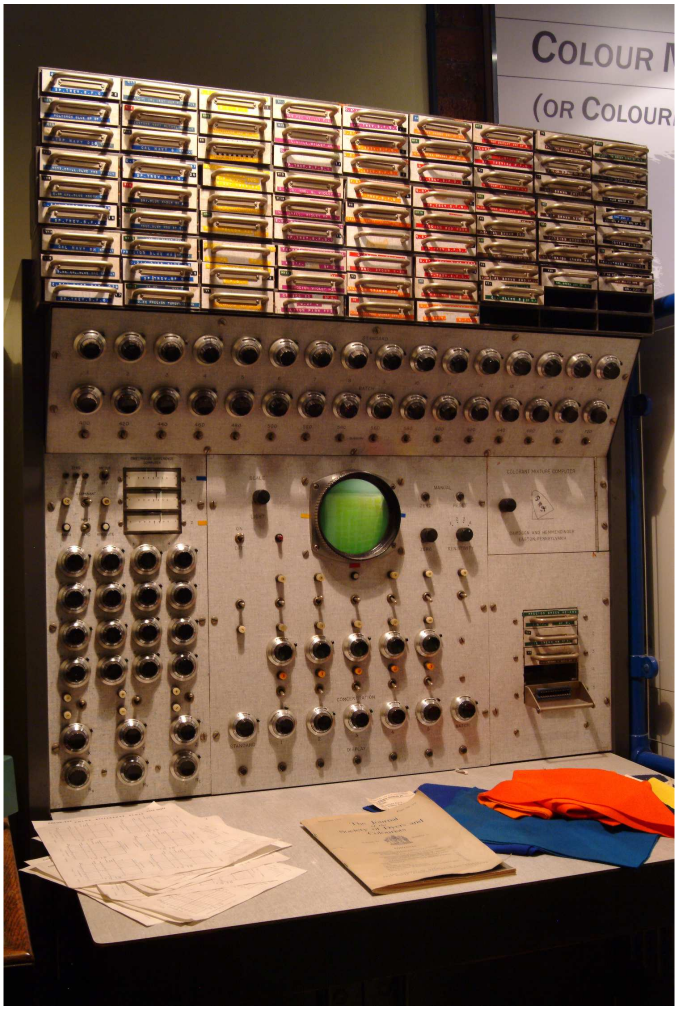

Image courtesy of the Society of Dyers and Colourists

COMIC: An Analog Computer in the Colorant Industry

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1. Introduction

In the early 1960s, Davidson and Hemmendinger, Inc (D&H), a small company that specialized in precise color measurement and specification, became the leading manufacturer of computers to calculate how to mix pigments or dyes to match a given sample. Its analog COMIC [COlorant MIxture Computer], had a major role in introducing and promoting the automation of this process, which had depended on visual matching until then. Although by the end of the 1960s this analog computer had been supplanted by digital computing, it is regarded as having been a breakthrough when it appeared.[1]

This article describes the color-matching problem and the theory behind computational solutions to it. It discusses the operation of the COMIC, its limitations, and its industrial use. It goes on to describe several related special-purpose computers, and the industry transition to digital computation. It concludes by reflecting on the relationship between analog and digital approaches to the problem and on the influence of the COMIC.

1.1. Color matching

Almost all production of consumer goods requires some kind of color matching. Successive runs of a fabric need to be dyed the same color. If a new batch of paint for red spice tins is slightly paler than the previous one, the tins may look faded and appear old when they are not. Many goods have parts made of different materials that must match — clothing outfits, metal appliances with plastic handles, or automobiles with matching paints, plastics, and fabric.

Finding a mixture of pigments or fabric dyes that match a color sample is a more complex problem than matching with a mixture of colored lights. According to a 1953 text, it is "[p]robably industry’s number-one color problem" [28, p. 338]. The book comments that if lights rather than pigments are mixed, the problem is simple, and that color television produces solutions "at the rate of more than a million a second."

A second problem is that when two different sets of colorants are used to produce a match in one light, such as daylight, it may not be a match in incandescent or fluorescent light. Such conditional matches, called *metameric*, can be a major problem when different kinds of materials — cotton and wool, or paint and plastic — are to have the same color, because they require different colorants for chemical reasons. Metamerism (having metameric matches) is also a problem with a single illuminant because people, even with normal color vision, may perceive color matches differently.

When the colorants of an object are the same as those of the sample to be matched, the problem is easier though not trivial. Even when a recipe gives the proportions of fabric dyes that produced the sample, it is likely to need adjustment when used again, given imperfect control of dye strength and dyeing conditions. When a match is metameric due to using different colorants for sample and object to be matched, there may be several choices of colorant combinations for the object, with differing degrees of metamerism.

The COMIC was designed by D&H in 1958 to help to solve these two problems [16]. During the 1960s, about 200 COMICs were sold in the USA, Europe, Japan, and South Africa. According to a 1975 survey of computer colorant formulation, it "heralded the start of widespread industrial use of computer formulas" [30, p. 2]. Before the COMIC and then digital computer programs for color matching appeared in the 1960s, finding and evaluating a color match depended on the skill of an expert colorist. Even with experience, the process would require multiple test

[1] The H of D&H was the author’s father. The information about the COMIC in this paper comes from several sources: technical journals, trade magazines, D&H publications, including a COMIC manual, and an interview with Ralph Stanziola, a COMIC salesman who went on to co-found Applied Color Systems, now Datacolor, a leading source of computer programs for color matching.

dyeings or paintings, with adjustments after each. Computer color matching didn't eliminate the need for several trials, but it reduced their number. In addition, visual color matching cannot evaluate metamerism since that depends on knowledge of spectral reflectances, which the eye does not perceive directly.

1.2. Analog computing

In a retrospective talk, E. I. Stearns of American Cyanamid reported that in 1959 he asked IBM if his company's computer was adequate to solve the color matching equations and was told that it was not [43, p. 47]. He didn't specify their computer model, and it isn't clear why their computer wasn't adequate. The computational problem is not very complex, and the data storage not large, so the major impediment may have been the cost of the time required to compute a large number of colorant combinations.

This account is thus not only a story about the introduction of automation in the colorant industry, but is also about the coexistence of analog and digital computation through the 1960s. General histories of computing such as those by Ceruzzi [14] and Aspray and Campbell-Kelly [5] have little if anything on analog computation. Bromley discusses it in a chapter in [11], and [12], [34], and [41] are three recent books on the subject. These works devote most of their attention to modeling and to control systems like gun directors and particularly, the differential analyzer that used integrators and feedback to solve differential equations.

Other analog computers used in industry solved simultaneous linear equations (like two of the earliest digital computers, Zuse's Z3 and Atanasoff and Berry's ABC). They were relatively simple, generally using resistive networks without time-dependent elements like those in alternating-current network analyzers. The COMIC was one such computer, which solved equations under operator control. There were several other computers that used similar techniques, built between 1933 and the mid-1960s. One by Rawlyn Mallock [31] set up equation coefficients on tapped transformers and was used at the University of Cambridge in the mid-1930s. Another was built in the mid-1940s by Clifford Berry [7] for use with a mass spectrometer in the petroleum industry [10]. This class of computer has received little attention in histories of analog computing (one exception is a paper by H. Petzold [37]). Bromley mentions Mallock in passing but refers to other such computing systems as "ad hoc", though a better term, borrowed from programming languages, would be "domain-specific".

A 1963 paper on an analog computer for simultaneous equations observes that the mass spectroscopy problem for which it was to be used required testing alternate choices, which "conflicts with the typical full schedule of a well-run digital computer" [39]. Care discusses the role of analog computers in experimental interaction, "where the human investigator was actively involved in the computation process" [12, p. 5]. This advantage of interactive analog computers such as the COMIC persisted until small digital computers like the IBM 1130 and minicomputers became available for dedicated use in the late 1960s.

Color theory [sidebar material]

A color can be specified with three numbers and so colors can be represented as points in a three-dimensional space. In 1931 the CIE (Commission Internationale de l'Éclairage) defined a standard color space; its coordinates, X,Y,Z are abstractions of real primaries such as red, green, and blue. The XYZ coordinates of a color are called its *tristimulus values* or coordinates. The description of colors in terms of tristimulus values or equivalents is *colorimetry*.

Colored lights combine additively, and the XYZ coordinates of a mixture are the sums of the X,Y, and Z values of the components. A mixture of three lights is characterized by the equation

(1) $$X_{mix} = c_1X_1 + c_2X_2 + c_3X_3$$

for quantity c_i of component i, with similar equations in Y and Z.

A simple form of subtractive color mixing occurs when white light passes through successive color filters, as is done in color photography. Its complete analysis requires spectral information — the fraction of light at each wavelength of the visible spectrum that is transmitted by the filter — and not just XYZ coordinates. Its "laws" are approximations that may fail. Blue and green filters generally combine to yield blue-green, but can yield dark red if each transmits some red light and there is little overlap between their transmissions of blue and green.

The complete analysis of subtractive mixing thus needs information about the fraction of light transmitted by a filter or reflected by a colored surface, as a function of wavelength. This information is obtained by means of a spectrophotometer, which measures the transmission or reflectance as it scans through the visible spectrum. The more sophisticated versions plot a curve of transmission as a function of wavelength of light, while simpler ones just give the values at discrete intervals of wavelength, say every 20 nanometers (nm) from 400nm (blue) to 700nm (red). Given this spectral information, the CIE XYZ coordinates may be calculated with formulas that the CIE established.

Mixing paints or dyeing white fibers is subtractive mixing, but is more complicated than combining colored filters. The color arises from a combination of absorption by pigment particles or the dye, and scattering of light both by those particles and by the substrate such as fibers or paper to which they are applied. The physics is quite complicated; the basic theory was developed in 1931 by Kubelka and Munk, but revisions are still discussed. A formula of Kubelka-Munk theory, used in the computers that we'll discuss, is for a colorant layer thick enough that no light passes through it. At a single wavelength of light, it is

$$K/S = \frac{(1-R)^2}{2R} \qquad \text{for} \qquad \begin{matrix}\text{absorption} & K \\ \text{scattering} & S \\ \text{reflectance} & R\end{matrix}$$

A reason for using K and S to characterize colorant mixtures is that they are linear functions of colorant concentration and are additive. That is, for colorants 1. . 3 with concentrations $c_1 . . c_3$, and the white substrate or pigment as the fourth component, we have

(2) $$(K/S)_{mix} = \frac{c_1K_1 + c_2K_2 + c_3K_3 + K_w}{c_1S_1 + c_2S_2 + c_3S_3 + S_w} .$$

If nearly all of the scattering is due to the white substrate, as it is in many dyed fabrics, or is due to the white pigment, as it is in pastel paints, then this expression can be simplified to use the scattering of only the substrate or white pigment. The result is a linear equation in K/S values, or more precisely, a set of similar linear equations for the K/S values at multiple wavelengths:

(3) $$\left(\frac{K}{S}\right)_{mix} = c_1\frac{K_1}{S_w} + c_2\frac{K_2}{S_w} + c_3\frac{K_3}{S_w} + \frac{K_w}{S_w} .$$

2. Color matching equations

To describe what the COMIC and some early digital color-formulation programs did, we need a very brief discussion of color theory, with more detail in the sidebar. The sidebar gives linear equations that describe the color of a mixture of lights or colorants in terms of the colors of the components. Solving the inverse problem — finding the amounts of three lights or colorants that will match a given color — can be done by solving a set of simultaneous linear equations. For additive mixing, these are equation (1) of the sidebar and analogous ones in Y and Z, with the XYZ tristimulus coordinates of the three lights as constants and the c_i quantities as variables. This problem is computationally simple, whether expressed in terms of XYZ coordinates or in terms of actual red, green, and blue lights.

For colorant mixtures, the appropriate linear equation is Equation (2) of the sidebar, which expresses the K/S ratio of pigment absorption to scattering by the substrate of the mixture at one wavelength in terms of the concentrations of three component colorants, given their K/S values. As with additive mixing, a set of such equations, for multiple wavelengths, can be solved to find the necessary concentrations. This equation that uses only K/S ratios is an approximation, however, and for most paints, particularly dark shades, the more general Equation (2) of the sidebar that sums K and S values separately (the so-called two-constant form) is more appropriate.

Colored surfaces present the additional complication of metamerism: their color results not only from their reflectance curves but also from the spectral characteristics of the illuminant, because the light reflected by a surface depends on both. Two surfaces may have the same color — have the same tristimulus values — in daylight but may be different in incandescent light, which has more red and less blue in it. (There are many different daylight spectra, and the CIE has defined several standards, such as D65, derived from average north sky light.) Figure 1 shows reflectance curves of two colors that may match in standard daylight but not in red-rich incandescent light since one reflects much more red than the other.

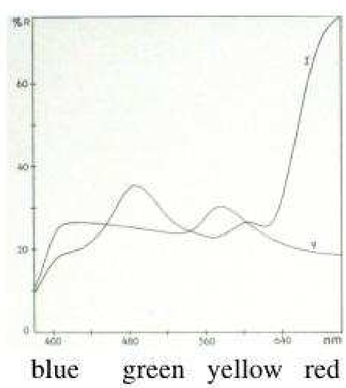


Figure 1 Reflectance curves of a metameric match of two colors

To summarize: tristimulus colorimetry is sufficient in dealing with mixtures of lights. The color of a mixture of pigments or dyes on a substrate depends on the spectral reflectance curves of the components, and also on the spectral curve of their illuminant. Given all of that information, the XYZ values of the mixture may be calculated and two mixtures with the same XYZ values will match in that illuminant, but they will not have the same XYZ values in a different illuminant unless their spectral reflectances are identical. Spectrophotometry as well as colorimetry is needed to solve the practical problem: to find a mixture of colorants to match a sample, and to find those colorants that do so without significant metamerism.

3. Early computational approaches

When the basic theory of colorant mixing was worked out in the 1930s, industrial practice depended on the experience of skilled colorists and a certain amount of trial-and-error. With that theory, it was possible in principle to solve the problem: given a reflectance curve of a color to be matched by a mixture of several colorants, find the proportion of each one needed, more efficiently than by trial-and-error.

One graphical technique that was introduced in 1938 [38] and refined in various forms for the next two decades depended on graphs of the logarithm of (K/S) vs wavelength. The advantage of this function is that the graphs of different concentrations of a colorant have approximately the same shape and differ just in their vertical displacements (for concentration c, $\log(c(K/S)) = \log(K/S) + \log(c)$). Such graphs thus give the "fingerprint" of a colorant, and they also lend themselves to nomography. One nomographic technique used a special cam for the industry-standard General Electric (GE) recording spectrophotometer [21] that plotted log(K/S) against wavelength, rather than the usual plot of reflectance R. The method used special graph paper with a non-linear scale and a ruler with a logarithmic scale. In a somewhat complicated procedure these could be used to find the approximate amounts of three dyes to match a sample. It worked if the dyes were similar to the ones used in the sample, so that the match would be nearly exact (non-metameric) [19].

A 1955 paper on an instrumental approach to color matching [6] describes a simple analog device for a related method (Figure 2). It had three wires, each bent in the shape of the graph of a function that was similar to the $K/S = (1 - R)^2/2R$ function for one of three dyes. They were mounted on pivots between a screen and a lamp with a lens to collimate its beam. The screen had a suitably calibrated grid on it, and the pivoted wires could be rotated by three knobs to raise or lower them so that they cast their shadows on the screen. The curve of the sample to be matched was traced on the screen and the knobs were rotated so that the sums of the ordinates of the three wire-shadows matched the sample — the addition still had to be done manually. The concentrations of the three dyes could then be read from scales for the knobs. The paper reports good results in matching several samples that used the same three dyes. It is not clear whether multiple instruments were built to work with different dyes, or indeed, if the device was actually used beyond demonstrations.

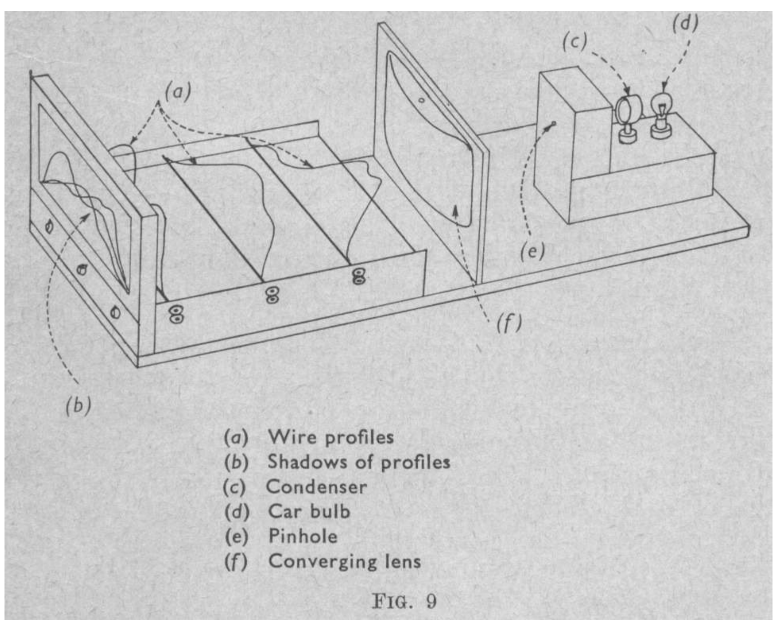


Figure 2: Analog device for color matching, from [6].
(From the *Journal of the Society of Dyers and Colourists*, published by the Society of Dyers and Colourists.)

This instrument is rather crude, but the author argues that greater precision in calculation would offer no benefit in view of the variability in the dyeing process, in which the effect depends on factors such as temperature, fiber properties, and the rate at which a dye bath becomes exhausted. Both nomography and his device are thus useful only for obtaining rough results, and he concludes that "It is extremely unlikely, however, that the methods discussed will ever replace the colourist" who must make the final adjustments and judge the result by eye. Within six years, the author was one of the developers of digital computer programs to automate color matching at Imperial Chemical Industries in Britain.

4. The COMIC

Hugh Davidson and Henry Hemmendinger formed the D&H company in 1952, having met in the US Navy Operations Research Group during World War II and met again, I believe by chance, when they both worked on color physics for General Aniline and Film Co. Davidson was an electrical engineer and Hemmendinger, a physicist. The D&H company provided color measurement and specification services to industry, and prepared color standards for such diverse applications as blood tests, false teeth, and peaches. In 1956, it specified the paints for the Munsell Color Atlas and produced the volume. Davidson had experience with mechanical and electrical analog computers for torpedo guidance, and in 1949, together with Lewis Imm, the Librascope Company founder, had built a mechanical analog computer that used Librascope ball-and-disc integrators to convert reflectance data from the GE recording spectrophotometer to XYZ tristimulus coordinates. He was responsible for the design of the COMIC circuits, while both partners designed its user interface.

The COMIC was announced in 1958 and put on the market in 1959. It appeared in the *Science* new-products notice in April, 1961 [45], and DuPont had an in-house publication on it late in 1961 [20]. Its prototype, built in 1957-58, used a multipole stepping switch that rotated continuously to generated a display on an Eico oscilloscope, which I recall was distinctly noisy, both aurally and electrically. The computational circuit was a resistive network that used no electronics, unlike most other analog computers for similar equations . It represented the $K/S = (1 - R)^2/2R$ values with voltages, and added voltages to represent the K/S values of mixtures of colorants. The production model, shown in Figure 3, replaced the stepper switch with digital vacuum tube circuits that generated sequences of pulses to sweep a signal across a Hewlett-Packard oscilloscope built into the computer. It sold for about $10,000 in 1960 and $18,000 a few years later, and could be leased for several hundred dollars per month.

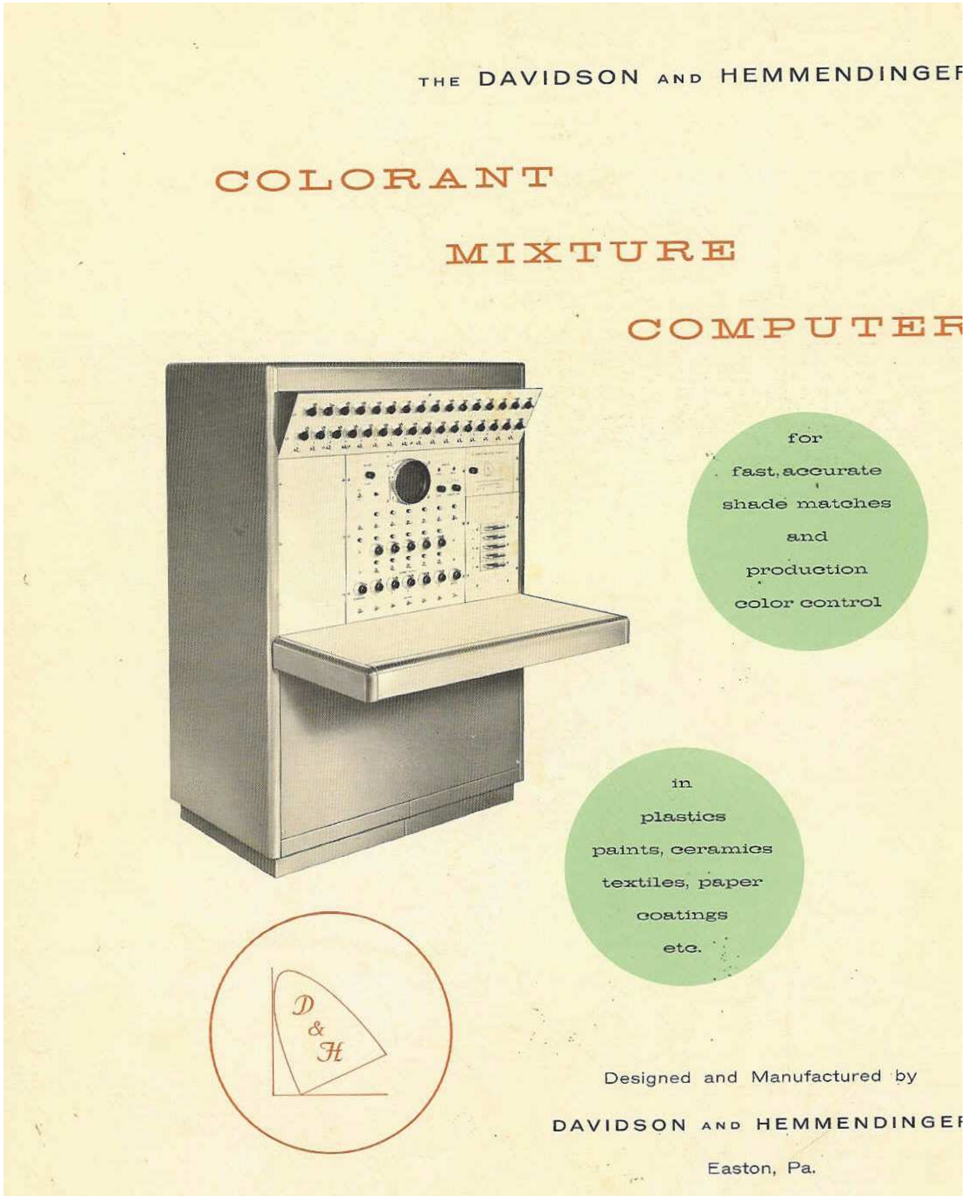


Figure 3: COMIC sales brochure

Like graphical techniques and the simple analog device just described, the COMIC solved a set of 16 linear equations, each an instance of sidebar Equation (3) for a different wavelength. The equation constants were the K/S values, generally obtained by spectrophotometric measurements of reflectance manually converted to K/S via a table, and the variables were the colorant concentrations. The inputs were 16 K/S values for a sample to be matched, set up on 10-turn potentiometers (variable resistors), and 16 K/S values for each of up to five colorants. The latter were provided in plug-in boxes that held 16 linear potentiometers, set with a screwdriver through previous reflectance measurements of the colorants. These components are shown in Figure 4.

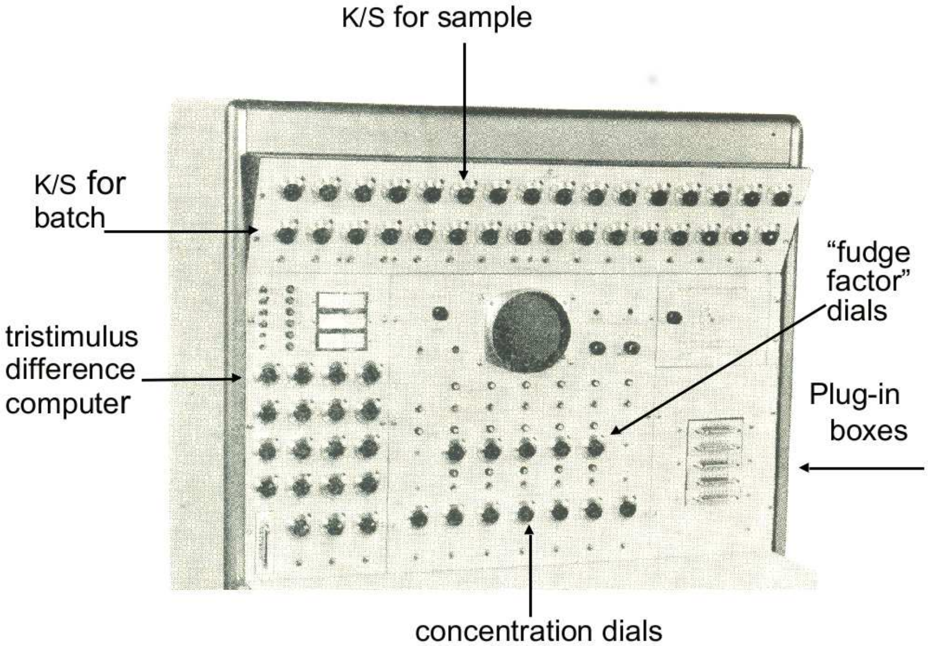


Figure 4: The COMIC panel

The scope showed the difference between the K/S absorption curve of the sample and the sum of the curves of the colorants at concentrations determined by five more potentiometers. The curve was displayed as 16 dots that represented the difference at 16 points of the spectrum — every 20 nm from 400 to 700 nm. The operator adjusted the concentration potentiometers to try to bring all of the dots down to the horizontal zero line, and if this could be done, the result was an exact spectrophotometric match: the reflectance curve of the mixture was identical to that of the sample. Figure 5 shows an example of matching a light brown (the curve of which is in Fig. 5a) with a green, red, and yellow dye. Adding green would increase absorption of red light, and hence bring down to zero the long-wavelength section of the displayed dots (5b). Adding red would then not change the absorption of red significantly, but would absorb some green, bringing the middle section of dots to the zero-line (5c), and adding yellow would absorb blue, bringing down the short-wavelength section of dots (5d), producing a correct match. If the dyer had chosen a blue instead of green to absorb red, since it would also absorb more yellow then the green dye did, the dots would not all be brought down to the zero-line, indicating a poorer choice of dyes (5e) and a possibly metameric match.

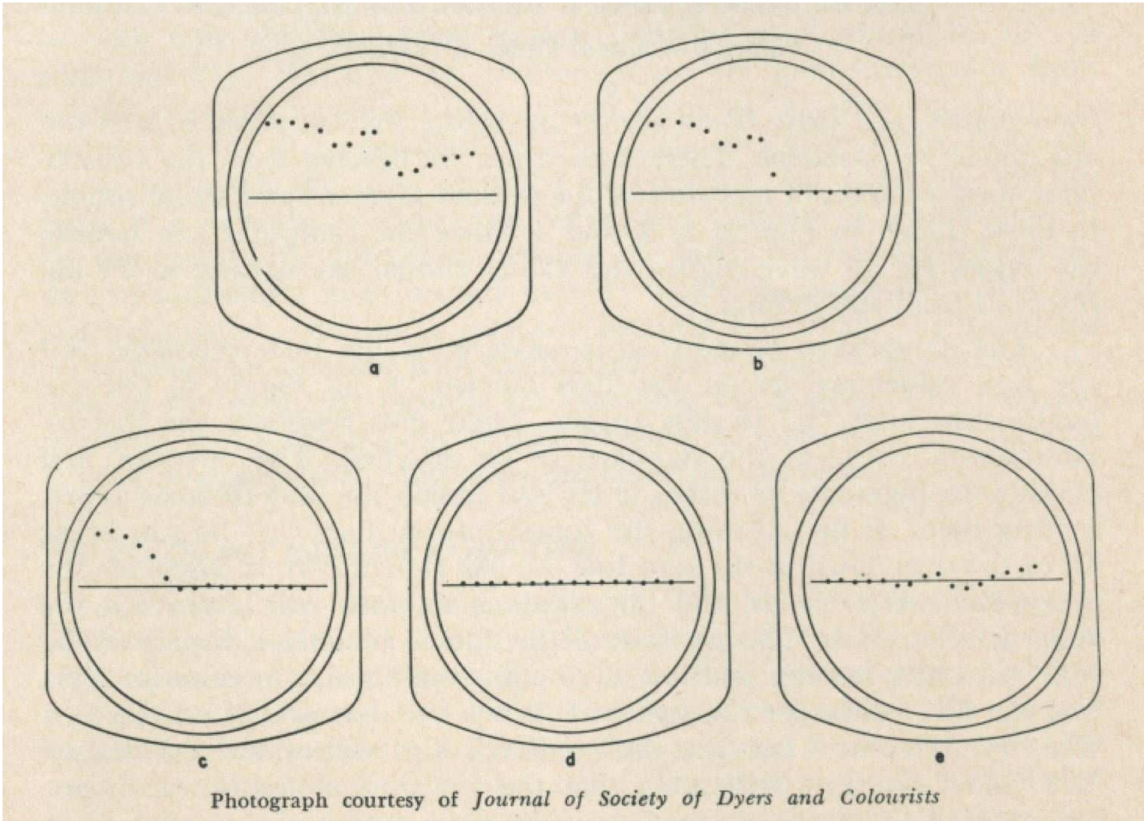


Figure 5: The COMIC display in use. The operator would adjust the concentration potentiometers to try to bring all the dots to the zero line.

The system of 16 equations in three to five unknowns was heavily over-constrained, and an exact solution would generally be possible only if the colorants were the same ones used in the sample. In effect, the operator was solving three to five equations by bringing their dots to the zero line and then seeing if the others had followed them. That could not always be done, either because the appropriate colorants were not available, or because the material to be colored required different dyes from the standard. A color standard might be a dyed cotton, to be matched by dyed wool or silk, which generally require different dyes for chemical reasons. With different choices of colorants, it would not be possible to bring all the dots down to the axis, showing that a spectrophotometric match was not possible. In that case, a colorimetric match might be possible; i.e. one that provided an exact match for a particular illuminant like standard daylight or incandescent light, but that would have some degree of metamerism — mismatch in other illuminants.

The COMIC provided an auxiliary unit, the Tristimulus Difference Computer (TDC), to find colorimetric matches. The operator had to enter another 16 values, for dR/d(K/S) (the rate of change of R with change in K/S) of the sample to be matched, as a function of R (also available from tables). Three of the concentration dials could then be adjusted until three meters displayed null values, indicating a colorimetric match, one in which tristimulus values for the mixture match those of the sample for the given illuminant. (If there were more than three colorants in the mixture, ratios would have to be fixed to provide three variables to adjust, since such a tristimulus calculation solves three linear equations in three variables.) The match would be metameric, and the TDC could be switched between two illuminants, typically daylight and tungsten light standards, to show the difference in tristimulus values in the second illuminant. If the metamerism was too great, another set of dyes could be tried by replacing the dyestuff plug-in boxes. If the mixture used the best available combination of dyes, the operator could also choose to compromise by setting the concentration dials to produce a modest mismatch in both illuminants.

The result of dyeing with the calculated mixture would generally not yield an exact match, due to the approximations of the Kubelka-Munk model and the variability of the dyeing process — temperature, preparation of the fiber, and rate of exhaustion of the dye bath. In addition, it was common in the dyeing industry to mix a dye bath with less of the dyes than would be needed, rather than risk using too much of one and having to use more of the others, an added expense. The COMIC had another set of 16 K/S inputs for (manual) process control. The K/S values of the trial dyeing would be entered on these dials, setting potentiometers whose values would be subtracted from those of the sample so that the oscilloscope display would show their difference. The concentration dials could then be adjusted to add or subtract colorants from the first trial to zero the row of dots, thereby giving a corrected second trial. Since the first calculation would have found the appropriate colorants to use for a match, however, another faster method was to enter just the three tristimulus values of the first trial into the TDC and adjust the concentration dials to produce a colorimetric match.

The COMIC provided another set of adjustments, essentially in series with the concentration dials. These were for correction factors that would be empirically determined, and were intended to be used to accommodate differences between a dye used in production and that used to calibrate its plug-in box, as well as variability due to parameters of the dyeing process such as temperature and fiber properties. In short, they offered a "fudge factor". Although intended to let the operator calibrate the computer for a particular dyeing process, these adjustment dials also helped to extend the range of applicability of the COMIC. Since the equations that the COMIC solved assumed that the colorants introduced negligible scattering, it could calculate formulations for dyeing fabric, and for light colors of plastic or pastel paints. It was not intended for matching deeper colors, but two reports found that by using the correction-factor controls to take into account deviations from linearity when higher concentrations of colorants were used, and by adopting empirical modifications of the additive K/S function to take into account surface reflections, good results could be obtained with deeper colors [8, 46].

The COMIC maintenance manual had a useful feature. In addition to a description of the computation and display circuits, it included a set of 30 drawings of the oscilloscope screen. Each showed a typical failure pattern and associated the defective visual display with the vacuum tube or other component likely to have caused that failure. The manual also provided several pages of blank oscilloscope screen drawings on which a technician could draw additional failure modes that might come up. In my experience, this is a more elaborate treatment of possible failures than most manuals provide.

4.1. Evaluation

The COMIC was generally recognized as the first practical computer for finding colorant mixtures. According to a 1964 paper on computer color matching,

> ... the first practical computer for everyday use in color formulation was the COMIC. All who are connected with textile mills must know that the introduction of a color computing device was very much of a revolutionary development. The very concepts involved in color computation were strange and unfamiliar to the dyer ... [3].

A paper on the use of the COMIC by a dyehouse subsidiary of the Monsanto Corporation reported:

> An average of eleven trial dyeings was needed before the computer system was installed, to match both a wool and an Orlon shade by eye. After three weeks work with the COMIC-TDC, the average number of trials was four for wool and three for Orlon, and later still lower [23].

Other papers from the same period and later historical reviews cite the COMIC as the first step in computer color matching and as an important influence in the use of instrumentation in the colorant industry. A review article written around 1975 refers to "Davidson and Hemmendinger's now famous Colorant Mixture Computer" [25] as the first commercial computer for the task.

A 1969 account of the use of the COMIC by yarn manufacturer Coats and Clark may be typical of many companies [32]. They had acquired a GE recording spectrophotometer, and had used graphical methods for color matching. In 1963 they acquired two COMICs, and also improved their dye standardization procedures, necessary to get good computational results. After using the COMIC for four years with "gratifying results," they switched to an IBM 1130, commenting that the COMIC was an excellent instrument but had inadequate storage; they had 80 of the COMIC dye description boxes, at a cost of $3200, but they were insufficient. The result was that having gone from an average of 5.5 dyeings with visual matching to 3.5 with the COMIC, they averaged 2.5 with the 1130, all with increased speed. The COMIC thus had a role as an intermediary to demonstrate to industry the value of computational methods, leading it to move on to more powerful tools.

To judge from its description, the COMIC must have been somewhat cumbersome to use: it required table lookups of data that had to be manually entered on dials; it required the operator to select a likely set of colorants, and when an exact match was not found by adjusting concentration dials, required more tabulated data to be entered on an auxiliary computer. It was also constrained by its use of the simplified form of the Kubelka-Munk equations that assumed that the substrate was responsible for the scattering of light, though users could sometimes extend its application beyond its intended function.

These limitations, however, also contributed to the success of COMIC. Dyers working in industry were accustomed to selecting colorants on the basis of experience and making visual assessments of trial dyeings; they generally did not think about reflectance curves. The COMIC still required them to choose colorants on the basis of experience, and it provided an easily-understood display of the effect of adding each to a mixture. The displays in Figure 5 illustrate how dye choices can either yield a good match or a poorer one, and they do this by also relating the colors to portions of the reflectance curves.

Once a trial match was made, the following steps of correcting the trial by comparing the result with the sample would also be familiar, except for the step of measuring the trial dyeing to obtain reflectances or tristimulus values. While a dyer's experience would play a role in choosing dyes and in adjusting the concentration dials to obtain a match, an inexperienced operator could achieve similar results, although less efficiently. Since the operator interacted with the COMIC directly, as with many analog computers, it had a significant educational function. An inexperienced operator could gradually acquire a sense of how color was related to the COMIC display of reflectance information, and become more proficient in making choices. According to Ralph Stanziola, one of the D&H salespeople, one of its most important effects was to get people to think about reflectance curves[2] and thus to educate dyers in the use of spectrophotometric curves and not just the three tristimulus values that specified a color. The dyer's knowledge of how to choose appropriate colorants would be extended by the ability to make the selection on the basis of properties of the reflectance curves of a sample and the dyes available.

[2] Interview, July 2006.

Among disadvantages or limitations of the COMIC were the plug-in boxes that stored colorant reflectance data. Each cost about $40, according to the Coats and Clark paper cited above, which reported a considerable investment in them. Mr. Stanziola recalls that the boxes cost $90 initially, with the price eventually falling to $20, and said that D&H tried a cheaper design that used stiff paper cutouts to set the potentiometers (reminiscent of the wires bent in the shape of the K/S curves), but they didn't work. Each box represented just one concentration of a colorant, and different concentrations could be used by setting a concentration dial on the machine.

Not everyone was enthusiastic about the COMIC. Mr. Stanziola described his visit to a textile mill whose technical director was enthusiastic about it and asked him to talk to their dyer.

> After the technical director introduced him to me, the dyer said, "Oh, this is the Yankee who came down here to tell me about a machine that will replace me." After I explained that was not the case, he said, "Come on boy — it's too noisy here to talk." He put his arm around me and directed me (not too gently) towards a gray door at one end of the dye machine area. I assumed it was his office. It wasn't. He pushed me out the door. I found myself outside at the bottom of the hill, and had to crawl on my hands and knees to get back to the parking lot and my rental car. I assumed he wasn't interested [42].

A web page describes having used the COMIC at Uniroyal and provides a photo with a label, "where you attach the anchor rope" [36].

One may ask why the COMIC didn't take reflectance values and compute the K/S values itself, freeing its operator from having to look up K/S in a table. That would have required circuits to generate the voltages representing the $(1 - R)^2/2R$ function. It could have been done, but would have made the computer more complex and probably considerably more expensive, since this non-linear function would have required vacuum-tube circuits. It might also have been done with a large function table such as ENIAC had, again, at some expense. I have not seen any discussion of this issue, but it is plausible that the COMIC designers would have judged the expense not to be worthwhile. One task they had was to persuade people unfamiliar with automated methods to try them, and fuller automation at a higher cost may well not have seemed entirely beneficial.

5. Other special-purpose computers

The COMIC designers made it clear that the merits of their machine did not depend on its analog nature, except so far as the computer had a relatively modest cost and for that price, provided sufficiently good performance that it served the needs of many dyeing and paint mills [17, p. 603.] In the mid-1960s, two special-purpose computers, the digital Pretema FR-1, made in Switzerland [40] and the digital-analog Redi-Colour, by Redifon in England [15], did essentially the same job as the COMIC, solving similar equations. Unlike the COMIC, they both took in reflectance values directly and computed K/S or a similar function. The FR-1 stored dyestuff data on magnetic tape, while the Redi-Colour used plug-in boxes like those of the COMIC. The Redifon computer, in particular, looks quite like the COMIC and its designer describes its display by contrasting it with that of the COMIC. As far as I can determine, neither became widely used. Stevenson Dyers in Derbyshire had a Redifon system, which also had a built-in spectrophotometer that provided reflectance data directly to the computer. In an interview, its operator[3] said that he didn't know how many computers were sold, as he used the first or second to be made. He reported that it worked only moderately well. After two years, the company stopped using it and he didn't know what might have replaced it. A 1978 review comments that entering data into the COMIC or "more particularly, REDIFON, involves the operator in a 'jack in the box' sequence of

[3] Ross Sharp, 3 September 2013

standing up and sitting down, sixteen times per dye in the case of the REDIFON." [24]

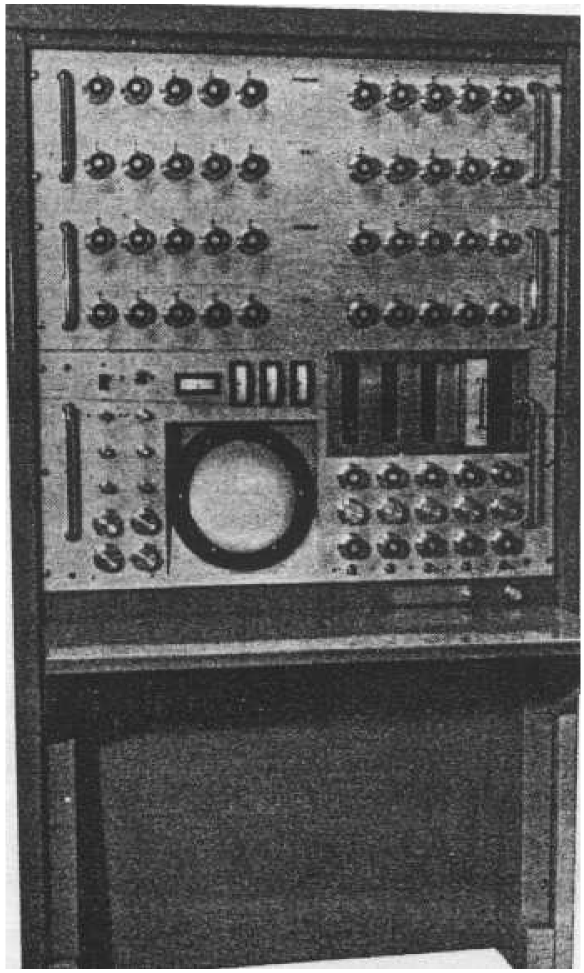


Figure 6: The Redifon Redi-colour, from [15]
(From the *Journal of the Society of Dyers and Colourists*, published by the Society of Dyers and Colourists.)

The D&H digital COMIC II (Figure 7) came out in 1967. It was the size of two desks, built with 400 printed-circuit boards with discrete components, and used a magnetic drum for main memory, with both programs and data loaded from paper tape. (Was this the last computer to be built with a drum for main memory?) It took direct input from a GE spectrophotometer, ran several color-matching programs, and could be programmed for special-purpose computations. The COMIC II preserved the oscilloscope display of the original COMIC. D&H had one, as did the Ford Motor Company [18]. The University of Virginia Computer Museum (`www.cs.virginia.edu/about/museum`) has photographs of several of the COMIC II boards, one of which is labeled "Celanese Coatings Co.", but it isn't clear how many were made. The D&H company was acquired by the Kollmorgen Corporation in 1968, and it does not appear to have promoted the COMIC II

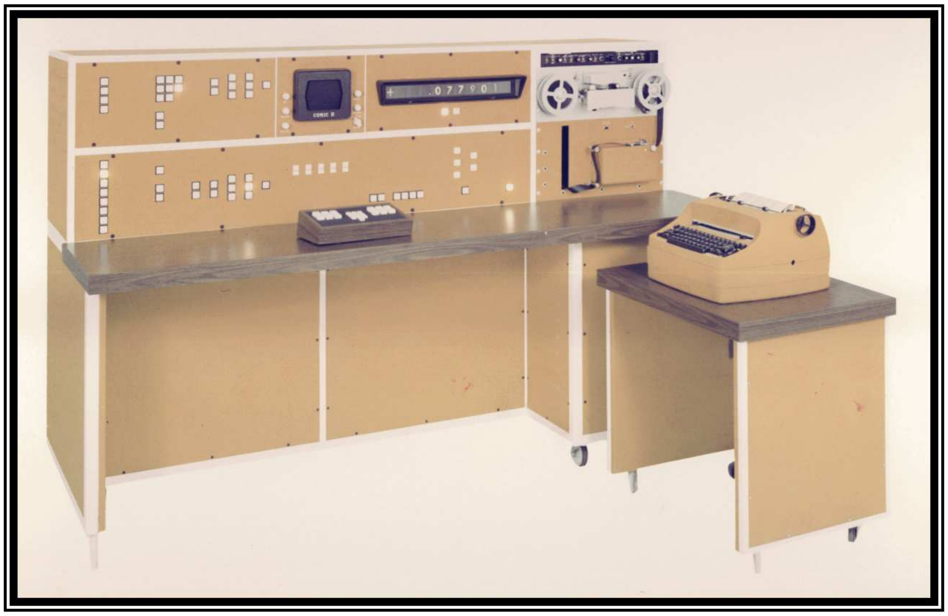


Figure 7: COMIC II, courtesy of Hugh Fairman.

Although the COMIC II is #50 in an online list of "50 ideas that changed plastics" [35], this reference probably confuses it with the analog COMIC, which had much more influence. According to Mr. Stanziola, "COMIC II was obsolete the day it came out." It was a special-purpose computer, built at a time when general-purpose digital computers were becoming cheap enough for small industries to afford. It was designed by Davidson and other engineers at D&H, who had not worked in the digital computer industry, and they do not appear to have used any standard processor design in the COMIC II.

6. General-purpose digital computers

The first digital computer programs for colorant matching appeared in the early 1960s. A 1960 paper [9] described a program for formulating transparent colors, which is relatively simple. It ran on a Univac and an IBM 650 and found formulations with three dyes chosen by the colorimetrist, taking "often less than five minutes per formulation."

Programs to compute formulations of opaque colors followed shortly. Among the first were the Instrumental Match Program (IMP, 1961-1963) developed by Imperial Chemical Industries in Britain [2], which ran on an Elliot 803B [30, p 15]. The IMP found a colorimetric match between a sample and three or more colorants by iteratively solving three simultaneous equations that expressed the X, Y, Z tristimulus coordinates as functions of the K/S values of the colorants. Since it found only a colorimetric match, not a spectral match, it could not deal with metamerism. American Cyanamid's Computer Color Matching system (CCM, 1963) [44], initially ran on an IBM 1620 and later on an 1800 for process control. This program was described in an IBM press release in late 1963 [27] that said "For the first time in textile history, a computer is being used by an American dye manufacturer to match colors for fabric dyers." The regional qualifier is there presumably because ICI's program was earlier, but "computer" should also have been qualified as "digital."

These early programs were developed by colorant manufacturers for use with their own dyes. A 1963 IBM Midwestern Region technical report by C. W. Carroll on the application of digital computing to color control in the paper industry [13] contains a very thorough introduction to the science of color. It includes six Fortran programs that ran on a 20KB 1620, and one that required a 40KB machine. It refers briefly to the COMIC (p. 87) and goes on to discuss the advantages of digital computation: speed, exactness of solution, and flexibility (the last is not really an analog/digital issue, but rather a contrast between a special-purpose and a general-purpose computing system, and the latter could be either analog or digital).

This report may be the basis for the 1967 program 1130-16.3.001 in the IBM Contributed Program Library [22]. A 1975 book on colorant formulation [30] attributes it to him, though the IBM program catalog doesn't include Carroll among the authors. The book author elsewhere characterizes the program as "commonly used" [29], and cited its use at the Coats & Clark Company, mentioned earlier, as an example. Coats and Clark spent five months loading data for 3700 dye-substrate combinations onto punched cards to use with programs on the 1130. The programs would try all three-dye combinations, though it would quickly reject impossible combinations, e.g. that required negative dye quantities. The company reported being able to find all 120 formulations that used three out of a given ten dyes in 10 minutes, though it would take over five hours to compute with a set of 30 dyes.

The IBM archives have several other 1967 and 1968 press releases about the use of their computers by textile and paint companies. The releases mention the 1130 and 1800 computers, and it is likely that they all used the same program.

The computer programs used spectral reflectance information for the sample to be matched and the dyes, but worked with it indirectly. They would find a rough colorimetric (XYZ) match and then correct it iteratively — one paper said that two to four iterations generally sufficed. The mathematics required was stated succinctly in matrix terms in 1966 [4], though it had been used earlier; one virtue of the matrix formulation was that programs could draw on standard matrix-calculation libraries. With additional correction steps, the programs could use the more general two-constant expression of Kubelka-Munk theory.[4] In either form, program output would include dye cost and degree of metamerism, and would identify the cheapest and least metameric combinations. CCM could also work with four or five dyes, like the COMIC, and determine if they provided better solutions.

It is instructive to compare the operation of the COMIC and digital computer programs since they solved similar equations. The process of bringing the dots of the COMIC display to the zero line solved the set of simultaneous equations; it was equivalent to inverting a matrix to get the initial rough solution digitally. Since it would not generally be possible to bring all of the points to the zero line, the COMIC operator would use the auxiliary TDC to get a colorimetric match of XYZ coordinates by adjusting the concentration dials. That amounted to an unsystematic iterative process of making small changes to the concentrations until the colorimetric match was found. In the computational sense, the COMIC operator was quite literally in the loop, making the repetitive adjustments that the program would do automatically. The analog/digital tradeoff was between operator control on the one hand, along with use of reflectance-curve information, and automatic generation of all possible solutions with their figures of merit on the other.

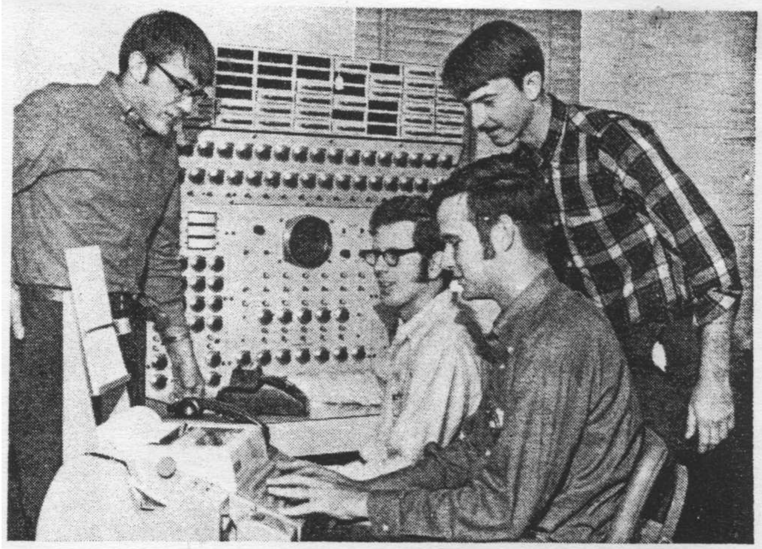
Except for the early IMP, all of these programs as well as the COMIC, COMIC II, and Redicolour computers could assess metamerism. Both COMICs were used by the Ford Motor Company. Metamerism might not appear to be a problem in matching vehicle paints, plastic parts and fabrics since they are generally seen only in daylight. There are many daylight spectral distributions, however, so that one cannot escape metamerism even in daylight. More significantly, according to Bill Longley, who worked on color specification at Ford, it was important to assess metameraism and to try to obtain non-metameric matches because the degree of metameric mismatch between a standard daylight and incandescent light was a good predictor of the degree of

[4] According to Rolf Kuehni, of the University of North Carolina, the one-constant form was generally used for dyeing textiles and paper, while the two-constant form was used for pigments in paint and plastics.

mismatch that different observers might see in one light.[5] He added that they could generally avoid metamerism among pigmented paint, plastics, leather, and vinyl, but often not between them and dyed fabric without close attention to spectral properties.

7. Conclusion

A 1966 article in *Chemical and Engineering News* [1] on computational methods for color matching reported that "While some larger companies, like Cyanamid, use digital computer programs for color-matching calculations, most use more modest special-purpose analog computers such as the Davidson and Hemmendinger Colorant Mixture Computer," and adds that D&H had sold 172 COMICs. The COMIC went out of production in 1967, though it continued to be used in industry and for educational purposes (Figure 8). (Mr. Stanziola reported that a New Jersey high-school math teacher acquired a discarded COMIC to use in teaching about simultaneous equations.)



Seniors are learning to do it themselves in an experimental color program at North Carolina State University's Department of Textile Chemistry. They have access to the sophisticated colorant mixture computer (background) and a computer terminal connected to the advanced facilities at the Triangle Universities Computation Center. They are (left to right): E. R. Anderson of High Point; Jay Privette of Conover and Phillip Johnson of Fayetteville (both seated) and Ray Wilson of Winston-Salem (standing at right).

Figure 8: The COMIC in a student lab (this photograph first appeared in *American Dyestuff Reporter*, **58**:25, p. 33 (1969). Used with permission of the American Association of Textile Chemists and Colorists.)

Economic factors contributed to the success of the COMIC and to its eventual replacement by digital computers. A 1968 symposium paper on the paint industry describes continued use of the COMIC and says, "initially it was generally felt that [digital] computers could not be used exclusively for color matching because of their high cost. If they were installed for other purposes and computer time became available, they were used to solve color problems. Fortunately this phase was short-lived" [26]. When the COMIC appeared, small analog computers were almost the only systems cheap enough for dedicated interactive use. The "desktop" Bendix G-15 and

[5] Email, 18 September 2013

Librascope LGP-30 might have been exceptions at about $50,000 each in 1956, but they had no role in the colorant industry, so far as I know. A year's lease of a COMIC for several thousand dollars, would give experience with its use (color-measuring equipment would also be needed). By contrast, the IBM 1620, which appeared at the same time, cost over $100,000 and a six-month rental exceeded the COMIC initial purchase price and would incur programming costs.

In 1967, an IBM 1130 such as Coats and Clark used cost $32,280 (without a disk drive) and leased for $695/month. That is still more than the COMIC cost, but together with the IBM library program for color-matching, it provided greater power. A COMIC $40 colorant box was for a single concentration of one colorant, and as a company became familiar with computational tools and wanted to expand their use to many colorants at many concentrations, the flexibility of a small digital computer became worth its price. Each of the 3700 dye-substrate combinations that Coats and Clark used required only a punched card.

By the early 1970s, still-cheaper minicomputers had become the natural locus of color-matching and other color-related programs. They were cheap enough that small companies could own one and that larger companies could have them in several departments. They were readily programmed and could be interfaced to measuring or control equipment.

One company, Applied Color Systems, founded in 1970, had a leading role in developing minicomputer color-matching programs. Its first programs ran on time-shared PDP-10s, but it later used PDP-11s extensively. Its founders included Ralph Stanziola, who had worked for the Davidson and Hemmendinger company as a COMIC salesman. In Europe, the Pretema company played a similar role, and the two companies merged in 1988 as ACS-Datacolor, and after a 1990 merger with Instrumental Colour Systems (UK), it became Datacolor International.[6]

Industry publications document the role that the COMIC had in introducing automation to color matching. Although its analog character was not essential, as evidenced by the digital alternatives that soon appeared, that character, as used by the COMIC designers, probably contributed to its success. The hands-on operation of its controls — the dials that represented reflectances and dye concentrations — and the oscilloscope display of a curve that showed color-matching meant that it provided a less-highly mediated experience than did the printouts of early digital computers. This is not to say that the experience of color-matching with the COMIC was unmediated; there was still considerable mediation, but it made connections with the activity of dyers that most digital computers did not (the Redi-Colour computer was an exception, but it was partially analog, and designed to look like and be operated like the COMIC).

When graphical interfaces became common, digital computation could easily provide visual output like that of the COMIC, though manual control was likely to be provided by on-screen buttons to be clicked, not by turning a dial. That last distinction may not be important, but overall, modern integrated systems makes it relatively easy to solve problems without an understanding of the principles that underlie the solution. Discussions of automation in the colorant industry have raised this as a possible disadvantage from time to time An early example appeared in the discussion of the paper that presented the Redi-Colour, in which its being coupled with a spectrophotometer for direct data input was criticized as making that measuring instrument be a 'black box' whose operation need not be understood [15, p. 607]. A more recent comment about understanding principles comes from an interview in 2000 with Charles Mertz, then of Minolta, who had used the COMIC and COMIC II while at Ford and who later became a vice-president of Applied Color Systems and of Datacolor. In response to a question about automation, he said:

> The downside has been losing many of the knowledgeable people who really understand the "science" of instrumental color control. The instruments and computers that are used to solve the various challenges of today's color problems are merely tools.

[6] Thanks to Michael Brill, Datacolor, for this information.

> Put these tools in the hands of an experienced colorist who understands the plant's processes and you have a powerful team. These same tools placed in the hands of someone who does not understand the science of color and the processes of their plant's operation can lead to frustration and unfulfilled expectations. In many cases, that person is simply looking at numbers without really understanding what it took to generate the data. Because of that, he or she cannot properly diagnose what is happening in the overall process [33].

Mertz goes on to speak of the need for education. The COMIC had an educational role. It not only introduced automation, but it called attention to the importance of looking at spectral reflectance curves and not just tristimulus (or RGB, or CMYK) values to understand the interaction of colorants. This role was continued in the digital domain by companies like Applied Color Systems, and in that respect, the influence of the COMIC has outlived that interesting but limited machine by some decades.

Acknowledgments

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