Leonardo, Vol. 14, No. 3, pp. 187–190, 1981.
Printed in Great Britain.

0024-094X/81/030187-04$02.00/0
Pergamon Press Ltd.

ON PRODUCING COLOURS USING BIREFRINGENCE PROPERTY OF TRANSPARENT, COLOURLESS STRETCHED CELLOPHANE

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Abstract — *The authors discuss the birefringence property of transparent, colourless stretched cellophane and describe the colours produced when one or more layers of such cellophane is sandwiched between a pair of polarisers. The parameters that can be altered in order to vary the colours are explained, and a convenient method is suggested for viewing the range of colours produced.*

I.

The conventional method of producing colour is to pass 'white' light (sunlight, daylight, lamplight) through a medium that *selectively absorbs* light at some wavelengths more strongly than at others. The emergent light will then have a different composition in which components at some wavelengths will have intensities that are significantly higher than the intensities for the rest. Light compositions of this type provide the stimulus causing the sensation of colour. Pigments used in painting perform the function of selective absorption, as do dyes on a textile substrate. When colours are produced by light reflecting from a layer of transparent paint, the principal process is that of absorption; the light traverses the thin pigmented layer twice and is subjected to absorption before and after reflection at the substrate.

There are other methods for producing light in which some wavelengths are more intense than others. *Interference* between the light reflected at the two surfaces of a thin transparent film is responsible for the array of colours (iridescence) seen on an oil-slick and in the wings of certain insects [1]. *Differential scattering* by small particles accounts for the blue of the sky and the varying redness of a sunset. Another well-known method of producing colours makes use of an optical property known as *birefringence*. This property is possessed by a large number of crystals, including calcite, quartz and tourmaline, and also by certain organic polymeric materials having a crystalline character such as transparent, colourless cellophane sheet that has been stretched in one direction during its manufacture. Another form of stretched cellophane is adhesive cellophane tape, which is readily available (in Great Britain under commercial names such as Sellotape and Scotchtape). Several applications in static and kinetic artworks of the birefringent property of stretched cellophane and stressed plastics have been described in articles in *Leonardo* [2–6].

When transparent, colourless stretched cellophane is placed between two colourless polarisers (Polaroid sheet is a convenient form of polariser) and 'white' light is passed through the sandwich, the emergent light is seen to be coloured (Fig. 1). In the remainder of this article we shall explain this phenomenon and describe the parameters that govern the colour seen at any point on a piece of such cellophane.

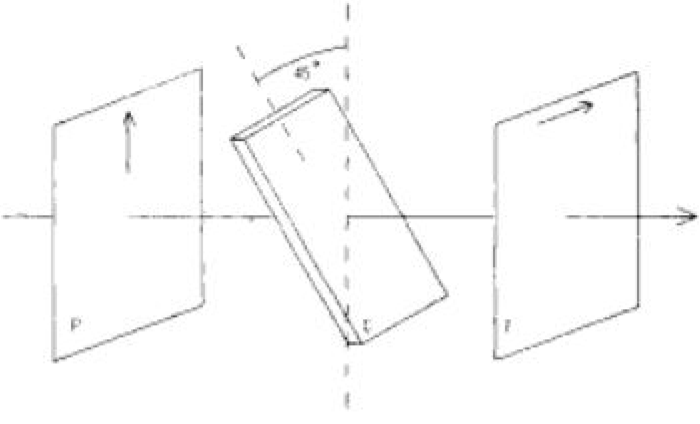

Fig. 1. Production of coloured light by transmission through cellophane (C) between crossed polarisers (P).

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II.

For most materials, the speed of light is independent of the angle between the plane of vibration of the waves of the light and any axis one may select for its passage through the materials. Hence, the speed of light is constant for any direction of its propagation through them; such materials are termed *optically isotropic*. The birefringent materials mentioned above, however, exhibit *optical anisotropy*. For the crystals the structural arrangement of the ions is such that the speed of light is dependent on the angle between the plane of vibration of the light waves and a crystal axis; in a birefringent material the speed of light varies with the angle of propagation of the light through it. There is one plane of vibration at which light is transmitted with a maximum speed, and this plane is known as the *fast axis* of the material. The minimum speed occurs for vibrations in the plane at right angles to the fast axis; this plane is termed the *slow axis*.

The speed of light within materials is not usually given directly but in terms of the ratio of the speed of light in vacuum to the speed of light through the material; this ratio is known as the *refractive index*, n. One can, therefore, say that an isotropic material has a single refractive index, while an anisotropic material has a refractive index that varies from a maximum value n_s for the slow axis to a minimum value n_f for the fast axis. The difference between these two refractive indices $(n_s - n_f)$ is known as the *birefringence* of the material. In our investigations we have determined the birefringence of transparent, colourless stretched cellophane tape to be 0.01 [7].

When transparent cellophane tape is stretched during certain procedures of manufacture, its long twisted macromolecules tend to straighten out and align in the direction of the stretch, producing an order that gives the material certain crystalline properties. One result is that two extremes of refractive index n_f and n_s occur along and perpendicular to the longitudinal axis of the tape. Consequently, light with its vibrations parallel to the length of the tape (that is, *plane-polarised* in this direction) will travel through the tape with a speed different from that of light whose vibrations are at right angles to the length of the tape.

If a plane-polarised light is incident on certain cellophane tapes with the plane of polarisation at 45° to the axis of a tape, it can be considered in terms of two component vectors of equal intensity whose vibrations occur along and perpendicular to the axis of the tape (Fig. 2). These two vibrations will start off in phase, but on emergence one vibration will be retarded with respect to the other. The magnitude of this *retardation*, R, depends on both the birefringence $(n_s - n_f)$ and the thickness of the tape, t; the retardation of the material is given by $R = (n_s - n_f)t$. It is as if one of the vibrations has travelled a distance $(n_s - n_f)t$ further than the other as they traverse the cellophane. Consequently, when the two vibrations emerge from the cellophane they will be out of phase with each other by an amount that depends on the retardation and on the wavelength λ

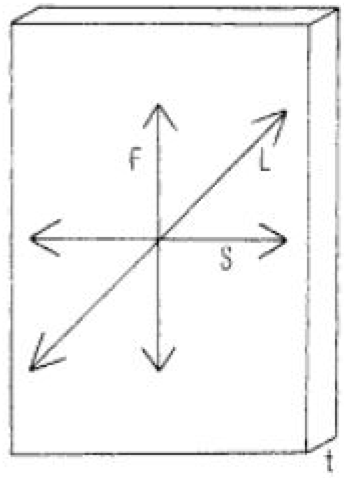

Fig. 2. Polarised light (L) *incident on cellophane at 45° to both fast axis* (F) *and slow axis* (S).

of the light. The vibration along the slow axis will be delayed by R/λ wavelengths of light. The type of light that emerges depends on the value taken by the quantity R/λ. If this quantity happens to be an integer, then the two vibrations emerge exactly in phase, and they recombine to reconstitute the incident light, plane-polarised at 45° to the axis of the tape. For any value R/λ that is not an integer, the two beams emerge out of phase, and the result is known as *elliptically polarised light*. It is called elliptically polarised light, since it is possible to show mathematically that the result of combining two vector vibrations at right angles that are also out of phase is a single vibration that continuously alters its direction and its magnitude, so that the extremes of the vibration trace out an ellipse (Fig. 3).

The actual shape of the ellipse depends on how far out of phase the two vibrations are on emergence, and, since this depends on the value taken by $(n_s - n_f)t/\lambda$, it is wavelength-dependent. This means that, if the incident light is 'white', then the state of polarisation of the emergent light will be different for each wavelength present, being plane-polarised at some wavelengths and elliptically polarised at others. A possible situation is illustrated in Fig. 4.

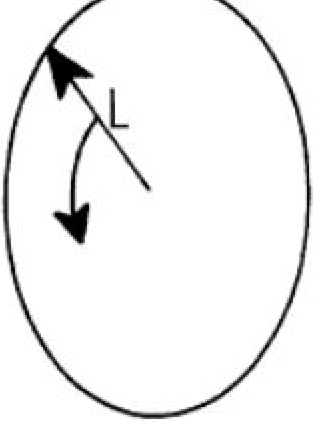

Fig. 3. Elliptically polarised light in which the plane of vibration of the light (L) *is constantly changing.*

Fig. 4. The shape and attitude of the ellipse varies from wavelength to wavelength across the visible spectrum.

Table I.

Layers of cellophane	Hue
1	Pale yellow
2	Strong blue
3	Magenta
4	Lime green
5	Purple
6	Pale green

If the emergent 'white' light is now passed through a second polariser with its maximum transmission axis at right angles to the plane of polarisation of the incident light, the emergent wavelength, for which R/λ is an integer, is cut out, since it is plane-polarised at right angles to the maximum transmission axis of the final polariser. For wavelengths that do not correspond to the cut-off wavelength, the transmission increases until it becomes a maximum when R/λ is $N + \frac{1}{2}$ wavelengths, when the emergent light is plane-polarised in the direction of maximum transmission of the second polariser. This variation of transmission with wavelength means that the emergent light will be seen as coloured.

III.

The actual colour produced at any point on a piece of birefringent cellophane depends on the retardation R and on the angle between the axes of the two polarisers. In our initial experiments we investigated the range of colours obtainable by varying the thickness of the cellophane only, keeping the polariser sheets with their maximum transmission axes at right angles, that is, crossed polarisers [7]. The cellophane used was of thickness 0.0335 mm, and the thickness was increased by superimposing sheets. Large changes of colour were observed for one to six sheets, but for additional thicknesses little change was evident to the eye, as they appeared to produce 'white' of slightly different hues. The reason for the loss of strong hues in thick layers of birefringent cellophane is that R became so large that it was possible for R/λ to be an integer for a number of wavelengths within the visible range. This means there are a number of wavelengths cut out by the second polariser, and, as these are uniformly distributed in the visible range, the emergent light is 'white'.

In our previous work we measured the colour of the transmitted light for one to 15 layers of birefringent cellophane, but strong hues were obtained for one to six layers only, that is, for overall thicknesses of less than 0.2 mm. The observed hues are named in Table I.

The colours for which the hues are named in Table I are solely a function of the thickness of the cellophane used in our measurements. With certain other thicknesses more saturated colours are obtainable. It is possible to observe these more saturated colours, and others, by making the light travel obliquely through a polariser-cellophane-polariser sandwich shown 'edge on' in Fig. 5. In this case the effective thickness can be changed continually by decreasing the angle of incidence of the light from 90°. When the angle of incidence is equal to 90°, then magenta is observed, and, as the angle is decreased, the colour changes to orange, yellow, lime green. (It becomes, effectively, four layers thick at a very oblique angle of incidence of the light).

The thickness effect can be reproduced by varying the angle between the axes of several pieces of cellophane between the crossed polarisers. When two pieces of cellophane are superimposed with their fast axes (parallel) at 45° to the crossed polarisers' axes, then their retardation adds, but, if the axes of the cellophane are mutually at right angles, they subtract. This means that, if one starts with three pieces of cellophane with their axes in the same direction, magenta is observed. If one of these three pieces is rotated, the colour observed changes continuously to blue and finally to yellow, when it is at right angles to the other two. In this way the whole gamut of colours may be produced that are obtainable with one, two and three layers of tape.

A different effect is observed if cellophane is rotated between the fixed polarisers. If the polarisers are *crossed*, then no light is transmitted when the axis of the cellophane layer is parallel with the axis of either polariser. As the cellophane layer is rotated, colour changes occur in which there is no change in hue, very little change in saturation, but there is a continuous increase in brightness up to a

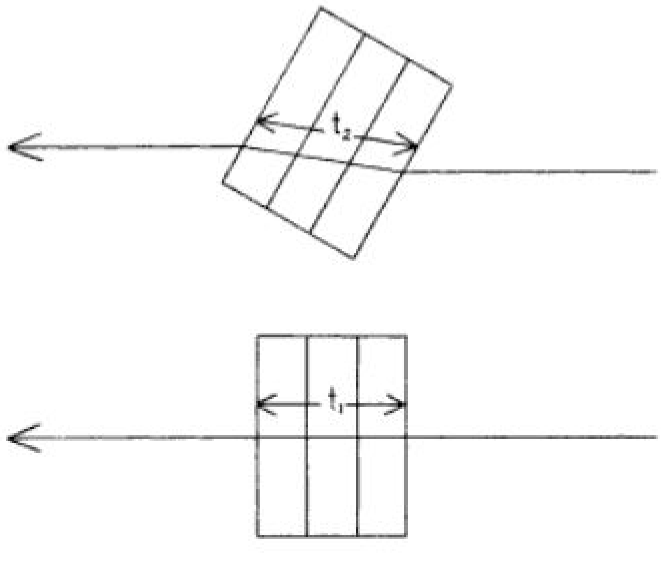

Fig. 5. The oblique path (t_2) is longer than the perpendicular path (t_1) through the same thickness of cellophane.

maximum brightness when the cellophane axis is at 45° to the axes of the polarisers. If the axes of the polarisers are *parallel*, then the cellophane is colourless when it is parallel to the polariser axes. Then, as the cellophane layer is rotated, colour changes occur in which the hue and brightness remain constant, and the saturation reaches a maximum when the cellophane axis is at 45° to the axes of the polarisers. The hue in the latter case (parallel polarisers) is complementary to the hue in the former case (crossed polarisers).

It is interesting to observe the changes caused by continuously varying the angle of the axis of one of the polarisers. If the cellophane layer is fixed with its axis at 45° to the axis of the first polariser, then, as the second polariser is rotated, the colour associated with any particular thickness of cellophane varies as follows: Starting from one hue listed in Table I for crossed polarisers, the saturation decreases from a maximum until the cellophane is colourless when the polariser axis coincides with the axis of the cellophane. The saturation then increases at the complementary hue to a maximum when the axes of the polarisers are parallel and decreases once again to become colourless when the polariser axis is at right angles to the cellophane axis. For one layer of cellophane the observed sequence of colours is: yellow, colourless, blue, colourless.

Colours are also observed at any points where the cellophane has been strained. This is the well-known phenomenon of photo-elasticity that is used as an engineering stress analysis technique. Certain materials, such as Plexiglas or Perspex, that do not normally exhibit birefringence become birefringent when strained; the colours exhibited by a particular sample can be used to determine the distribution of the strain throughout the sample [3]. This technique is very useful in analyzing stresses in models of engineering structures such as bridges. In our case, coloured fringes and streaks occur near tears and creases in the cellophane because of marked variations produced in its birefringence.

We have found it very useful when investigating a new type of cellophane to determine initially the range of colours it will produce. This can be done by laying progressively narrower pieces of cellophane on top of each other to form a series of steps, displaying an increase in thickness from one to seven layers. When the series is viewed between crossed polarisers, the range of colours is displayed (Fig. 6 and Fig. 7, cf. colour plate). If one polariser or the cellophane tape is then rotated, the colour variations described above may be observed.

We have made calculations that enable one to predict colours obtainable with various thicknesses of a layer of cellophane [7]. We have found that we would be able to produce colours of still other hues and colours of considerably higher saturation if we

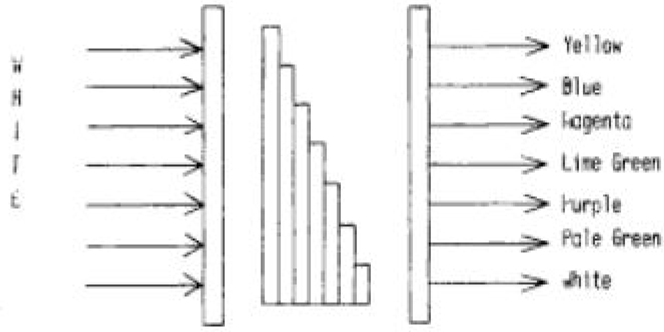

Fig. 6. Range of colours produced by one to seven layers of cellophane between crossed polarisers. (Cf. Fig. 7, colour plate).

employed certain intermediate thicknesses of cellophane. We also found that cellophane tape from different rolls, even of a given brand, showed considerable variations in thickness. Hence the colour produced by a certain number of layers varies from roll to roll.

In our tests we employed a Philips Colour Match 55 lamp as a 'white' light source. If one used, for example, different types of fluorescent lamps, different hues and perhaps certain hues in higher saturations could be obtained.

Artists should note that the polariser-cellophane-sandwich could be employed in conjunction with colour filters. Or, equally, coloured cellophane could be employed. But in either case the brightness of the transmitted light would be diminished.

Cellophane tape and cellophane sheet are cellulosic products that cannot be regarded as permanent art materials. Ways may be found to use them, however, that will assure a satisfactory life. In any case, what we have demonstrated with cellophane may possibly be produced with other stretched transparent polymeric materials of better durability.

We, as physicists, have been fascinated by the variety of colour produced simply by rotating the cellophane between crossed polarisers. We hope this article will be useful to visual artists who already have applied or wish to apply the phenomenon.

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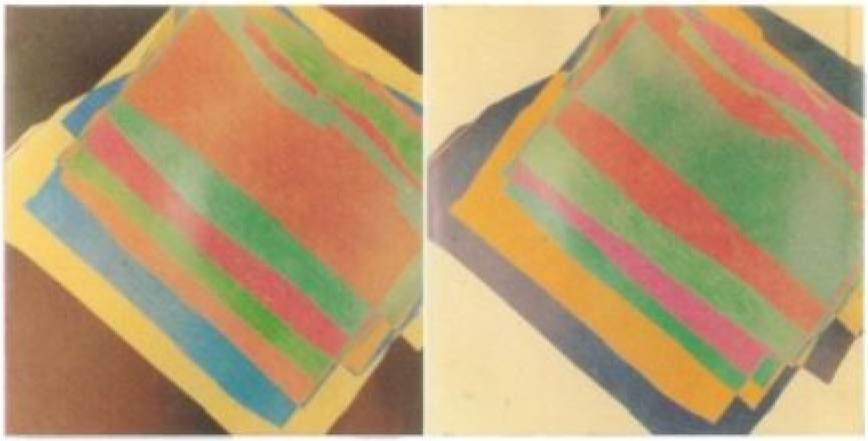

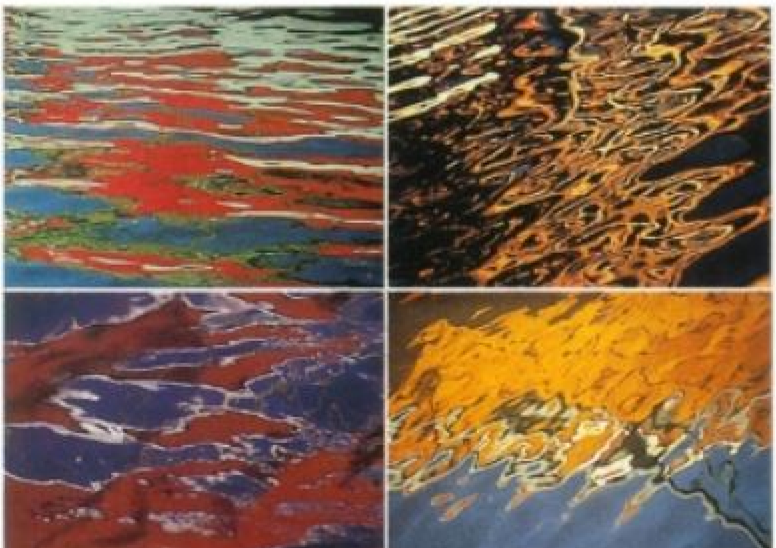

Top left: *Dmitry Mitrokhin. 'Glass', pencil and watercolour on paper*, 18 × 12.5cm, 1972. (Fig. 3, cf. page 225)

Top right: *Nicholas Orsini. 'Fossil Garden', oils, oil pastels on canvas*, 150× 108cm, 1977. (Fig. 8, cf. page 180)

Center: *S. J. Edwards and A. J. Langley, Colours produced by one to seven layers of cellophane (left) between crossed polarisers and (right) between parallel polarisers.* (Fig. 7, cf. page 190)

Bottom left: *K. Wejchert. 'Water Portraits' with colour-patch characteristics without distinct shapes, colour slides.* Location (clockwise from top left): Copenhagen, Denmark; New York City, U.S.A.; Lulea, Sweden; Sidi-Farush, Algeria. (Fig. 4, cf. page 217)

Bottom right: *Jean-Louis Viora. 'Kinetic Sculpture, No. 61', mobile, iron wire with plastic sheath* (diam. 2.7cm), *cotton thread* (0.25g/m), 50 × 45 × 45cm, 1980. (Fig. 1, cf. page 213)