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The new physiology of vision—Chapter XXV. The colours of natural and synthetic gemstones

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Glasses exhibiting colour are made by the addition of the oxides of various metals to the materials used in their manufacture. Amongst the additives used for this purpose in different cases may be listed the oxides of copper, cobalt, iron, nickel, chromium, manganese, titanium and uranium. Black, blue, green, amber, yellow, orange, red, purple and violet are amongst the colours that have been produced. We begin the present article with a reference to coloured glasses for the reason that they afford excellent illustrations of the role played by the characteristics of human vision in the production and perception of colour.

A familiar example of the use of coloured glass is for signal lights, viz., red, yellow and green. It is essential for such use that the colours perceived should be highly pronounced and distinctive, and that the glass should transmit light of sufficient brightness for it to be readily perceived. Examination of the signal glasses used on railways shows how these requirements are met. It is found that the red signal-glass cuts off completely the blue, green and yellow sectors of the spectrum and transmits only wavelengths greater than 600 mμ. The "green" signal-glass actually appears bluish-green and exhibits a free transmission of wavelength between 450 and 560 mμ, in other words, part of the blue sector and the whole of the green but cuts out completely the yellow and red sectors of the spectrum. The yellow signal glass shows a nearly complete extinction of the blue sector and transmits the rest of the spectrum without any noticeable absorption.

Blue glasses are of particular interest. Four specimens were examined which exhibited different depths of colour. All the specimens showed an absorption of the yellow over the wavelength range between 570 to 600 mμ. This absorption was evident even in the case of the most lightly coloured specimen and progressed to a complete extinction in the case of the most deeply coloured glass. All the four specimens also exhibited an absorption band in the red located at 650 mμ and in addition a general absorption in the red region of the spectrum. A weak absorption was also noticeable in the green between 510 and 540 mμ and this was progressively stronger with increasing depth of the colour exhibited by the glass. In all cases, there was a free transmission in the green between 540 and 570 mμ.

This appeared in the case of the deep blue glass as a bright band in the spectrum with dark bands on either side of it.

In the collection of specimens of glass presented many years ago to the author by the American Optical Company, there is a piece of spectacle glass which exhibits a brilliant blue-green colour by transmitted light. The spectroscope reveals that this colour results from a free transmission of the blue and the green sectors of the spectrum and a complete cut-off of the yellow and the red sectors. This specimen as well as the other cases mentioned above illustrate the extremely important role played by the yellow sector of the spectrum in the perception of colour. Only when the yellow sector has been completely eliminated by absorption can red, green or blue manifest themselves to perception as highly chromatic sensations.

Blue glasses also illustrate the general principle that in the perception of colour, strong sensations may mask sensations which are much weaker and prevent their being perceived. Thus, when the yellow has been eliminated, the blue sensation becomes dominant and prevents the green and the red from being perceived even though they are present in the spectrum. In general, however, composite sensations are experienced, the nature of which is determined by the particular circumstances of the case.

Colours of synthetic corundum: As is well-known, cylindrical boules of crystallised alumina can be prepared by the Verneuil process which are perfectly colourless and transparent if pure alumina is employed, but can also be made exhibiting varied colours by the use of appropriate additives. A collection of such boules prepared by an Indian manufacturer was available for study. The collection included fourteen colourless boules besides an equal number of specimens showing various colours, viz., three blues, one yellow, four greens, two purples and four reds. We shall proceed to describe the results of a study of these specimens.

The three *blues* showed essentially the same spectral pattern of absorption but developed to different extents. All the three specimens showed an extinction of the yellow of the spectrum in the wavelength range 570 to 600 mμ. Two other bands of absorption were also observed, one in the green from 540 to 550 mμ and another in the red from 630 to 660 mμ. The parts of the spectrum in the green, orange and red which were actually transmitted had apparently no effect on the colour of the light perceived which was a clear blue for all the specimens though the luminosity varied from specimen to specimen.

The *yellow* boule showed a rather pale colour which was the result of a diminished transmission of the blue region of the spectrum. The four *green* boules also did not exhibit that colour in any striking fashion. Both the red and the blue sectors showed a diminution of intensity in the transmitted light, and the yellow was also weakened. But in the net result, the green sector did not show any particular degree of prominence in the spectrum. The poverty of the resulting colour was therefore not surprising.

Of the two *purple* boules, one was of a much deeper colour than the other. But even the faintly coloured specimen showed a readily observable diminution in the intensity of the yellow sector relatively to the rest of the spectrum. The more strongly coloured specimen showed a nearly complete extinction of the yellow of the spectrum over the wavelength range from 560 to 600 mμ, while the red, green, and blue sectors maintained their normal relative intensities.

The *red* boules owed their colour to an absorption of light manifesting itself in the wavelength range between 500 and 600 mμ. Two of the boules which were optically clear and perfect showed the phenomenon of dichroism in a very striking fashion. The colour of the boule as seen by transmitted light showed a large change when it was viewed transversely and rotated about its cylindrical axis. In one position, the colour was a rose-red, the spectrum exhibiting a relatively weak absorption in the green with its maximum around 550 mμ. In the other position, the colour was a deep purplish-red and the absorption was practically complete over the wavelength range from 500 to 600 mμ, thus covering both the green and yellow regions in the spectrum.

Colours of natural corundum: As is well-known, the gravel-beds below the soil in the vicinity of Ratnapura in Ceylon have for many years been the source of gemstones of various sorts. Some years ago, while on a visit to Ceylon, the author was the recipient of a generous presentation of some hundreds of specimens of the materials found at this site. They were sorted out and preserved and have been made use of for the observations presently to be described. Many of the specimens were colourless and some of them were so heavily coloured as to be nearly opaque. Excluding these, the rest of the material could be classified in the following colour-groups: blue, purple, red, green and yellow. Under an ultra-violet lamp, these groups behaved quite differently. The blue and green specimens were non-luminescent. The purple and the red stones showed a red glow of varying degrees of brightness, while the yellow specimens exhibited an orange luminescence.

Spectroscopic examination of the transmitted light showed that the blue stones owed their colour to a more or less complete extinction of the yellow sector of the spectrum and a cut-off of wavelengths greater than 650 mμ at the red end of the spectrum. The spectroscope also revealed that the characteristic purple colour exhibited by numerous specimens in the collection had its origin in the powerful absorption exhibited by these specimens in the wavelength range between 560 and 600 mμ, in other words, of the yellow part of the spectrum, while the blue, green and red sectors remained conspicuously visible.

The red stones in the collection are rather small and of irregular shape, and also not optically clear. The difficulties arising from these defects in the study of their spectroscopic behaviour was overcome by setting each specimen in an aperture made in an opaque screen. Holding this close to a brilliant source of white light, enough light diffuses through the specimen to enable its spectral character to be observed. The spectrum observed in this fashion differs from specimen to specimen, and *pari passu* there is a variation in the colour of the emerging light and of its brightness. Certain general features were however noticeable. In all cases, the red sector of the spectrum emerged freely. Certain sharply defined absorption lines appeared in the region of greatest wavelengths, but despite such absorption, the red remained the brightest part of the spectrum. The spectral region between 500 and 600 mμ also exhibited absorption. But the strength and the spectral range of this absorption varied from specimen to specimen. As a consequence of the weakening of the green and yellow sector in the spectrum, the red becomes dominant and determines the observed colour. In this, it is aided by the absorption noticeable in the region of shortest wavelengths in the blue sector.

The "green" stones in the collection could be more accurately described as greenish-yellow. They owned their colour to a strong absorption of the light in the blue and blue-green parts of the spectrum and to a very noticeable weakening of the red sector. The "yellow" stones owed their colour to a partial absorption of the blue sector, the rest of the spectrum remaining unaffected.

The green colour of emerald: The variety of beryl known as emerald shares with ruby and sapphire the rank of 'precious stone' in the popular estimation and, as with the corundum gems, its rarity and costliness have served to stimulate man's ingenuity in providing artificial substitutes. Just as the red of ruby and the blue of sapphire cannot be properly matched by any other natural mineral, so is the pure emerald green unequalled by any other transparent natural gemstone.

Beryl is a silicate of beryllium and aluminium and the colour of emerald is due to traces of chromium, which replaces to a small extent the aluminium ions in the crystal lattice of the hexagonal lattice of the hexagonal beryl crystal. It is a feature of this colouring agent which also causes the red in ruby and in spinel and the betwixt-and-between colour in alexandrite, that even when it produces a green colour, it transmits a proportion of deep red light.

The foregoing quotations from B W Anderson's book on Gem Testing state very clearly the reasons why the emerald is held in such high esteem, viz., its beautiful green colour and the rarity of material of the requisite high quality, which together make it a much valued gemstone. It should be mentioned that beryl is itself a mineral of fairly common occurrence and that though it is colourless in the pure state, it frequently exhibits colour, this presumably arising from the presence of impurities. Iron is the impurity responsible for the familiar bottle-green colour of cheap glassware; oxides of iron if present in beryl as impurities would also give it a green colour. But it is not difficult to recognise the special variety of beryl in which the colour arises from the presence of chromium as an impurity. Spectroscopic examination reveals the presence in such cases of a group of sharply-defined absorption lines falling within the wavelength range between 600 and 700 mμ, and indicating the presence of chromium in the crystal lattice.

The author had at his disposal an extensive collection of beryl specimens including especially several which had a green colour. A few of these were large and clear enough to permit of the absorption spectrum being seen by merely holding up the specimen against the sky and examining the transmitted light through a pocket spectroscope. In most cases, however, the specimens were either too small or else were not optically clear enough to permit of their being thus dealt with. In such cases, the specimens were set within an aperture in an opaque screen and this was held close up to a brilliant source of white light. The light emerging through the material could then be conveniently examined. To make the present study more complete, the author used besides the beryls at his disposal also a real emerald of small size but of good quality and two specimens of the well-known synthetic product made by Mr Carroll F Chatham of San Fransisco and marketed under the trade name of "Chatham Created Emerald".

The comparative study of these specimens made it evident that the beautiful green colour of emerald owes its origin to the absorption of the yellow sector, in other words of the wavelength range in the spectrum between 560 and 600 mμ. The more complete this absorption is, the more striking is the green colour which results. The removal of the yellow sector and the simultaneous weakening of the blue and red sectors leaves the green as the dominant feature which determines the observed colour. It should be remarked that the blue and red sectors are not completely extinguished in any case. But they are so weak that they are masked by the stronger green and prevented from being perceived. The larger of the two Chatham emeralds examined by the author shows the absorption of the yellow sector in a particularly striking fashion. The red sector, though weakened, is also very clearly seen and exhibits the characteristic absorption lines due to the chromium impurity with extreme sharpness and clarity.