Maxwell's Color Photograph

A hundred years ago the great physicist projected a photograph in full color. How this was done has been something of a puzzle. The mystery has now been cleared up by repeating his experiment

by Ralph M. Evans

In 1861 the great British physicist James Clerk Maxwell exhibited the world's first trichromatic color photograph during a lecture before the Royal Institution in London. Using separate projectors, he superposed three images produced by photographing a colored ribbon separately through red, green and blue filters. Each image was projected in the color in which it had been photographed. It appears that Maxwell invoked photography to demonstrate that a full spectrum of colors could be produced by using light of just three colors, which would support the trichromatic theory of color vision put forward by Thomas Young around 1800. It also seems he wished to prove that the appropriate colors for such a demonstration were red, blue and green, not red, blue and yellow (as a number of investigators then believed). Maxwell suggested that the images on his photographs represented "the red, the green, and the blue parts [of the colored ribbon] separately, as they would be seen by each of Young's three sets of nerves separately."

There is one puzzling thing about Maxwell's demonstration: it should not have worked. It is quite certain that the photographic emulsions available to Maxwell in 1861 were sensitive only to the extreme blue end of the spectrum and not sensitive at all to spectral green, yellow and red. How, then, did Maxwell get the "green" and "red" separation images (actually black and white positive transparencies) to put in his "green" and "red" projectors?

There is no doubt that Maxwell's demonstration was successful enough to delight and impress his audience. Maxwell's own account, confirmed by others, is that "when these [projected separation positives] were superposed, a coloured image was seen, which, if the red and green images had been as fully photographed as the blue, would have been a truly-coloured image of the ribbon." Thereby Maxwell acknowledged some deficiency in the red and green images, but a later generation of photographic experts was left mystified as to how he could obtain any red and green images at all. Recently my associates and I at the Color Technology Division of Eastman Kodak reproduced Maxwell's experiment according to the records of the day, and we believe we can account for the images that, in principle, it should not have been possible to make.

The photographic details of the experiment were recorded not by Maxwell but by Thomas Sutton, a teacher and lecturer on photography to whom Maxwell turned for technical assistance in preparing the lecture. During his career Sutton was, for a period, editor of a lively publication called *Photographic Notes,* and he later designed a wide-angle lens that was remarkable for its time.

Sutton's subject was "a bow made of ribbon, striped with various colours," which he placed on a background of black velvet and photographed in bright sunlight. The photographic emulsion used by Sutton was wet collodion incorporating silver iodide as the sensitive material. Silver iodide is sensitive only to radiation having a wavelength shorter than about 430 millimicrons, a wavelength that lies in the extreme blue region of the visible spectrum. The normal eye is sensitive to radiation lying between 400 and 700 millimicrons. The color (more properly the hue) we recognize as green lies roughly between 480 and 560 millimicrons, yellow between 560 and 590, orange between 590 and 630, and red beyond 630. To all these wavelengths silver iodide is insensitive.

For red, green and blue filters Sutton used glass cells filled with colored solutions of metallic salts; for a yellow filter he used a piece of "lemon-coloured glass." We cannot identify the yellow glass, but its exact nature is not crucial to the experiment. Sutton's own description of his filters and exposures is as follows:

"1st. A plate-glass bath, containing the ammoniacal sulphate of copper which chemists use for the blue solution in the bottles in their windows, was first placed immediately in front of the lens. With an exposure of six seconds a perfect negative was obtained. This exposure was about double that required when the coloured solution was removed.

"2nd. A similar bath was used, containing a green solution of chloride of copper. With an exposure of twelve *minutes* not the slightest trace of a negative was obtained, although the image was clearly visible upon the ground glass. It was therefore found advisable to dilute the solution considerably; and by doing this, and making the green tinge of the water *very* much paler, a tolerable negative was eventually obtained in twelve minutes.

"3rd. A sheet of lemon-coloured glass was next placed in front of the lens, and a good negative obtained with an exposure of two minutes.

"4th. A plate-glass bath, similar to the others, and containing a strong red solution of sulphocyanide of iron was next used, and a good negative obtained with an exposure of eight minutes.

"The thickness of fluid through which the light had to pass was about three-quarters of an inch.

"The negatives taken in the manner described were printed by the Tannin process upon glass, and exhibited as transparencies. The picture taken

FIRST THREE-COLOR PHOTOGRAPH was exhibited in 1861 by James Clerk Maxwell. He projected in register through separate red, green and blue filters black and white transparencies that had been made by photographing a ribbon through filters of the same three colors. This reproduction was made by the author on Ektacolor Print Film from copies of Maxwell's original transparencies.

MAXWELL'S SEPARATION POSITIVES look like this when printed in blue, green and red ink to simulate light of the color in which they were originally projected. The photographs were made at Maxwell's request by Thomas Sutton, a writer and lecturer on photography. For filters Sutton used solutions of metallic salts: ammoniated cupric sulfate for blue, cupric chloride for green and ferric thiocyanate for red (*see bottom illustration on next page*). Unbeknown to Sutton, his photographic emulsion was insensitive to green and red light. How he was able, nevertheless, to obtain "green" and "red" separation negatives is explained in the text.

MAXWELL TYPE OF COLOR PHOTOGRAPH was made by the author with interference filters to simulate the liquid filters used by Sutton. The author's film, like Sutton's, was sensitive only to the extreme blue end of the spectrum. The black and white separation negatives obtained with this film were printed, through color filters, on Ektacolor Print Film.

SUTTON'S FILTERS were solutions of metallic salts in glass cells. For blue he used ammoniated cupric sulfate *(far left)*, for red, ferric thiocyanate *(second from left)*, and for green, cupric chloride *(remaining samples)*. The solutions in the cells represent the concentrations used by Sutton. The two flasks show how cupric chloride shifts to bluish-green on dilution. For transmission characteristics of Sutton's filters see top illustration on page 122.

through the red medium was at the lecture illuminated by red light, that through the blue medium by blue light, that through the yellow medium by yellow light, and that through the green medium by green light; and when these different coloured images were superposed upon the screen a sort of photograph of the striped ribbon was produced in the natural colours."

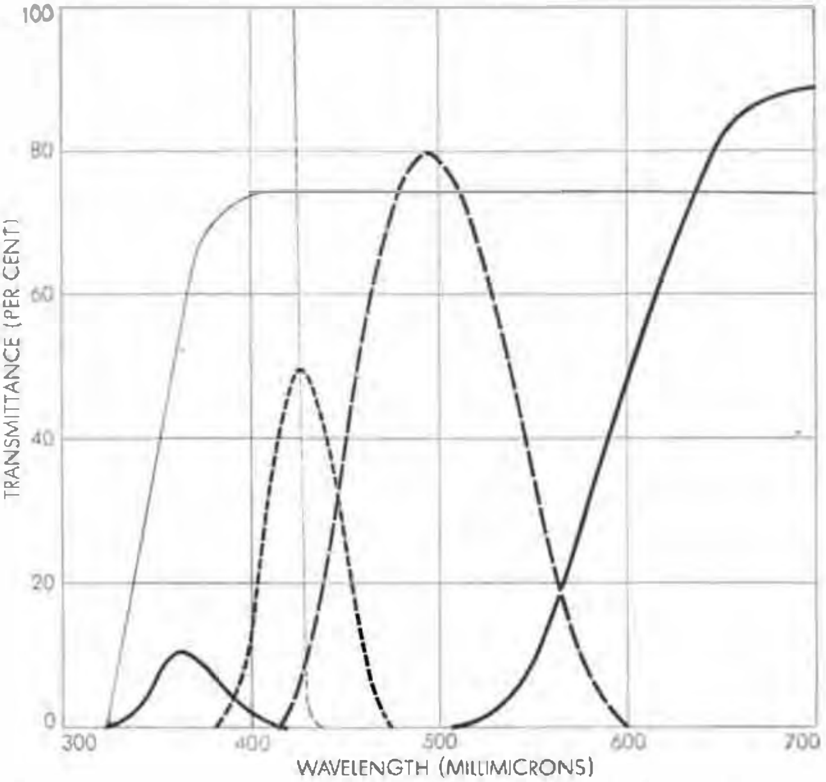
In spite of Sutton's statement it is quite clear from other sources that the positive from the yellow filter was *not* used by Maxwell at his lecture. In fact, in a separate demonstration he used colored lights to show how red and green combine to create yellow.

In 1940 Douglas A. Spencer of Kodak Limited reported that the original positives used by Maxwell were still in existence at the Cavendish Laboratory of the University of Cambridge. Spencer borrowed these positives and published a color reproduction showing how the projected picture might have appeared to those attending Maxwell's lecture. In this reproduction one can see reds, greens, blues and purples, and the background is distinctly green.

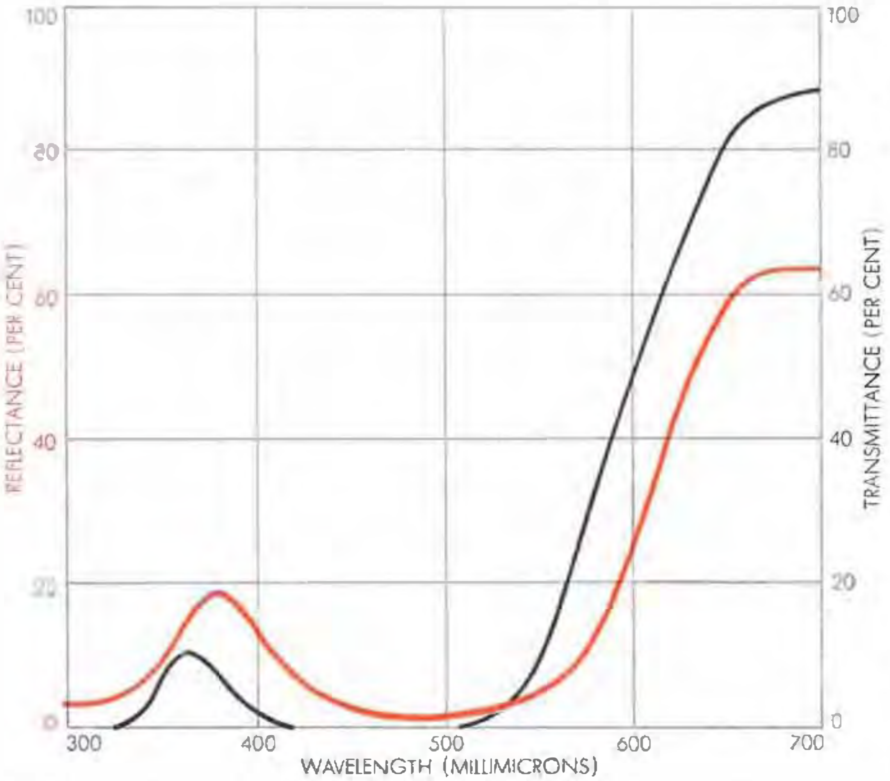
In pursuing the problem we were able to obtain another set of copy positives through the courtesy of Spencer, the Cavendish Laboratory and Kodak Limited. A new color reproduction made from these positives appears at the top of the preceding page. Considering that the original emulsions were sensitive only to blue, it is rather curious that blue does not emerge very prominently in the picture. Since the original colors of the ribbon are unknown one cannot say whether the low content of blue is an artifact or not.

It seemed that the best way to solve the mystery of the red and green images would be to attempt to repeat Sutton's procedure. To do this it was desirable (though not essential) to have a photographic material with the same sensitivity as that used by Sutton. A material with a sensitivity cutoff at about 430 millimicrons was specially made for the experiment by my colleague Burt H. Carroll of the Kodak Research Laboratories.

The new emulsion was of course much "faster" than that used by Sutton, but this presented no difficulty. The problem was to re-create, in proper strength, the chemical solutions that Sutton had used as filters. His account does not describe their concentration. Nevertheless, he provided the one essential clue needed when he stated that with the blue



SPECTRAL SENSITIVITY of Sutton's photographic plates was limited entirely to wavelengths below 430 millimicrons. The shaded area, defined in part by the transmissivity of the lens, shows the wavelengths that could affect Sutton's plates. His filters passed varying amounts of these wavelengths ranging from ultraviolet to blue.



SPECTRAL ANALYSIS OF RED CLOTH used in the still life on page 120 shows that it reflects a sizable amount of ultraviolet light at around 380 millimicrons. It was presumably light of this wavelength, not red light, that Sutton recorded through his red filter.

liquid filter the exposure was twice what it was without any filter: six seconds compared with three seconds.

Accordingly we made up solutions of different concentrations, using the same metallic salts that Sutton had used, until our exposures for red, green and blue were in the same ratio as Sutton's exposures. To produce the "blue" image the concentration of ammoniated cupric sulfate ("ammoniacal sulphate of copper") was adjusted until a picture taken through a three-quarter-inch cell of the solution produced a "perfect" negative when the exposure was twice what it was when no filter was used. To produce the green image the concentration of cupric chloride was decreased until a "tolerable negative was eventually obtained" at an exposure 120 times that with the blue filter. The dilution was so great that the solution no longer looked deep green but was bluish-green. Chemists have long known that the color of cupric chloride changes in this way as the solution is diluted. Finally we prepared a red filter from ferric thiocyanate ("sulphocyanide of iron") that produced a "good negative" with an exposure 80 times that with the blue filter.

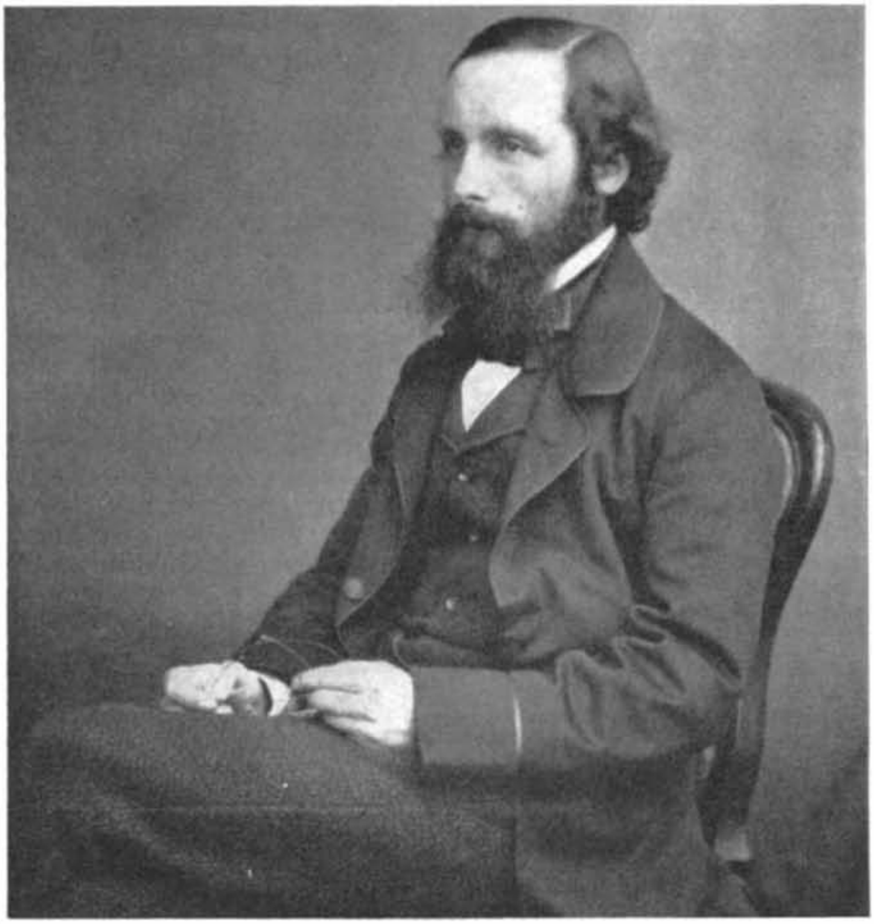
When we used these filters to photograph a still life containing a variety of colored fabrics and projected the individual black-and-white positive transparencies through colored filters, as Maxwell did, the resulting picture was a surprisingly colorful reproduction of the original scene. It is true that some of the hues were considerably shifted in quality; nevertheless, we were able to obtain blues, greens, yellows, reds and purples. If desired, the separation negatives (or positives) can be printed on standard color film to create a color transparency. Such a transparency is reproduced at the top of page 120. In this case the separation negatives were made with interference filters that simulated the effect of Sutton's liquid filters.

Now for the explanation. It is clear that our film, like Sutton's, was sensitive only to extreme blue and ultraviolet. The fact that images were obtained not only with the blue filter but also with the green and red filters indicates that all the solutions transmitted light of wavelengths shorter than 430 millimicrons. In other words, the only radiation acting on the emulsion was light in the extreme blue end of the visible spectrum and still shorter wavelengths of invisible radiation extending into the ultraviolet. Our lens, which was much like Sutton's, transmitted ultraviolet out to about 325 millimicrons. The wavelengths transmitted by the lens and the three solutions, as diluted, are shown in the spectrophotometric curves at the top of page 122.

It is at once apparent that the three filters rather neatly divide the blue and ultraviolet regions of the spectrum into three distinct bands, although the green is contained within the blue. Quite by chance the filters Sutton selected to divide the visible spectrum act also as separation filters for a relatively narrow wedge of short-wavelength light. It must be remembered in looking at these curves that the green exposure was 120 times and the red 80 times the blue exposure. The curves have not been multiplied by these factors.

One can now see how blues can be separated from other colors and how a good green could be separated from blue. But offhand it would seem that anything colored red would not register at all. As it happens, many red dyes reflect not only the wavelength we see as red but also a good deal of ultraviolet light [*see bottom illustration on page 122*]. As a result a red object can produce a strong image on the "red" plate not because it is red but because it is more ultraviolet than objects that to our eyes look blue and green. We do not know, of course, what red dyes were actually used in the ribbon photographed by Sutton. Moreover, there is no record of the actual colors of the original ribbon; hence we cannot be sure that the areas of the ribbon that registered most strongly on Sutton's red plate were actually red and not some other color with a high reflectivity in the ultraviolet. It seems unlikely, however, that Maxwell would have shown the photograph if the reds had not been in the right place. If so, they were created by an ultraviolet-red dye in the ribbon—a happy accident that neither Maxwell nor Sutton could have foreseen.

One can conclude from an examination of Maxwell's positives that a number of other forces were at work to add color to his projected picture, in addition to the fact that the filters achieved a separation in wavelength. In the first place the "tolerable" green negative was badly underexposed. In the second place the range of contrast in the three negatives is quite different. The



JAMES CLERK MAXWELL, who lived from 1831 to 1879, was the leading color authority of his day. In his lecture before the Royal Institution in 1861 he invoked photography to support the trichromatic theory of color vision proposed by Thomas Young around 1800.

net effect of these technical shortcomings would be to add colors not actually present in the original. For example, the black velvet background may have looked green in the picture as Maxwell projected it.

Moreover, Maxwell's positives, still at the Cavendish Laboratory, are quite yellow. If they were yellow at the time of the 1861 lecture, a still further variation of contrast—and hence of color—would have been introduced. We cannot be certain of the light sources in Maxwell's "magic lanterns," but the typical magic lantern of the day was the famous limelight, in which a block of calcium carbonate was heated to incandescence by an oxyhydrogen flame. Being very hot, such lights are much bluer than the incandescent lamps used today in home projectors. It is also possible that Maxwell's projectors contained electric carbon arcs, which would have produced a light even hotter and bluer than limelight. In either case the yellow color of the positives would have made the picture that was projected through the blue filter much more contrasty than the one projected through the red. The one projected through the green filter would have been of intermediate contrast.

The effects obtained were not all due to contrast and density mismatches, however. The existence of true color separation among the red, green and blue pictures can be demonstrated by superposing the negative of one image, say the red one, over the green or blue positive. If one uses negatives of various contrasts, it should be possible to "blank out" a positive if negative and positive are really alike. But no combination of negatives made from the Maxwell positives will result in such blanking out. There is less separation between the green and blue than between the blue and red, as we would expect. Somewhat ironically, considering Maxwell's main thesis, the yellow-filter negative was essentially the same as the green, and probably could have been substituted for it with little change in the result.

Although our interpretation of Maxwell's experiment seemed plausible, a lingering doubt remained. Was it possible that Sutton's collodion plates might have had some trace of red and green sensitivity? It is now known that under certain unusual circumstances such sensitivities can occur even without using sensitizing dyes, which were not discovered until 1874.

These doubts were happily dispelled by a discovery we made one day when we were studying the copies of the Maxwell transparencies. In making the photograph Sutton had used "a portrait lens of full aperture." This could only have been a Petzval lens, and this lens did not cover the plate used; that is, the image formed was confined to a circle of somewhat smaller area than the plate. We noticed that the diameters of these circles were not all equal. The blue positive had the smallest diameter, the green a larger diameter and the red the largest. It was apparent that Sutton had refocused for each color of light and that for red light the lens had been farthest from the plate.

This immediately explained something else that had been rather baffling: the red image was by far the least sharp of the three images. Sutton had focused his camera for visual red light but had photographed by invisible ultraviolet.

The pieces of the puzzle thus all fit together nicely. But we are still left mystified on a crucial point. It seems strange that Maxwell, one of the leading authorities on color of his day, could have been unaware of the fact that wet collodion plates were not sensitive to green and red. Yet we are forced to believe that this is so. He would hardly have suggested the demonstration had he known it. And Sutton certainly did not know of the lack of sensitivity to green. In fact, he considered this an important discovery growing out of the experiment. He wrote: "We now see why it is so difficult to reproduce by photography the details of green objects in shadow.... The photographer who turns his camera towards a view in which the foliage is not well lighted, must not therefore be disappointed if, instead of masses of fine detail, he discovers in his negative hideous patches of clear glass."

Collodion emulsions had been discovered only 10 or 12 years earlier and were so much more sensitive than any previous photographic materials that perhaps it was assumed they had *some* sensitivity to all wavelengths even though obviously much less for the long wavelengths than for the short. Spectrophotometry was certainly not developed to the point where Maxwell and Sutton could possibly have guessed the true explanation of their results.

Be that as it may, the principle devised by Maxwell and put into practice by Sutton was a valid one for producing a color photograph. And because of the fortuitous circumstances we have described, the experiment worked, allowing Maxwell to invent three-color photography almost 15 years before there were sensitizing dyes that would have made his experiment "possible."