Electronic Imaging, a Tool for the Reconstruction of Faded Color Photographs and Motion Pictures

Franziska S. Frey
Image Permanence Institute, Rochester Institute of Technology
Rochester, New York
Rudolf Gschwind and Lukas Rosenthaler
Institute of Physical Chemistry, University of Basel, Basel, Switzerland

Abstract

The dyes of common photographic three-color materials are chemically rather unstable. Restoration of faded materials by chemical processes, while possible for black-and-white photography, is not possible for color photography, because dye fading is an irreversible process. A method to reconstruct faded color materials by digital image processing is presented. The algorithms used for reconstruction are based on photographic experiments, i.e., accelerated fading tests of various photographic materials. Based on these tests, a mathematical model for the fading process can be determined. The method shows good results for color slides, prints, and motion pictures.

Introduction

Photographic images play an important role as information carriers, artistic media, and historical documents, representing cultural values of the last 150 years, which have to be preserved. In many cases, the storage of the images is unsuitable, and many are in poor condition due to the fact that photographic film and paper are chemically unstable media. A lot of images are already badly affected or even useless because of advanced deterioration. Frank Hodsoll, a former chairman of the National Endowment for the Arts, gave a grim assessment of the situation in the United States: “I was appalled to learn that one-half of the theatrical films produced before 1952 have already been irretrievably lost due to decay and neglect. Under present conditions, most of the remaining half will not survive this century…Every film is a time capsule which tells us how we saw ourselves, and how others saw us, at a point in our past. The disappearance of a film is therefore not only a loss of an artistic object, it is also partial obliteration of our nation’s history.”[1] Similar remarks can be made about still photography.

Of all photographic materials, color emulsions show the quickest degradation behavior.[2-4] The dyes of common chromogenic processes are chemically rather unstable. Both the thermodynamic and the photochemical stability are low, and the expected life span of color materials is in the order of years to decades. Improper processing and/or environmental influences such as light, chemical agents, heat, humidity, and storage conditions affect images by fading the dyes and/or producing stain. Photographic emulsions also contain other components such as sensitizers, color couplers, and stabilizers which can alter the image appearance with time. Lowering humidity helps to prevent fading to a certain extent, but the only reliable method to keep color photographic materials for a long time is in dark storage at low temperature and low humidity. In the case of unsuitable storage conditions where photographs and movies have faded, the question of restoration becomes evident. Restoration of faded materials by chemical processes, while possible for black-and-white photography, is not possible for color photography, because dye fading is an irreversible process.

Table.1. Effect of Temperature on Dye Fading Rate (40% Relative Humidity). The Values Given in this Table are Approximate and Do Not Apply Exactly to all Color Photographic Materials.[5]

Storage Temperature	Relative Fading Rate
86°F / 30°C	2
75°F / 24°C	1
66°F / 19°C	1/2
60°F / 16°C	1/4
54°F / 12°C	1/5
45°F / 7°C	1/10
14°F / -10°C	1/100
-15°F / -26°C	1/1000

Methods to restore images through photographic copying have been developed.[6-8] However, these methods are slow, need skilled operators, and work only if fading has not proceeded too far.

This paper presents an approach to reconstruct faded color photographic materials by digital image processing. Note that digital reconstruction is not a restoration in the classical sense. In black-and-white photography, the image is usually restored and conserved on its original support. In the case of color images, a restoration of the original is not possible because the original dyes cannot be reconstructed.

Therefore, the aim of the reconstruction is to restore the *appearance* of the original colors as accurately as possible on a new material.

The presented method using digital image processing is quick, cheap, and does not affect the original photograph. Moreover, the method is universal and can be used to restore any chromogenic color material. As an additional advantage, the image is available in digital form ready to be used in a data base, allowing fast and easy access to the images.

Concept of the Digital Reconstruction Process

To carry out a color reconstruction, the photographic fading processes have to be well known. There is a difference between the Arrhenius image stability data published by manufacturers and the data needed to obtain a model for the fading mechanism. In the latter case, the question of durability is secondary. To describe the fading process, information about the behavior of the dyes throughout the whole density range is necessary. As little relevant data is published, accelerated fading tests had to be carried out to obtain the necessary information.[9]

Various gray and color wedges were exposed on different photographic three-color materials. These materials were faded under different conditions of illuminance, temperature, and relative humidity. The test conditions met the ISO Standard 10977 requirements.[10] The densities of the original and the faded materials were measured (Figure 1 and Figure 2).

As today's photographic materials must be used for the fading tests, the results are in fact only true for current emulsions. Earlier materials are not available for testing, and, in many cases, no information can be found.

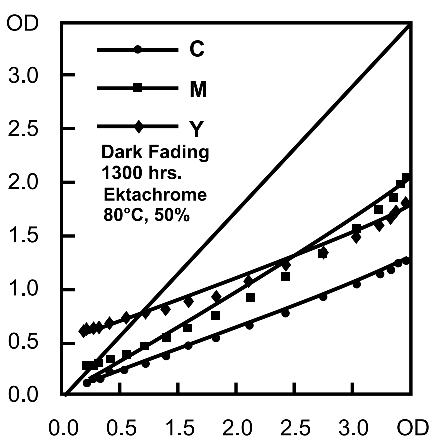

Figure 1. Ektachrome 100 dark fading (1300hrs, 80ºC, 50% RH). Comparison of the integral densities (gray wedge) before and after fading (Y = yellow, m = Magenta, c = Cyan). Fading is proportional to dye concentration. The yellow stain can be clearly seen.

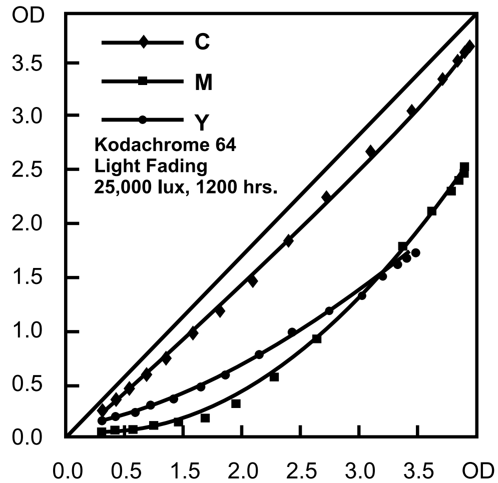

Figure 2. Kodachrome 64 light fading (25,000 lux, 1200 hrs). Comparison of the integral densities (gray wedge) before and after fading. Fading can be heavily subtractive as in the case of the magenta dye.

The goal of the tests was to develop a general mathematical fading model. The model should be as simple as possible, containing only a few free parameters while covering as many fading behaviors as possible. The model developed to describe the fading for nearly all chromogenic materials under different conditions is defined by the following linear equation:

$$\begin{pmatrix} Y' \\ M' \\ C' \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \bullet \begin{pmatrix} Y \\ M \\ C \end{pmatrix} + \begin{pmatrix} a_{14} \\ a_{24} \\ a_{34} \end{pmatrix}$$

Y', M', C = optical density of the faded dyes
Y, M, C = original optical density of the dyes (yellow, magenta, cyan)

The equation takes care of different effects. Normally, the dyes fade proportionally to their original density which means also proportionally to their concentration (a_{11}, a_{22}, a_{33}). Fading may also cause transformation of faded or other colorless substances into colored artifacts, which is referred to as staining. The additional coefficients a_{14} - a_{34} describe an increase or decrease of base density. The base density coefficients are positive when white elements of the images are affected by stain. In the case of light fading, when fading is often not proportional but subtractive, the coefficients are negative. The amount of light fading of each layer depends also on the density of the neighboring layers, as they act as filters (a_{12}, a_{13}, a_{21}, a_{23}, a_{31}, a_{32}).

This model allows a much better description of the fading process than the Arrhenius stability data published by the manufacturers. The 12 coefficients subsequently will be referred to as the fade matrix. This fade matrix varies not only for different storage times and storage conditions but also for every material type.

From a chemical perspective, fading is a function of the changes of individual dyes. If it is possible to quantify the spectral variations of the dyes through fading tests, the reconstruction becomes simple:

- Produce color photographs with colored test patches (gray and color wedges).
- Determine the relationship OD (faded) = f [OD (unfaded)], by measuring the optical density (OD) of the patches before and after fading.
- Digitize the faded photograph.
- Apply the inverse of the relationship to recalculate the original densities of the colorants.
- Output the restored digital image, i.e., with a film recorder on color film.

But as usual, reality is more complicated than a laboratory setting. In most cases, the only available information is the deteriorated material itself, and nothing is known about the film type and the fading and storage conditions. In addition, a majority of the images do not contain any known reference colors. Hence, an automated reconstruction is not possible. Therefore:

- Reconstruction has to be carried out interactively under the visual control and judgment of a human operator.
- In order for the colors of the image to be restored and not only retouched by subjective taste, the reconstruction process must obey the laws of fading that are known from the accelerated fading tests.

There is a further complication: scanners or densitometers measure the integral densities. For the reconstruction of images, analytical densities are needed for two reasons. First, as mentioned above, fading is a function of the concentration of the individual dyes. The absorption of the individual dyes is called analytical density, which cannot be measured directly but has to be calculated from the integral densities of all three dyes. This implies that the absorption spectra of the individual dyes are known. Second, the side absorptions of the dyes have to be accounted for. If the reconstruction is based on integral densities instead of analytical densities, the image shows a poor color rendition with desaturated colors.

The operator processes the image on the computer following the fading model until the correction is satisfactory. Since it is difficult to estimate the coefficients of the linear fading equation directly, the user may work with more familiar visual and photographic parameters such as contrast, brightness, color cast, and saturation. The program converts these parameters to coefficients of the fading equation. Once the correction is satisfactory, the final coefficients of the fading equation are used to transform the input image. To obtain a hard copy, the reconstructed image can be exposed on color film with a high-resolution film recorder.

Color Reproduction Aspects for Scanning

There are no guidelines or accepted standards for determining how much image quality is required in the creation of digital-image databases for access or preservation of photographic collections. As a result many institutions now starting their scanning projects will be disappointed sooner or later, because the choices made were not thought through or good enough for the technology of the near future. Right now, the cycle of understanding image quality is repeated for the new imaging technologies. Furthermore, the preservation field must address policy issues in digital conversion.

It has to be kept in mind that scanning from an archive is different from scanning for prepress purposes. In the latter case, the variables of the process the scanned image is going through are well known, and the scanning parameters have to be chosen accordingly. If an image is scanned for archival purposes, the future use of the image is not known, and neither are the possibilities of the technology that will be available a few years from now. This leads to the conclusion that decisions concerning the image quality of the archival image scans are very critical. In addition, the scanning process has to be documented carefully and backwards compatibility has to be ensured.

During the scanning process of the images two aspects must be considered to ensure correct color reproduction:

- The photometric resolution must be a minimum of 10 bits per channel or higher to adequately capture the high dynamic brightness range of color materials.
- Channel separation must be executed with narrow-band interference filters (i.e., 450, 550, and 650 nm; half-width ≈ 20 nm) to achieve accurate spectral resolution.

As mentioned above, the reconstruction process requires accurate information about the concentration of the dyes. Values can be deduced by applying the Beer-Lambert law stating that the optical density is proportional to concentration. However, the law is valid only for monochromatic light. Ordinary color scanners are equipped with broad-band color separation filters, and the Beer-Lambert law does not hold. The aim of most commercial color scanners is to measure colors and *not* colorants, i.e., pixel values represent colorimetric data. The spectral sensitivities of the three scanner filters have to be broad to fit the colorimetric tristimulus curves. Figure 3 shows an example of the spectral sensitivity curves of a commercial CCD camera equipped with broad-band filters. Through a suitable linear combination of the sensor signals, the CIE 1931 tristimulus values can be fitted from the spectral sensitivities S_{blue}, S_{green}, and S_{red}.

The spectral halfwidths of these CCD filters are very broad compared to the absorption band of today's photographic dyes, and the maximum red sensitivity at ≈ 590 nm is much too short compared to the absorption maximum of the cyan dye at ≈ 640 nm.

The determination of analytical densities with such broad-band filters is problematic, as shown in Figure 3. The black bars represent the optical densities for the sum of all three dyes (= gray) as measured with this device. They represent the so-called printing densities. The shaded bars equal the printing densities of each dye in its pure state.

Two points have to be noted:

- The sum of the printing densities of the dyes in their pure states (total length of the shaded bars) is less than the printing density of the sum of the three dyes (length of the black bars). This is a direct result of the broad spectral sensitivities of the scanner. As a consequence, analytical densities can only be estimated roughly. With narrow-band sensitivities, this inaccuracy does not exist, because the Beer-Lambert law is fulfilled. For the commercial CCD camera shown in Figure 3, these sensitivities can be obtained by placing narrow-band interference filters in front of the light source.
- The sensitivity of the red "colorimetric" sensor falls between the absorption maxima of the magenta and cyan dyes. Consequently, the measured optical density in the red does not originate primarily from the cyan absorption, but is caused up to half by the side-absorption of the magenta dye. This is especially problematic for color materials where the cyan dye has faded the most. In this case, the "red sensor" of a colorimetric camera detects more or less only the magenta side-absorption, and a correct reconstruction is no longer possible. These types of colorimetric scanners are also problematic for color negative materials, as the absorption maxima of the cyan dyes in commercial color negatives are at even longer wavelengths, ca. 700 nm.

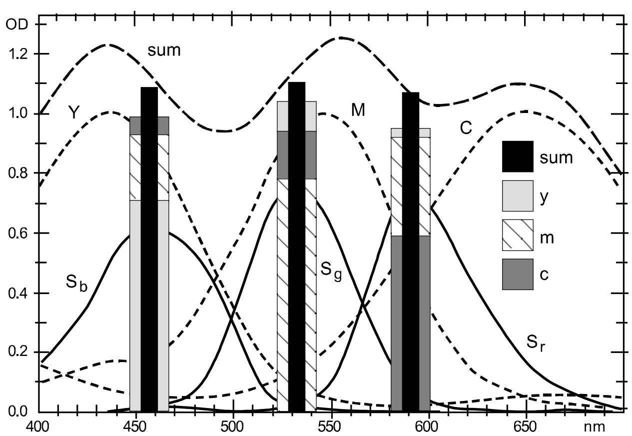

Figure 3. Spectral sensitivity curves S_b, S_g, S_r of a commercial CCD camera (solid lines), and the absorption curves of today's photographic dyes (dashed lines). The bars represent the printing densities as seen by the CCD for the individual dyes (shaded bars) and the integral sum (black bars).

Determination of Dye Spectra of Faded Photographic Materials

For the determination of analytical densities, and consequently for a correct restoration, the dye spectra of the faded materials should be known. The manufacturers are able to supply this information for today's emulsions. However, it is difficult or even impossible to obtain the spectra for old, faded materials. The manufacturers, if they even exist anymore, no longer have the needed information available. In addition, neither film type nor manufacturer are known for certain images.

The lack of knowledge of the faded images' dye spectra can lead to problems in the described reconstruction method. Therefore, an estimation of the spectra is calculated by means of a spectroscopic analysis.[11]

Especially in the case of heavily faded emulsions, it is important to know the absorption maxima of the dyes to measure the optical density at this wavelength. Figure 4 shows the spectra of a faded film measured with a spectrophotometer. The absorption maxima of the dye spectra indicate which narrow-band interference filters have to be used for scanning. Cyan dyes of old materials often have absorption maxima at longer wavelengths than today's emulsions.

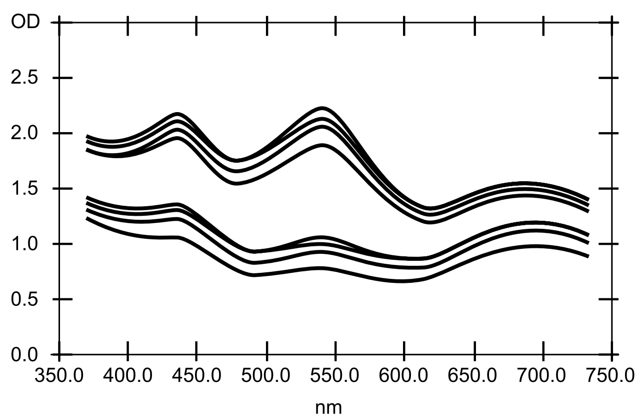

Figure 4. Spectra of old, faded Agfacolor slide film (1943). Note that the cyan dye has the absorption maxima at much longer wavelengths than today's material.

As long as the color patches for the analysis contain pure or mostly pure dyes, the method results in a good estimation of the three dye spectra. However, most faded color images do not contain color patches, but only scenes with restricted color gamut, i.e., mixed colors. Therefore, a larger set of possible spectra results. The more the emulsions are faded, the larger is the resulting set of possible spectra. The spectra must be interpreted by using photographic knowledge. Figure 5 shows the results of the described method when applied on the dye spectra of Figure 4.

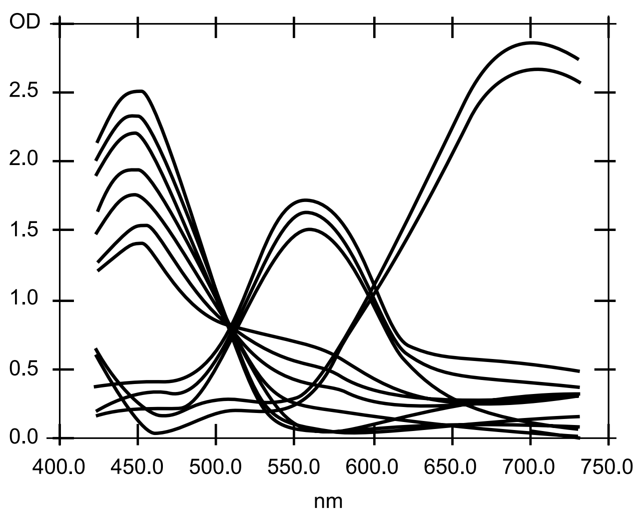

Figure 5. Set of possible dye spectra of Agfacolor 1943. Determined after the method described in Ohta.[12]

Another possible way to determine the dye spectra would consist in scratching away the different layers and examining each dye individually. The disadvantage of this method is that the faded originals are partially destroyed.

Digital Reconstruction of Old Motion Pictures

The same factors that limit the permanence of still photography limit the permanence of motion pictures. The dyes of color movies fade with time, the finely distributed silver particles of black-and-white movies oxidize and hence discolor, and the film base itself (cellulose acetate or nitrate) degrades and shrinks. Additionally, mechanical wear and abrasion produce dust and scratches.

Since the material of color movie films is the same as that used in color photography, the method of reconstructing the color is identical, as described above. However, mechanical stress during projection and handling produces defects such as scratches, dust, etc., on the film; these are usually quite prominent and degrade the quality severely. It should be noted that the color reconstruction process generally makes dust and scratches even more noticeable. Because of the large volume of data presented by movies, an automatic method of restoration of these defects is a necessity. Therefore, we propose the use of methods of computer vision for the recognition of image defects resulting from mechanical stress. From this point of view, the main problem is to find algorithms that are able to separate image structures into two distinct classes: image features and image defects.

A movie scene can be considered as a temporal-spatial dataset, where image defects are characterized by certain properties. Dust particles typically can be found on one frame only and will therefore present a strong discontinuity on the temporal axis. The boundary of dust particles have step-like profiles. However, intrinsic movements of objects within a scene, or general movements (pan) also result in local discontinuities on the temporal axis. These discontinuities can be distinguished from image defects by a motion analysis in a local neighborhood.

Scratches, which mostly result from mechanical stress during projection of a movie film, consist of long, vertical lines (with a typical line-like profile). Typically a scratch is visible at the same location on several subsequent frames, and is extended from the bottom to the top of each image frame.

Consequently, for each frame the prominent image features have to be detected and characterized according to the above properties. Once an image feature has been recognized as a defect, an interpolation using both the spatial and temporal domain is performed to fill in the missing information.

The digital reconstruction of movie films is an area of active research where both the algorithms and the computer hardware are pushed to their limits.

Permanence and Conservation

It is a reasonable requirement that the images, once restored, should be saved and stored for an extended period of time (> 100 years). The best option is still photography, but even modern photographic materials fade over time. Another approach is the digital storage of the data. Digital storage media are not yet very stable—a modern tape has a lifetime of approximately ten years—but it is possible to copy digital data without any loss. In theory, digital data has an endless life, if copied regularly. Nevertheless, even the best digital copy is no substitute for the original.

Outlook and Conclusion

In most cases, the described method results in excellent digital color reconstruction. Nevertheless, fading effects exist where a global reconstruction procedure fails. If the fading is not homogeneous throughout the whole image, electronic masking techniques have to be applied that allow different reconstruction parameters for different parts of the images. Complications also arise if the degradation is accompanied by the formation of colored spots. This happens frequently when slides are mounted between glass plates. In this case, methods of electronic retouching have to be utilized.

If the dyes of a color image are completely destroyed, as they often are in the case of light fading, a reconstruction is no longer possible.

Because there is still a subjective part in the reconstruction process, the following questions which determine the color reproduction have to be answered. Does one reconstruct the original photograph, the original colors, or the most pleasing image? Should the reconstruction correct defects of the original photographs such as exposure errors?

If there is only one single image of a certain emulsion type available for reconstruction, there may be too many degrees of freedom for a correct color reproduction. Although the different brightness levels of the photograph can be calibrated if the image contains a gray wedge, it does not contain the needed information to calibrate the colors. If a whole series of images of a certain material type has to be restored, the different reconstruction parameters can be averaged, which will lead to better results.

There still remain a few questions that have to be analyzed carefully. However, the results obtained to date are very promising. Perhaps the most important lesson learned so far is that communication has to be improved among all the participating parties. Due to the fast-changing and complex imaging technologies involved, collection managers need to work together with engineers and imaging scientists, who often lack collection-related knowledge. Both sides need to be willing to learn the special problems and needs of the other party. This is the only way to make sure that future generations can enjoy the documents of our century.

References

1. H. Wilhelm, *The Permanence and Care of Color Photographs,* Preservation Publishing Company, Grinell IA, USA, 1993.
2. R. T. Tuite, Image Stability in Color Photography, *Journal of Applied Photographic Engineering*, **5** (4): pp. 200-207, 1979.
3. K. B. Hendriks, S*tability and Preservation of Recorded Images; in: Imaging Processes and Materials*, Nebelette's 8th edition, Van Nostrand, NY, pp. 637-684, 1989.
4. S. Anderson and R. Goetting, Environmental Effects on the Image Stability of Photographic Products, *J. Imaging Technology*, **14** (4): pp. 111-116, 1988.
5. Kodak Professional Imaging Products, Technical Information, Eastman Kodak Company, 1992.
6. Eastman Kodak Company, Restoring Faded Transparencies by Duplication (White Light Printing Methods), in: *Current Information Summary* **CIS-22,** July 1979.
7. Eastman Kodak Company, Restoring Faded Transparencies by Duplication (Tricolor Printing Method), in: *Current Information Summary* **CIS-23**, August 1979.
8. H. C. Bradley, Corrective Reproduction of Faded Color Motion Picture Prints, *SMPTE Journal,* **90** (7): pp. 591-596, 1981.
9. F. Frey and R. Gschwind, "Mathematical Bleaching Models for Photographic Three-Color Materials," *Journal of Imaging Science and Technology* **38**, no. 6: pp. 513-519, 1994.
10. ISO-Standard 10977, Photography-Processed Photographic Colour Films and Paper Prints - Methods for Measuring Image Stability, First edition 1993-02-01.
11. R. Gschwind and F. Frey, "Electronic Imaging, a Tool for the Reconstruction of Faded Color Photographs," *Journal of Imaging Science and Technology* **38**, no. 6: pp. 520-525, 1994.
12. N. Ohta, Estimating Absorption Bands of Component Dyes by Means of Principal Component Analysis, *Anal. Chem.*, **45** (3): pp. 553-557, 1973.