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The new physiology of vision—Chapter XXVI. Structural colours

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The studies of the visual synthesis of colour described in several of the preceding chapters were made with various materials exhibiting highly pronounced colours by reason of their ability to absorb certain well-defined regions in the spectrum while freely transmitting the rest. The reason for choosing them as the subject of study was, besides the availability of the materials, the possibility by making use of them of arriving at definite conclusions regarding colour and its relation to the spectral constitution of light. There are, however, numerous other ways in which colours can arise and be perceived. It is clearly desirable that such cases should also receive consideration in our survey of the origins of colour and its visual perception.

The colours of interference: The colours of thin films are amongst the most familiar phenomena in physical optics and we naturally begin by considering their nature and origin. A very convenient way of producing them for the purpose of a detailed study is to put together two similar flat plates of glass, each about half a mm thick and two or three cm square in area. When pressed into contact after careful cleansing, they adhere in certain areas and are separated by an air-film in other areas. As seen by reflected light, the areas of adhesion appear quite black, while the other regions exhibit colour. It is often possible to get the plates adhering all along the outer edges, while the area within shows a sequence of interference colours appearing as a series of closed curves.

It is a significant fact of observation that the colour sequence in the fringes exhibited by air-films of progressively increasing thickness is the same irrespective of whether the fringes are straight or curved or irregular, irrespective of whether they are broad or narrow, and irrespective of whether they are equally or unequally or even randomly spaced. These facts become intelligible if it be recognised that the lines of colour follow the contours of luminosity in the field. The illumination at any point in the field of observation is determined by the thickness of the air-film at that point and its relation to the wavelength of the part of the spectrum which is visually the most effective. This is the yellow sector of the spectrum and its average wavelength may be taken as 580 mμ. Where the luminosity of the field as determined by the thickness of the air-film in relation to this wavelength is a maximum, the field would exhibit a yellow colour, and the rest of the spectrum would have but little chromatic effect. *Per contra,* it is in those parts of the field where the intensity due to the yellow sector is zero or small, that the other colours in the spectrum can manifest themselves most clearly.

The regions of zero intensity for light of wavelengths greater than that of yellow light and for light of wavelengths less than that of yellow light would evidently adjoin the regions of zero illumination for yellow light, but would be located on opposite sides of the same. Hence, in the regions where the light of such greater wavelength has a low intensity, the light of the smaller wavelengths would be dominant and determine the observed colour. Vice versa in the regions where the light of the smaller wavelengths has a low intensity, the light of the greater wavelengths would dominate and determine the observed colour.

The foregoing considerations are fully supported by the actual facts of observation. In particular, it is evident on inspection that the bands of colour follow the contours of minimum luminosity in the field and that the colours are most vivid in the regions adjoining them on either side. On the other hand, along the contours of maximum luminosity, the colour exhibited is yellow, while green and red appear respectively on the two sides of the lines of minimum luminosity.

The classic illustration of the colours of interference is the phenomenon first described by Newton and known by his name which is exhibited by an air-film between two polished surfaces of glass having different curvatures. The interferences appear as circular rings surrounding the point where the two surfaces are in actual contact, this appearing as a black spot. If the rings are formed between two surfaces of which the curvatures are not nearly the same, the area over which the interferences are visible in white light would necessarily be limited and the successive rings would be close to each other. In such cases, it is found that though the rings can be seen quite clearly when the air-film is held at the usual distance of distinct vision from the eyes of the observer, no colours are visible, the pattern exhibiting only variations of brightness. Five or six rings can be counted, the contrast between the dark and bright rings falling off in the successive rings. To observe colours in such cases, it is necessary to examine the interference pattern closely through a magnifier. The colour-sequence as described earlier can then be recognised.

The explanation of the remarkable facts stated above is not far to seek. Newton's rings exhibit the fluctuations of luminosity which arise from interference as observed in white light and the appearance of colour is only an incidental circumstance. The eye perceives only the fluctuations of brightness and does not perceive any differences in colour unless the regions in which the spectral characters of the light differ are widely enough separated for the eye to recognise them as distinct areas in the field.

The colours of rotary dispersion: Very interesting cases in which structural colours are observed present themselves when plane-polarised light traverses a crystal having a chiral structure. The best known example is that of quartz. The colours under reference are observed when a plate of this crystal cut perpendicular to its optic axis is set between two polaroids and a bright source of light is viewed through the combination. To observe the colours at their best, one should use a pair of polaroids which give a perfect extinction of light without perceptible colour when they are in the crossed position. The rotation of the plane of polarisation produced by the passage through the crystal is proportional to the thickness of the plate and depends on the wavelength of the light. Hence when a plate of any particular thickness is used, it is possible to extinguish any specified part of the spectrum by a suitable setting of the polaroids with respect to each other, while the rest of the spectrum is transmitted. As the position of the spectral band of extinction can be varied by rotating one of the polaroids, the spectral constitution of the emerging light is altered and its observed colour also changes. By using a set of quartz plates of different thicknesses, the relation between the perceived colour of light and its spectral constitution can be studied in this manner in a great many different cases.

In the present studies, seven plates of quartz of different thicknesses were used. Four of the plates had thicknesses which were fractions of a mm, while the three others had thicknesses of three, five and six mm respectively. These thicknesses and the optical rotations to which they give rise to for various wavelengths are shown in table 1. The figures were computed from Chandrasekhar's formula which is quite simple and represents the optical activity of quartz with great accuracy over the entire range of wavelengths.

Table 1. Rotation in degrees of arc for different wavelengths.

Plate thickness (mm)	400 mμ	450 mμ	500 mμ	550 mμ	600 mμ	650 mμ
0·46	23	18	14	12	10	9
0·68	34	27	21	17	14	12
0·84	42	33	26	21	18	15
0·96	48	38	30	24	20	17
3·00	150	117	93	75	63	54
5·00	250	195	155	125	105	90
6·00	300	234	186	150	126	108

When a plate of quartz is interposed between two crossed polaroids, there is a restoration of light which cannot be quenched by a rotation of one of the polaroids. It is however possible in the case of the quartz plates of the thicknesses listed in table 1 to find a setting in which the light emerging through the combination has the minimum brightness. In these circumstances, the emerging light is found to exhibit a purple colour. A rotation of the polaroid away from this setting in one direction or the other results in a brightening of the field as well as a change of colour, this being different for the two directions. In one case, the field exhibits a blue colour and in the other case it becomes bright yellow. The magnitude of the rotation required for the change of colour from purple to blue or from purple to yellow increases with the thickness of the plate. Transitional colours appear in the intermediate stages.

Spectroscopic examination of the light of purple colour emerging along the optic axis at the setting for minimum transmission reveals a dark band of extinction covering the yellow sector, the green and blue sectors being clearly visible on the one side and the red sector on the other side of the spectrum. A rotation of the polaroid away from that setting results in a displacement of the extinction band in the spectrum; it moves from the yellow to the green or from the yellow to the red respectively for a rotation in the two directions. Such spectral displacement results in an increased brightness of the transmitted light and also a change in its colour.

The magnitudes of the rotation for different wavelengths listed in table 1 enable us to understand why the colour of the transmitted light is blue for some settings of the polaroids and yellow for other settings. The colour is determined by the luminosity of the blue and green sectors relatively to the yellow and red sectors in the spectrum of the transmitted light. The great difference in rotatory power at the two ends of the spectrum results in the short-wave end or the long-wave end becoming its dominant feature as determined by the setting of the polaroids. In the former case, the resultant sensation is blue, and in the latter it is yellow.

The difference in the optical rotation at the two ends of the visible spectrum is less than 180° for all the plates listed in table 1 except the thickest for which it is slightly in excess of that value. Hence, only one extinction band can appear in the spectrum of the transmitted light and this would shift from one end of the spectrum to the other as one polaroid is rotated, finally passing out of the spectrum altogether. When the latter is the case, the transmitted light could, if at all, exhibit colour only by reason of the altered distribution of intensity in the spectrum which results from the presence of the second polaroid. The effects thus arising are scarcely noticeable in the case of the four thinnest plates. They are, however, observable in the case of the plates which are three or five mm thick, and are quite conspicuous in the case of the six mm plate.

The colours of the sky and the sea: When white light traverses a transparent medium, its molecules scatter or diffuse the radiation and the light thus diffused when perceived by the observer is found to exhibit colour. The explanation of this effect usually given is that the scattering power of the medium depends on the wavelength of the radiation traversing it. The proportion of the scattered to the incident light varies inversely as the fourth power of the wavelength and is thus much greater for the short-wave regions in the spectrum than for the long-wave part of it. This argument is clear enough from a physical standpoint; but it leaves the actual facts of the case, viz., the perception of a blue colour, without any real explanation. The inadequacy of the argument becomes evident when an observer views the blue sky through a pocket spectroscope and compares it with the spectrum of a white cloud floating in the sky. In both cases, the entire solar spectrum is visible and in both cases the green, yellow and red sectors are much more luminous than the blue sector. The blue sky is much less bright than a white cloud; hence the spectrum in the latter case is the more brilliant. Scrutiny reveals that this difference in brightness is more evident for the green, yellow and red sectors than for the blue sector. In other words, the blue sector gains relatively to the green, yellow and red sectors in the spectrum of the blue sky. Nevertheless, these sectors continue to be more luminous than the blue sector. Why then do we see the sky as blue while the cloud appears white?

The answer to the paradox stated above is furnished by the phenomena of the superposition and masking of colours which formed the subject of an earlier chapter. The sensation of white light is the result of the superposition of radiations appearing in the two parts of the spectrum of which the wavelengths lie respectively in the ranges from 400 to 500 mμ and from 500 to 700 mμ. The superposition of radiations appearing only in the first range results in the chromatic sensation which we call blue. The superposition of the radiations appearing only in the second gives the chromatic sensation which we call yellow. When superposed in an appropriate ratio, these two sensations merge and give rise to an achromatic sensation. But if one is present in excess, either sensation can mask the other and prevent its being perceived. The presence of the sensation which is suppressed however makes itself felt as a dilution or weakening of the chromatic sensation which survives.

In diverse fields of experience, the foregoing ideas find confirmation. For example, many flowers contain the carotenoid pigments in their petals and exhibit a yellow colour. But the intensity of the colour varies from the palest cream to a rich golden hue as determined by the strength of absorption of the blue sector by the pigments. The familiar variations in the colour of the sky from the palest blue to the deepest azure are likewise explicable in terms of the spectral nature of the scattered light in various circumstances. As sunlight is progressively denuded of the components of shorter wavelength in its spectrum by traversing long paths in the atmosphere, a stage is reached when an observer would perceive its colour as yellow. Thus, the colours of the twilight sky can be explained on the same basis as the complementary phenomenon of the blue colour normally exhibited by the sky.

The molecular diffusion of light also plays a highly important role in producing the blue colour exhibited by the water in deep lakes and by oceanic waters when the turbidity which results in a lack of transparency is at a sufficiently low level. In such cases, it is noticed that the blue colour is much deeper than the colour of the sky. The reason for this difference is to be found in the absorption of sunlight when it traverses long columns of water. This absorption is weak but selective, being confined to the long-wave region in the spectrum. This part of the spectrum would be weakened when the incident light traverses the medium and again after diffusion returns to outer space. As a result of these processes, there would be a large preponderance of the short-wave part of the spectrum in the diffused light emerging from the medium. The highly pronounced blue colour actually exhibited by such waters thus finds a natural explanation.