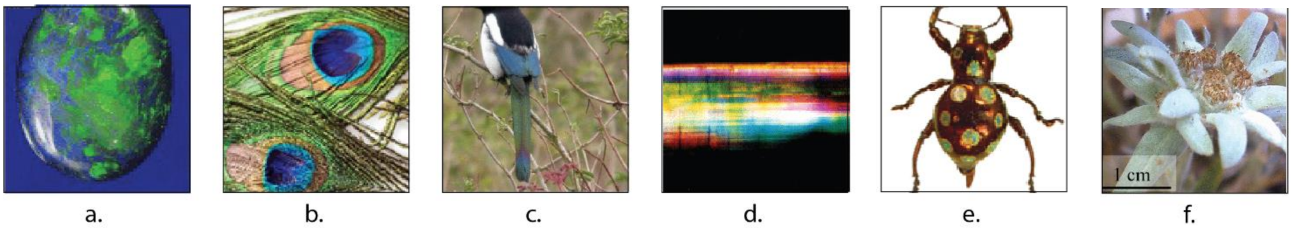

Figure 9: Examples of colours created with photonic crystals. (a) Opal gemstone [68]; (b) Peacock feathers (photo: Eeva Suorlahti); (c) Magpie tail feathers [69]; (d) A "photonic crystal fiber" – the spine of the polychaete aphrodita [51]; (e) Beetle pachyrrhynchus gemmatus [9]; (f) Edelweiss flower [70].

Metals and colour

When considering colour related to metals, it is important to distinguish between colour that (1) looks metallic, and colour that (2) is generated by metals, i.e., elementary metallic matter. It is possible to create metallic-looking colour without using any metallic matter, and conversely, metallic matter can generate non-metallic -looking colour.

Metallic surfaces naturally generate metallic colour. Some effect pigments with a metallic shine contain metals as elementary substances, which are responsible for the visual effect. Here, the metallic colour is generated through absorption of light (via plasmons, which will not be further discussed). However, visual metallic effects can also be generated by using structural coloration if the material has a multilayer reflector structure[8]. The material components of the multilayer structure are rarely metals

[8] See section *Multilayer reflectors* on Page 34.

(and the colour arises without plasmons). If the layer spacing in the structure varies evenly, the sum of all the colours reflected leads to a silvery appearance. If the same structure contained a comparatively larger number of layers reflecting light with middle to long wavelengths (yellow to red colour), a gold colour would be perceived. All metallic-looking colour found in living things comes from multilayer reflectors, and many synthetic effect “pigments” which visually appear as metallic rely on multilayer reflectors.

Metallic nanoparticles can create non-metallic colours, e.g., deep blues, reds, and greens. Here, the exact size of the particles determines which spectral colour is reflected. This phenomenon is based on incoherent light scattering, a sub-category of structural colour.

Man-made structural colours and related terminology

Pearlescent pigments and goniochromatic and holographic colours

According to Schenk and Parker [8], most industry-produced "pigments" that utilise the principles of structural colour are currently based on thin-film interference and multilayer reflectors. Although these are often referred to as pearlescent "pigments", all colours associated with this technology do not visually resemble pearls (mother of pearl).

Pearlescent "pigment" technology has its roots in the first pearl colour "Essence d'Orient", made by Jaquin in 1656, which is said to be the first pearl-like "pigment" [8]. Note that the first scientific references to structural colour did not appear until a few years later by Hooke [71] and Newton [72], and most likely the term "structural colour" did not yet exist in scientific literature when Jaquin invented “Essence d´Orient”. For a long time, Jaquin's technique of crushing the scales of silver-coloured fish such as herring was the only way to make pearlescent colours [8].

In the 1920s, attempts were made to create pearl-like lustre synthetically, as "Essence d´Orient" was expensive and only available in limited quantities. After this, transparent flakes or semi-transparent flakes that form metallic colour effects without metals were called "pearlescent effect pigments” [8]. Although pearlescent effect “pigments” produce a variety of iridescent and shimmering colours, Schenk and Parker [8] point out that in many cases, the production of these pearlescent effect "pigments" is a relatively expensive process and that these "pigments" are not yet widely used by artists. Also, mixing some of these "pigments" can be challenging compared to mixing chemical colours, as it might require the adoption of additive colour mixing theory[9] [8].

Over the years, pearlescent effect “pigments” have evolved especially for use in the cosmetics, automotive and plastics industries [8,32,73,20,74]. According to Maile *et al.* [20], pearlescent effect “pigments” are often used to create the illusion of optical depth. However, it is challenging for users to determine whether the pearlescent effect “pigment” colours stem from purely structural colours or both structural colours and pigment colours. Perhaps there has not been much incentive for the effect “pigment” developers to classify them based on their colour formation mechanism. For this reason, publications about these pigments might not underline whether the colour from the colourants arises due to structural coloration, absorption pigments (chemical colour), or from a synergy of both.

The term “pearlescent effect pigment” can be somewhat misleading to readers unfamiliar with effect “pigment” technology. “Pearlescent” strongly refers to the colours found in mother of pearl (natural pearl colours are usually shimmering, light pastel colours, as seen in Figure 5, example 5l). However, in

[9] See section *Additive colour mixing* on Page 35.

practice, pearlescent effect “pigments” cover a wide range of different colour effects that are usually glittering and based on ceramic crystals [8].

Sometimes publications also refer to goniochromatic colours, which is another commonly used name for a certain type of effect “pigment”: Materials which have a strong angular dependent reflection behaviour and hence show a colour impression that depends on the spatial arrangement of illumination and observation relative to the surface of the artefact. The basis of such goniochromatic materials are special effect pigments, the colours of which are based on the interference effect and exhibit different colours at different viewing directions [75]. Some of these paints form a smooth-looking metallic surface that changes colour depending on the angle of view. Some have subdued, very small but distinguishable flakes that glitter in different colours and create many different effects. In some paints, the flakes are reminiscent of glitter and clearly visible.

In the automotive industry, the names of effect colours can vary greatly depending on the source. The colours have names such as Holographic, Ghost Pearls, Ice Pearls [76] “Prizmatique®”, “Harlequin®”, and “Crystal Pearl™” [77]. Different manufacturers and sellers use different names for the same colours.

The meaning of the word “holographic” depends on whether it’s used in a scientific context, or to describe the appearance or colour in certain consumer products, such as effect pigments. In the former, a hologram is essentially a recording of a three-dimensional object in a two-dimensional diffraction grating. The three-dimensional image can be accessed by shining a given light beam through the hologram, i.e. the diffraction grating, at different angles. Apart from the viewing angle dependency, there is no connection between the above technical definition of a hologram and its use in the context of iridescent effect pigments. In the latter context, there is no exact definition for holographic colours and the word is used very freely. However, the word is often used to describe a rainbow-like reflection that depends on the viewing angle. The manufacturers might also call these effect colours as “prismatique” or “prismatic flakes” [77]. The term “holographic” or “HOLO” is repeated in several different iridescent products’ marketing and in popular culture (example: Lekka Angelopoulou, [78]). It is important to note, that these colours might not have any connection to real holograms.

A new source of biomimetic structural colour

Cellulose nanocrystals (CNC) offer an opportunity to create structural colour [15]. This nanomaterial is obtained by hydrolysing pulp or other biomass sources and is therefore a renewable resource [79]. In their 1992 paper, Revol *et al.* [80] discovered the tendency of CNCs to self-assemble into a helicoidal nanostructure that selectively reflects a certain wavelength bandgap, while itself being transparent, thus giving rise to structural colour. This discovery sparked extensive scientific interest [81], although there are still no commercially available products utilising this technology. Most efforts focus on potential applications in optical devices, such as optical sensors [82], holographic displays [83], and diffraction gratings [84], as well as in areas of nanophotonics [85] and optical coding [86]. Droguet *et al.* [19], however, explored the potential of larger-scale manufacturing for sustainable effect “pigments”.

Certain other visual characteristics of structural colour

Hydrochromicity

Certain nanostructures giving rise to structural coloration are hygrochromic. They respond to changes in moisture or humidity by altering the nanostructure dimensions, and thereby the reflected colour. The reflected structural colour generated by helicoidally assembled nanostructures of CNCs is drastically changed by exposing the nanostructure to liquid water [87-88]. In essence, the colour shifts in the direction of larger wavelengths, i.e., it redshifts, in a matter of seconds after immersion, and the nanostructure generally ends up reflecting infra-red wavelengths, meaning that it appears transparent to the viewer. The perceived colour shift occurs in the following order: Transparent (ultraviolet), blue, green, yellow, red, transparent (infrared).

Hygrochromic colour has also been reported in a few beetle species. A reversible colour change is induced by partially hydrating or dehydrating multilayer structures, and as the refractive indices of the porous layers change, the observed colour also changes [9].

The coffee-ringing effect

Structural colour based on cellulose nanocrystals produces a unique visual effect in which the edge of any surface coated with the nanostructure attains a redshifted colour in respect to the central part of the coated surface [89] (Figure 10a). Due to the coffee ring effect [10], a suspension of colloidal particles (here, CNCs) dries faster in the edges of a coated area. This results in a thicker coating at the edges than at the centre due to capillary flow of particles toward the edges. In the case of CNCs, this effect leads to a gradual redshift of the structural colour towards the edges of the coating [90]. The coffee ring effect has been seen as a burden in previous literature, due to the unevenness in the colour. However, in our previous work [89], we explored the potential of the resulting rainbow-like border colours to create visually and aesthetically appealing effects (Figure 10b). In the fields of design and art, this effect could be used as a highlighting effect since it can enhance the shapes and forms of the coloured area.

Figure 10: (a) An example of the coffee ring effect in a textile sample coated with nanocellulose that generates structural colour. The effect makes the edge colours transition towards yellow and red. (b) The "Morpho" artwork showing the coffee ring effect being utilised to create patterns for design objects. Edge colours play an important role in the pattern design of the work called Morpho. Artwork: Structural Color Studio (Noora Yau and Konrad Klockars) Photo: Esa Naukkarinen.

Discussion and conclusions

As previous sections demonstrate, a wide variety of phenomena affect the perception and experience of structural colour. As the description varies among disciplines, a common language should be developed to describe the visuality and experience of colour, or what is seen, to provide more accurate, cross-disciplinary information on structural colours. The measured wavelengths and the optical mechanisms underlying structural coloration provide some information but are insufficient alone to describe its visual diversity. While designers seem to discuss these colourants with varying, undefined, and loose terms, scientists tend to discuss these topics in very technical language.

The behaviour of structural colourants differs in many respects from the behaviour of pigment and dyes. Much of what designers and artists learn about colour is specifically related to the behaviour of pigments, as most colourants are based on them. If structural colours gain popularity, the basic knowledge about mixing, their interaction with light and angle dependency needs to be considered. A future is envisioned, where comprehensive knowledge about structural colour will lead to the utilisation of new colour effects in both technical and artistic contexts.

Seago *et al.* [9] introduced the need for more precise definitions of iridescence, and we agree with this goal. Considering the current information, it is, for example, difficult to determine from where the iridescence begins. The diversity and nuances of the iridescent colours are at risk of being overlooked, and hence, our understanding of these colours will remain one-dimensional. More specific words and common terms to describe these colour effects are needed to give us an updated, more accurate overview of iridescence.

In addition to the description of the colour showcased in Figures 2, 5, 7 and 9, we believe that even more detailed descriptions could promote an understanding of the nature of structural colours shared across disciples and colourant users. Table 6 introduces a list of "questions" through which the perception of structural colour could be described, emphasising iridescence, as this term is too broad to accurately describe the appearance of specific instance of angle-dependent colour. The word "iridescent" does not tell how quickly the colour change occurs in relation to the change in viewing angle. For example, the iridescence associated with thin-film interference and the iridescence caused by 3D photonic crystals can be very different in appearance. Therefore, in the future, more precise terms, and subcategories for iridescence, would be needed in order to avoid misunderstandings and to describe iridescent colours more precisely.

Aspect of colour		Explanation of the feature
1.	The origin of the colour-generating substance	Is the substance, for example, synthesised through a laboratory experiment (like a coloured film in a petri dish) or created by nature (like a butterfly wing, a flower or a rock)?
2.	The colouring mechanism(s) (if known)	What formation mechanism underlies the coloured area? Is the colour pigment-based or structural colour, or do these colouring mechanisms work together? In the case of structural colour, is it based on incoherent light scattering, quasi-ordered light scattering or coherent light scattering? Is the detailed working mechanism of the nanostructure known, such thin-film interference, multilayer interference, diffraction grating, photonic crystals, or none of the aforementioned?
3.	The nature of the iridescence in case it is present	Are there (1) distinct detectable shades, or (2) is the colour changing more continuously? In case (1), how many distinct shades can be detected and in case (2), what is the range of the spectrum? It would also be good to report the speed at which the colours change in respect to the viewing angle. Do the colours change rapidly from one shade to another (as, for example, in some colours based on thin-film interference and multilayer reflectors[10], or is the change calmer, perhaps wavy, as in some colours based on three-dimensional photonic crystals[11]? This description could include measured data by a colour detection device, but also a description of what is seen. Pictures or videos of the object should be included.
4.	The degree of shininess	Is the colour metallic and shimmering, or perhaps a dimmer matte? The very metallic-looking luster of the *morpho* butterfly differs markedly from the whiteness of edelweiss flowers

[10] See sections *Thin-film interference* and *Multilayer reflectors*, respectively, on Pages 33 and 34.

[11] See section *Photonic crystals* on Page 38.

5.	The level of transparency	Is the colour transparent, translucent or opaque?
6.	The texture of the coloured area	The colour perception is affected by the texture of the coloured area. Is the coloured area mirror-flat or does the surface resemble glitter more, where the colour particles are clearly distinguishable from each other? For example, the scales of certain beetles (*chrysina chrysagyrea*) [9] have an almost mirror-like, flat and metallic-looking coloured surface. In contrast, some car paints based on structural colour create a "flaky" or "pointillistic" surface, which is also seen on the surface of the *pollia condensata* fruit. For example, graininess and coarseness of the colour can be discussed here.
7.	Possible patterns and three-dimensionalities of the coloured surface	Are there distinct and clearly discernable patterns, or do they form from a more continuous change in colour. How are the colours distributed in the pattern and are there iridescent areas? What kind of patterns appear when the colour changes? Does the pattern remain in a fixed position, as in the coffee-ring effect[12], or can it change its position and its shape as a function of the lighting conditions? Do patterns appear because of the three-dimensionality of the background, as the iridescent patterns in some beetles? Do patterns appear only when direct light interacts with the surface, as in a Compact Disc?
8.	The background colour if present	Is the structural colour affected by pigment-based background (as in peacock feathers, *morpho* butterflies and others)?
9.	The lighting conditions under which observations of the colour have been made	If observations have been made under varying lighting conditions, how do they affect the observed colour?
10.	Other features of the colour	Is the colour for example hygrochromic?

Table 6: This table provides the tools for reporting the visuality of a particular structural colour in a more detailed manner.

While Figures 2, 5, 7 and 9 display examples of structural colour, they do not solve the problem of representing iridescence and metallic colours in photographs. Future studies would benefit from a "colour palette" figure with even more visual examples. In the best-case scenario, this palette could be represented and communicated in video format or, even better, through virtual reality (VR) technology. This would portray the colour more thoroughly and enable a comprehensive colour experience.

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[12] See section *The coffee-ringing effect* on Page 42.

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