Chapter 4 Methods and techniques for Color film restoration

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Abstract
Color restoration, digitization and management requires skills in physics, chemistry, optics, computer science as well as art, psychology, design and visual language. In this heterogeneous context, film restoration is a fascinating field of application which provides to students examples and records of successful (or unsuccessful) multidisciplinary methods and techniques to restore and manage colors through different media.
A film can be considered as a content in which color is used to raise emotions or support the storytelling, or can be seen as a container, made of colorants which age and decay through the years.
In the Master course of Color, Design and Technology, we introduce the students to the field of color film restoration, and we guide them through the different techniques and methods to perform the main actions of digitization, retrieval and conservation. Through this approach, we focus on the main actions to keep under control in order to perform a correct color reproduction and management.

Keywords:
Film Restoration, Color Films, Cinematography, Color

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1. Introduction

The FIAF (Fédération Internationale des Archives du Film), in his Status, defines a film as:

[…] a recording of moving images, with or without accompanying sounds, registered on motion picture film, or on any other medium now known or to be invented (FIAF, 2016).

The name *film* originates from the fact that, historically, the medium used to record and display motion pictures has been a thin sheet of cellulose acetate or nitrocellulose coated with a radiation-sensitive emulsion for taking photographs (also called film stock) (Merriam-Webster, 2020). But film – with the meaning of movie or motion picture – also identifies a story, told in different ways and using different technologies, always with the goal of raising emotions and amuse the audience watching it on a screen in a theatre, on a television or, more recently, on a smartphone.

Therefore, a film has a dual nature, content, and container and film restoration practice aims at preserving both the materials which compose the film and the intangible experience produced on the audience.

In this chapter, we will explore the two aspects of a film related to colors: the content, where color is used to raise emotions or support the storytelling and the container, where colorants and filters are used to recreate the illusion of reality but are subjected to aging and decaying.

In the first Section we will present a brief historical *excursus* of film technology evolution since its ancestors to the currently DCP.

In Section 2, we will present the technologies and the phases more relevant for the film history evolution, thus the film both as container and as content, showing some of the pivotal moments and technologies fundamental to understand the evolution of cinema, from the first moving images to the modern DCP, mainly focusing on the technologies that allowed the use of colors in films.

In Section 3, we will analyse the film base composition, his structure, and the principles of the cinematographic technique.

In the last two sections, we will make an *excursus* of the best practices for storing (Section 4) and restoring (Section 5) film materials.

For practical reasons, we will mainly refer to the 35 mm standard film support, skipping the reduced film supports history (for example the 16 mm, 8mm or Super 8 for amatorial usages), that should require another extend analysis.

Aim of this work is the presentation of film restoration techniques, from the beginning practices to the new digital restoration tools, in order to underline which are the best practices to correctly perform the color management in film restoration workflow. To do this, we will use and analyse some examples and records of successful and unsuccessful multidisciplinary methods and techniques used during the years to restore and manage colors through different media.

2. History of cinematography: an overview

In this Section we will present the more relevant technological steps that have influenced the film history evolution, thus the film both as container and as content. We do not claim to be exhaustive of all the aspects, the technologies and the phases which characterize the history of cinema. In fact, in this Section we will explain the pivotal moments and technologies, which are fundamental to understand the evolution of cinema, from the first moving images to the modern DCP.

The date of birth of cinema is commonly considered the December 28, 1895. That day, at the Salon Indien of the Grand Café at the Boulevard des Capucins in Paris, took place the first commercial cinematographic demonstration. The audience had the possibility to watch 10 short films, which have been shot, printed and projected (at 16 frames per second) using the *Cinématographe*, patented February 13, 1895 by the Lumière brothers. This history-making presentation included their first film, *Sortie des Usines Lumière à Lyon* (Louis Lumière, 1895) (Britannica, 2021). In this period, the Cinématographe Lumière started one of the most flourishing industries, but cinematography was born from the accumulated efforts of lots of craftsmen and forerunners. Among them we remind the magic lantern, the zoetrope, the praxinoscope and the optical theatre as the main precursors of cinematography.

To obtain true motion pictures, two developments were necessary: (1) a mechanism to enable the acquisition of sequences of photographs with a single camera at regular and rapid intervals, and (2) a medium capable of recording those images. In fact, a motion-picture camera must be able not only to advance the medium rapidly enough to permit the acquisition of at least 16 separate exposures per second (i.e., the minimum number of images to have the illusion of movement), but also to record a correctly exposed image.

The first transparent and flexible film base material was *celluloid*, manufactured commercially in 1872 and perfectioned in 1889 at the George Eastman company, in Rochester. This first film base was sturdy, flexible and perfect to record motion pictures, but it is extremely flammable (Britannica,

History of film, 2021). The first to use the celluloid as film base were William K.L. Dickson and Thomas Edison, at the Thomas Edison's Company. They worked on a recording system called *Kinetograph* which was coupled with a second instrument, the *Kinetoscope*, used for film projections. The Kinetoscope was a viewing device, where a continuous 14-metre film loop ran on spools between an incandescent lamp and a shutter. The main difference between the use of the Cinématographe and the Kinetoscope was that this second device was made for individual viewers, instead of the Cinématographe which was like a modern projector andallowed a large group of people to watch the same film at the same moment. Furthermore, the international patents of the Kinetograph and Kinetoscope were not registered, so these machines were widely and legally copied, modified and improved throughout Europe. This situation allowed the Cinématographe of the French brothers to become the European standard during the early cinema era and the celluloid film base became the standard material used to record and project films (Britannica, History of film, 2021). The big success of the Cinématographe was also linked to the fact that, compared with other attempts at producing a movie camera, it was remarkably compact, and it did not rely on electrical power. The Cinématographe could be placed anywhere, both to shoot film and to project – all that was required was a magic lantern lamphouse with a gas or limelight illuminant. Thus, the Lumières quickly started to tour the Continent to exhibit their films privately and publicly, acquiring, in every country, new and local short films for their catalogue.
For what concerns the film as content, the shift in consciousness from films as animated photographs to films as stories, began to take place around the turn of the XX Century and it is clearly evident in the work of the French filmmaker Georges Méliès. He was interested in the illusionist possibilities of the Cinématographe and his first films are characterized by the use of stop-motion photography to make one-shot tricks in which objects disappeared, reappeared or were transformed in other objects. After this first phase, George Méliès began to make experiments with brief multi-scene films, following the logic of linear temporality to establish causal sequences and tell simple stories, anyway his main purpose remained the public amusement by showing prestige games, assembling independent episodes, or making theatrical shows as purely visual art. By 1902 Georges Méliès produced his most famous film *Le Voyage dans la Lune*, a film adaptation of a novel by Jules Verne, characterized by a length of one reel (i.e., about 25 meters, or 14 minutes) (Britannica, Motion-picture technology, 2021).
Together with Georges Méliès many other filmmakers started producing innovative visions of the world, trying to establish the temporal continuity

from one shot to the next. Among them, *The Great Train Robbery* (Edwin S. Porter, 1903) is widely acknowledged to be the first narrative film example of parallel editing comprising 14 separate shots of noncontinuous, nonoverlapping action.
After this experimental period, the cinematographic technique started developing: more modern motion-picture cameras and techniques were invented allowing the sound recording, the picture and sound editing, the creation of special effects and the animation production. In this heterogeneous context we are mainly interested in the technologies allowing the integration of colors in films.

2.1 Color films

Contrary to what we were used to think about film of the origins, the silent cinema was full of colors: silent films were colored using nonphotographic methods such as hand-coloring, *tinting* (i.e., process of soaking the film into dyes) and *toning* (i.e., replacing the silver in the emulsion with colored, silver salts, by means of chemicals.).
Hand coloring: The workers applied aniline colors by hand-coloring the film with thin camel hairbrushes, under a magnifier, frame by frame, to enhance particularly significant scenes or elements. With this technique colors can appear unnatural, too vivid and limited in range, furthermore, the process was very long and expensive. One of the more famous studios that made this type of colorization was the *Elisabeth Thuillier's coloring lab* in Paris, where two hundred people were involved in film hand coloring.
In order to improve the hand coloring technique, in 1903, the Pathe Company experimented the stencil color prints. This technique (*à poichoir,* in French) required the manual cutting, frame by frame, of the area to be colored from another identical print. The necessary prints were one for each color, usually from 3 to 6, and were characterized by soft pastels hues. After the production of a stencil for each color, it was placed in contact with the print to be colored (Montanaro, 2019).
With the advent of the feature and the conversion of the industry to mass production during the 1910s, frame-by-frame stenciling was replaced by mechanized tinting and toning. Occasionally, the two processes were combined to produce elaborate two-color effects (Cherchi Usai, 1991).
Tinting: It is a monochromatic technique that provided a uniform color of all the light areas of a picture. It was achieved by immersing a black-and-white print in a dye or using a colored film base for printing. In this way, the dye was absorbed by the gelatin, uniformly coloring the film, and it is distributed evenly across the film support. In this case, color extends also into the non-

image area, directly affecting the emulsion layer. With this technique, a wide range of color options were available, and color was used to emphasize specific emotional states: yellow for daytime sequences and blue for the night, green for the country scenes or red for passion and danger (Pritchard, 2021). Thus, positive release prints could be made from different color sections joined together. In 1921, Kodak introduced nine different colors for film tinting (i.e., red, pink, orange, amber, light amber, yellow, green, blue, and lavender) and in 1929, when sound-on-film became common, Kodak introduced a pre-tinted film stocks in seventeen different hues that could accommodate soundtracks (i.e., Sonochrome) (RTI I. P., Motion Picture Film Processes, 2021).

Toning: It is a chemical process that consists of treating film emulsion to color the dark areas of the print. Tinting only affects the developed parts of the image, without dyeing the gelatin in the parts that have been impressed (it does not affect the film base). One method to obtain film toning is the metallic toning, obtained through a chemical process that involves a reaction of the emulsion with appropriate substances, which cause the replacement of the silver in the emulsion with colored metallic salt like copper or iron. Here, the most popular obtainable colors were sepia (using the silver sulfide), Prussian blue (adding iron ferrocyanide) and red brown (using ferrocyanide). The second method to obtain film toning is the dye toning, also known as mordant toning. This technique requires the conversion of the silver image to a colorless salt which acts as a mordant. The mordanted image is treated in a basic dye solution, where dye molecules bind to the mordant and produce a colored image. The metallic-toned images tend to be more stable than organic dye-toned images and with these techniques, dyes penetrate only the upper surface of the gelatin layer and the dyes applied might be very imprecise (Pritchard, 2021).

While the advent of sound films quickly made silent films and theater musicians obsolete, color replaced black-and-white much more gradually. With the sound introduction, tinting and toning were temporarily abandoned, leaving the market open to new systems of color photography. Different experimental methods to reproduce the "natural colors" were introduced during the film history evolution both for amateur and professional use and using additive and subtractive processes, but only a few of them were successful (Flückiger, Eva, & Nadine, 2020).

Kinemacolor: It was the first successful color motion picture process, invented in England by George Albert Smith in 1906 and used commercially from 1908 to 1914. It was a two-color additive color process, used for photograph and project a sensitized black-and-white film exposed through an alternating red and green-blue filter. The colors resulted from the blending of the two separate red and green alternating images. The main limit of this system, as all the additive systems, is that it was very wasteful of light due to the absorption by the color filters that allowed only a little percentage of light to really reach the screen, resulting in an image that was dimmer than the typical black-and-white film. For this reason and partly due to the expense of installing special Kinemacolor projectors in cinemas, the use of additive processes for theatrical motion pictures had been almost completely abandoned by the early 1940s.

Technicolor: After some experiment with additive systems, Dr. Herbert Kalmus, Dr. Daniel Comstock, and mechanic W. Burton Wescott developed a subtractive color system for Technicolor. This system used a modified camera in which the entering light was split in red and cyan light, subsequently sent to adjacent frames of one strip of black-and-white film. From this negative, two different positive prints were created. The obtained positives were, subsequently, chemically toned in cyan (from the red negative) and magenta (from the cyan negative), then cemented together into a single strip of film. This innovative process was later refined through the incorporation of dye imbibition, which allowed the transferring of the two matrices color dyes into a single print (George Eastman, 2021).

The pivotal innovation that made Technicolor a successful company was the introduction of the three-strip transfer process (produced by Kodak), also known as Technicolor Process 4. The process was very expensive but the public really appreciated the films vibrant colors and the dyes were extremely stable. With this techniques, different films were made: *The Wizard of Oz* (Victor Fleming, 1939), *Gone with the Wind* (Victor Fleming, 1951), *Snow White and the Seven Dwarfs* (David Hand et al., 1931), *Fantasia* (Wilfred Jackson et al., 1940).

Kodachrome: The introduction of this monopack multilayer film in 1935 produced an immediate changeover from black-and-white production to color film. This film produced by Eastman Kodak incorporated three separate layers of differently color sensitive emulsion into one strip of film. It is based on the subtractive color system, which filters colors from light by using superimposed cyan, magenta, and yellow dye images, created from the record of the amounts of red, green, and blue light in each point of the scene.

Eastmancolor: In 1950, Kodak introduced the first economical, single-strip 35 mm negative-positive process incorporated into one strip of film. For the first few years, Technicolor continued to offer his three-strip system combined with dye-transfer printing, but by 1953, and especially with the introduction of the anamorphic wide screen CinemaScope, Eastmancolor

became the marketing imperator. More and more films were made in color, which soon became the rule. From the 1960s, chromogenic films predominate, and Technicolor prints became more and more scarce.
Today, the main problem of film color is that many of the dyes used in color films are unstable organic colorants affected by natural aging and fading. Dye fading reduces the overall density of the image, which results in loss of contrast and in shifts in color balance. This phenomenon is inevitable and it is accelerated by uncontrolled conditions of temperature and relative humidity.
The stability of chromogenic films varies considerably among film emulsions and the time of the film stock's manufacture. For instance, Kodacolor films from the period 1942- 1953 are known to have remarkably poor dye stability in the dark and exhibit intense yellow/orange staining. Kodak Ektachrome films introduced in the early 1950s are dramatically less stable than the Kodachrome films they replaced. For 35mm motion picture films, Kodak Eastmancolor negatives and prints from 1950 onwards exhibit poor dark stability, especially in comparison with the Technicolor films that employed a proprietary dye transfer printing process with very stable dark fading characteristics. From the mid-1980s onwards, chromogenic films achieved the best dark stability possible for the process (Enticknap, 2013).
Dye fading is irreversible and once the dye images have faded, it cannot be recovered but cold or frozen storage environments and moderate relative humidity will slow the process. However, digital color restoration techniques may approximate the original color balance and simulate the original color information.

2.2 Digital cinema

Digital cinema, also known as D-Cinema, indicates the distribution and the projection of digital films. The transition from analog to digital in filmmaking was already announced in the late 1970s and led to an increasingly hybrid film production practice throughout the following three decades, improving and rapidly progressing in digitization of mainstream film production. Just in 2012, digital distribution and exhibition outmatched the traditional analog workflow (Fossati, 2018). Digital 3D is considered one of the factors that contributed to the accelerated shift to digital, thanks to several successful film releases relying heavily on this technology. However, despite a drastic change in balance between analog and digital, analog film tradition is still very much alive. Indeed, it still serves as the basis of film practice and is essential for understanding, restoring, and preserving film history (Fossati, 2018).

The last decade has seen a few other developments related to the new possibilities of digital means in film production workflows. Image and sound aesthetics, and film preservation practices such as using cameras with digital image sensors to shoot, non-linear system for editing (NLE), and the new digital intermediate process (DI) led to the full digitization of films during post-production, digitizing film rushes or a film to be restored, or ingesting born-digital rushes, before post-production is carried out (from editing to final grading). DI can also be used to refer to the final result of such a process, which is the digital master used to create distribution copies (on film or digital) (Fossati, 2018). Then, it could be stored in a Linear Tape-Open (LTO) magnetic tape data storage, or digitally distributed to theaters tanks to the Digital Cinema Package (DCP), a compressed and encrypted digital file package, defined in the digital cinema initiatives specifications, that is sent to cinemas by way of media carriers, virtual private networks or satellite communications, and finally showed through a digital motion pictures projector instead of the historical 35 mm film stocks.
In the last few years, more and more filmmakers are turning to digital for shooting their films, and it is expected that in a few years digital distribution and projection will become the norm making the whole film production chain celluloid-free (Fossati, 2018).

3. Film as container

A motion picture film is a set of contiguous *scenes*, edited together following a plot. Every scene is a *segment* of a film – composed by only a sequence or by different sequences edited together – that depicts a single situation or incident. Every individual image on a strip of a motion picture film is a *frame* or photogram and every frame is separated by others through a frame line. A *cut* is the instantaneous change from one scene to another: successive frames over a cut contain a short overlap between the last frame of one scene and the first frame of the following.
If we analyze the stratigraphic structure of a film, it is composed by a protective layer, an emulsion layer, a base and an antihalation layer. The emulsion layer is where the film image is registered and it can be composed by one single silver layer (in black and white films) of by different colored layers (color film); it is very fragile, that is why the protective layer is essential to preserve the film emulsion from dust and external factors which could damage the film image. The film base composes the main thickness of the film and must provide transparency, flexibility and resistance to it. In conclusion, the antihalation layer absorb the light which passes through the emulsion, thus preventing any light from being scattered through the

emulsion from the rear surface of the base, which could cause halo effects on the surface.

3.1 Film base

To obtain the characteristic of transparency, flexibility and resistance, film bases have been produced in different ways and materials along the film history.

Nitrate films: As presented in Section 1, George Eastman introduced the first commercial roll film on transparent cellulose nitrate in 1889. In resolving the cellulose lack of chemical stability, great difficulty was experienced, and its high flammability caused significant explosions both during the manufacturing process and during the projection of films. In fact, passing through the projector's film gate, the films were exposed to high temperatures increasing the likelihood of auto-ignition and several incidents of this type resulted in audience deaths by flames and smoke.

Cellulose was used as photographic film base for a period of almost 60 years and then retired but the photographic industry and film archives is still having troubles with these two serious shortcomings with films that have been retained (Shanebrook, 2016) .

Nitrate decay is a daily struggle for the archivists, that are familiar to the increasingly pungent, noxious odor that accompany the decay. Once begun, it proceeds at an ever-increasing pace and results in the decomposition of the nitrate plastic itself. Over time, as nitrate film is exposed to moisture, heat, and acids, the nitro side groups break away, producing nitrogen oxides in the film's environment that react with moisture and produce nitric acid. Nitrogen oxides and nitric acid readily promote silver corrosion, decompose gelatin emulsions, and catalyze the chemical reactions that cause further nitrate decay. Decomposing gelatin may present as sticky bubbles on the surface of the film and cause negatives or wraps of film to adhere together (i.e., blocking), that eventually becomes irreversible, so that the film roll becomes a solid mass. The last phase of nitrate decay involves the decomposition of the nitrate plastic into red/brown dust comprised of cellulose and colloidal silver.

In this 35mm reel of film with a yellow tint, most of the image has already faded, discolored, and the gelatin binder is bubbling and sticky to the touch. The yellow tint is now only visible on the edges of the film, where no silver image is present. This reel contains very few salvageable images.

Acetate films: Since 1910s, the cellulose diacetate film was introduced but the nitrate film base was discontinued only in 1951 thanks to the gradual introduction of the cellulose triacetate base. The diacetate had the tendency

to become brittle and shows a high degree of distortion due to its high moisture absorption while the triacetate had the required strength and dimensional stability properties required for professional motion pictures, but rather is subject to other degradation problems such as the so-called *vinegar syndrome*. First, when acetate is not appropriately stored, and it is exposed to heat, moisture or acids of the acetyl groups could release free acetic acid staring a strong degradation process that causes the film base to become brittle and shrink.
Like the nitrate film base, acetate is subjected to distortion, embrittlement and shrinkage, and also to other specific problems such as delamination, antihalation layer color retrieval and plasticizer exudation (RTI, Visual Decay Guide, 2021) (Horak, 2005).
Polyester films: Since the acetate film base still presents many problems and issues of conservation, there was the need for a more moisture-resistant support, possibly hydrophobic and with very low affinity for water: a synthetic polymer. Many experiments have been tried along the 1940s and 1950s. The Polyethylene terephthalate (PET) was discovered in 1941 but the commercial production of this polymer occurred after World War II. Kodak's first salable Estar Film Base was made in late 1959, sensitized, and released for sale in 1960 but films continued to be made on cellulose triacetate films until the 1990's. Polyester films, are highly preferable for post-production, exhibition, and archival purposes because of their flexibility, strength, tear resistance, wet stiffness and thermal and humidity dimensional stability.
Various techniques have been used, to improve this film performances. To the film base have been added primers, antistatic layers, conductive layers, physical protection layers, and gelatin to counteract curl created by opposite side coatings. For instance, the antistatic greatly reduces static charging of the film, "shocks", and static discharge, even at high transport speeds; it also helps reduce static attraction of dirt to the processed film during projection, resulting in longer print runs with less build-up of black dirt and cinch marks. Furthermore, the antihalation layer has been added to the film base (as a dark layer coated on or in the film base) to absorb and minimize the reflection of light that penetrates the emulsion from the base-emulsion interface and that could cause a sort of secondary exposure and an undesirable reduction in the sharpness of the image and some light halation around images of bright objects.

3.2 Film light-sensitive emulsion

Black and white films: The emulsion layer in black-and-white film is made by silver halide (*AgX*) crystals suspended in gelatin and spread on a plastic substrate. Generally, the gelatin is a colorless glue, with a strong adhesive power that serves several purposes, e.g, it controls chemical diffusion and protects the silver halide crystals (Shanebrook, Making Kodak Film , 2016). The silver crystals are the light sensitive compound in the emulsion layer, and their sizes determine the sensitivity, contrast, and resolution of the film. When the silver halides are hit by light entering in the acquisition system, each crystal reacts to the electromagnetic radiation creating a latent image in the emulsion which can be chemically developed into a visible photograph. During the film development, the grains in the latent image are converted to metallic silver, resulting as the black part of the film negative.

The first film emulsions were *Orthochromatic*, thus they had high sensitivity to blue, green and bright yellow wavelengths, low sensitivity to orange and quite blindness to red (see Figure 1) (Montanaro, 2019).

This problem was solved with the introduction of the *Panchromatic* emulsions, which extended the films color sensitivity through the whole visible spectrum (see Figure 1), reproducing all colors in shades of gray approximately matching their subjective brightness (Britannica E. , 2021). The Panchromatic emulsions were introduced in 1904 for motion picture and completely replaced orthochromatic stocks by 1930.

Color films: In color films, the light-sensitive emulsion presents several layers (general one sensitive to the blue, one sensitive to the green and one sensitive to the red light) which contain thin grains in a variety of similar shapes and sizes, gelatin and other materials coated on film base.

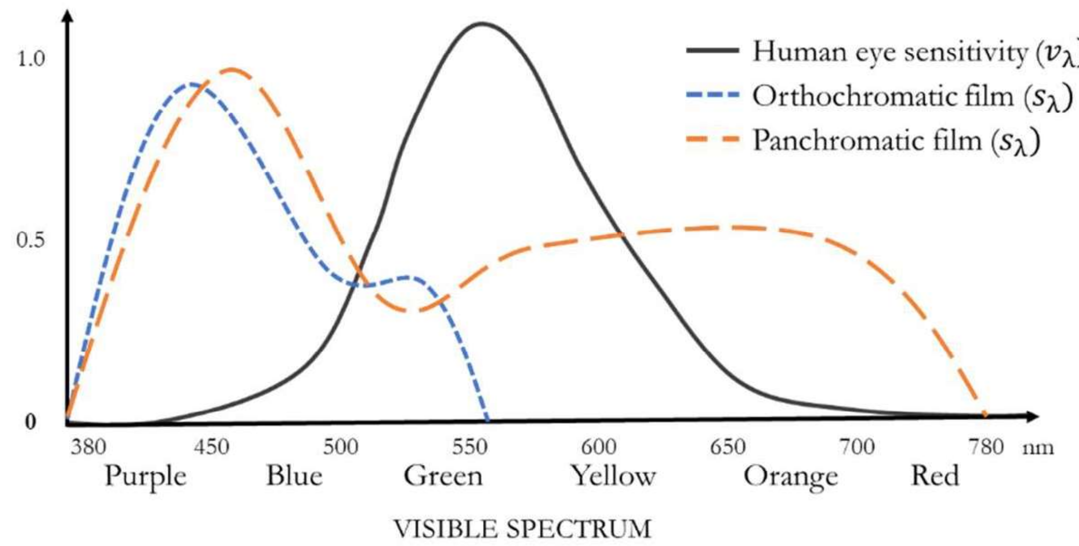

Figure SEQ Figure * ARABIC 1 Spectral sensitivities of the human eye compared with Orthochromatic and Panchromatic emulsions.

Considering a cross-section of a color negative camera film, its composition can be summarized as reported in Table 1. On top, there is an *overcoat matte* that lowers the surface coefficient of friction, reduces static electricity, and carries the materials (1). This layer is followed by the UV Filter Dye, that absorbs ultraviolet radiation (2) and then there are the three sensitive emulsions that creates three different latent images when exposed to color. While the Blue Sensitive Emulsion is divided in a Fast (3) and a Slow (4) emulsions, the Green and the Red Sensitive Emulsions are divided in a Fast (7), Mid (8) and Slow (9) emulsions. After the Blue layer, a yellow filter (5) prevents UV and blue light from exposing green and red layers. Between the color sensitive emulsions, an interlayer made of gelatin works as chemical barrier (6 and 10) and, an antihalation layer (14) composed of dye and particles absorbs the scattered light, filters light for printing and reduces static electricity.
Over the Cellulose Triacetate base, that provides physical strength to support the coatings, are applied on one side a subbing layer (16) that improves coating adhesion, and on the other side a backing layer (17) that protects the emulsion layer and reduces the static electricity.

<table>
<tr><th>Layer</th><th colspan="2">Materials</th></tr>
<tr><td>1. Overcoat Matte</td><td colspan="2">Plastic beads, Lubricant, Antistat, Polymer and gelatin</td></tr>
<tr><td>2. UV Filter Dye</td><td colspan="2">Dye</td></tr>
<tr><td rowspan="2">3. Fast Blue Emulsion</td><td colspan="2">Gelatin, silver halide and dye</td></tr>
<tr><td colspan="2">Yellow Image Dye Coupler</td></tr>
<tr><td>4. Slow Blue Emulsion</td><td colspan="2">Cyan Dye Coupler</td></tr>
<tr><td>5. Yellow Filter</td><td colspan="2">Dye</td></tr>
<tr><td>6. Interlayer</td><td colspan="2">Gelatin</td></tr>
<tr><td rowspan="3">7. Fast Green Emulsion</td><td rowspan="8">Gelatin, silver halide and dye</td><td>Magenta Image Dye Coupler</td></tr>
<tr><td>Cyan Dye Coupler</td></tr>
<tr><td>Yellow Dye Coupler</td></tr>
<tr><td rowspan="3">8. Mid Green Emulsion</td><td>Magenta Dye Image Coupler
Magenta Masking Coupler</td></tr>
<tr><td>Cyan Dye Coupler</td></tr>
<tr><td>Yellow Dye Coupler</td></tr>
<tr><td rowspan="2">9. Slow Green Emulsion</td><td rowspan="2">Magenta Dye Image Coupler
Magenta Masking Coupler</td></tr>
<tr></tr>
<tr><td>10. Interlayer</td><td colspan="2">Gelatin</td></tr>
<tr><td>11. Fast Red Emulsion</td><td rowspan="4">Gelatin, silver halide and dye</td><td>Cyan Image Dye Coupler</td></tr>
<tr><td rowspan="2">12. Mid Red Emulsion</td><td>Cyan Image Dye Coupler
Cyan Masking Coupler</td></tr>
<tr><td>Yellow Dye Coupler</td></tr>
<tr><td>13. Slow Red Emulsion</td><td>Cyan Image Dye Coupler
Cyan Masking Coupler</td></tr>
<tr><td rowspan="6">14. Anti-halation</td><td colspan="2">Dye and Particles</td></tr>
<tr><td colspan="2">Cyan Dye</td></tr>
<tr><td colspan="2">Magenta Dye</td></tr>
<tr><td colspan="2">UV Dye</td></tr>
<tr><td colspan="2">Yellow Dye</td></tr>
<tr><td colspan="2">Antistatic</td></tr>
<tr><td>16. Subbing</td><td colspan="2">Polymer</td></tr>
<tr><td>15. CTA Base</td><td colspan="2">Cellulose Triacetate</td></tr>
<tr><td>17. Backing</td><td colspan="2">Plastic beads, lubricant, polymer, anti-stat</td></tr>
</table>

Table 1. Cross-section of a camera negative film. Figure reproduced from *Making Kodak Film*. Robert L. Shanebrook.

4. Film conservation

As a medium, historic films have problems in terms of preservation and storage, and the motion picture industry is exploring many alternatives to save those records of past life. If properly stored, a film can theoretically last forever, but during the years, relatively few films have been correctly preserved, and many of these are still in poor conditions.

Every time a film runs through a projector, it is eventually worn, scratched, or damaged and it is impossible to avoid its deterioration. The only possible action is the film stock preservation in the best possible conditions, anyway this requires a careful and constant control of storage environments.

The earliest film archive is the Swedish Film History Collection, which has been followed by the film archives in Paris, London, and New York City. In 1938, the *Fédération Internationale des Archives du Film* (FIAF) was founded and still today this is an international federation which brings together institutions dedicated to rescuing of films both as art and as historical documents (FIAF, 2021).

The biggest problem of film preservation is that, even with a limited selection, acquisition and storage are expensive and difficult, and nitrate film requires regular tests to determine whether it has deteriorated enough to require copying. In this context, the preservation of color films presents the most serious difficulties, in fact all color films made since 1953 are subject to fading that can be arrested only by storing prints at very low temperatures (Nishimura, 1993).

The best way to preserve a film stock is to store it depending on the support. Furthermore, it is fundamental to remember that the effect of temperature on the decay rate is a continuum: the higher the temperature, the faster the decay, and vice versa.

To simplify the evaluation and planning of storage conditions for mixed media collections, the range of possible temperatures has been divided into four categories at a relative humidity between 30% and 50% (RTI I. P., 2021), where *room* is a temperature around 20°C, *cool* is around 12°C *cold* is around 4°C and *frozen* around 0°C. (see Table 2) There, *Unacceptable* means that the temperature may cause significant damage, *Acceptable* means that the temperature meets ISO recommendations and *Best Practice* means that the temperature will provide an extended lifetime.

	NITRATE	ACETATE (B&W; COLOR)	POLYESTER	
			B&W	COLOR
ROOM	Unacceptabl e	Unacceptable	Acceptable	Unacceptable
COOL	Unacceptabl e	Unacceptable	Acceptable	Unacceptable
COLD	Acceptable	Acceptable	Best practice	Acceptable
FROZE N	Best practice	Best practice	Best practice	Best practice

Table 2. Storage conditions defined by the Image Permanence Institute for every support. Figure reproduced from (RTI I. P., 2021)

5. Film restoration

Although institutional practices of film preservation date back to the 1930s, the field received an official status only in 1980, when UNESCO recognized *moving images* as an integral part of the world's cultural heritage. For many years *restoration* and *preservation* have been used as synonymous. They meant a series of ongoing efforts among film historians, archivists, museums, cinematheques, and non-profit organizations to rescue decaying film stock, to preserve the images contained and to create a durable copy without any significant loss of quality.

The National Film and Sound Archive of Australia and Michele Canosa give useful definitions of preservation activities:

> *Preservation are all the practices and procedures necessary to ensure permanent accessibility (with a minimum loss of quality) of the visual or sonic content of the materials. Preservation may be considered as having both active and passive dimensions.*
>
> *Passive preservation is synonymous with 'storage' meaning keeping the material in an ideal environment and not subjecting it to any mechanical risk through use.*
>
> *Active preservation includes such practices and procedures as technical examination, technical selection, conservation, methods of storage in correct environments, housekeeping and collection control procedures (such as maintenance of technical records, surveillance, labelling etc.), technical restoration, rejuvenation, duplication and quality control.*

In Boarini and Opela the operations of *conservation* and *restoration* are defined as:

> *Conservation is a part of preservation and are all the processes necessary to ensure the physical survival of the film with minimum degradation.*
>
> *Restoration is the process of compensating for degradation of an artefact in order to return its visual and sonic content to its original character and condition.*

These definitions give some guidelines about the terminology that concerns the restoration workflow of a film, but they remain general and do not specify the technical operations involved in the single actions. This weakness most always leads to every restoration laboratory and every restorer to follow its own guidelines according to their formation and experience. Thus, the lack of shared definitions and technical references for film restoration is leading to the creation of students and experts specialized in the use of specific instruments and software, strictly dependent by the school and laboratory of origin.

5.1 Film restoration workflow

Through the mid-'90s, film restoration work was done photochemically but since late 1990s, films were restored with digital techniques. Damaged frames could be scanned, repaired and a picture that would previously have been presented in fragments or severely truncated could now be seen in a version close to its original. Today, the whole restoration work is almost all done digitally, allowing films to have whole new live, anyway the technology sometimes drives the restoration choices, when it should be the opposite (Plutino, Tecniche di Restauro Cinematografico – Metodi e Pratiche tra Analogico e Digitale, 2020).

The restoration process is not limited to establishing the technical procedures necessary for the interventions to be carried out, but instead allows a better understanding of the film being restored. Whatever workflow will be undertaken, there are preliminary phases in common (see Figure 3). In this work, we are not considering the sound restoration but if the film object of the restoration has sound, the images and the soundtrack are treated and restored separately until the final combined positive copy is printed.

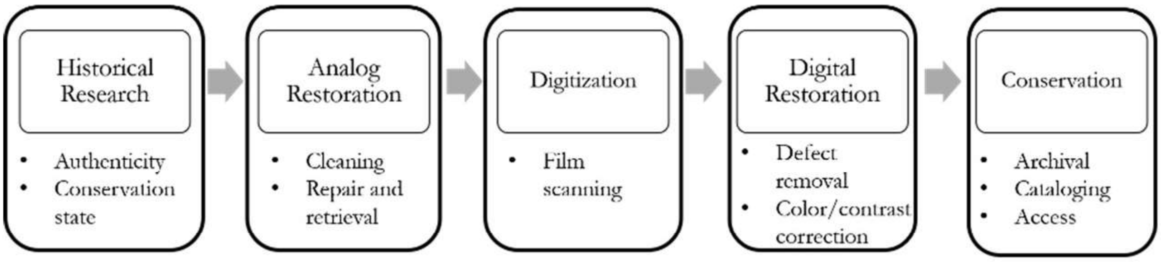

Figure SEQ Figure * ARABIC 3. General film restoration workflow.

5.1.1 Historical research

The first step of the restoration workflow is the *historical research*. In fact, when an archive or a lab decide to restore a certain film, it is necessary to look for the *availability* of other copies of the same movie around the world in order to identify where they are located and in what conditions they are.
In the field of the figurative arts, the same work can have various types of qualifications: the original, a copy of an author or a collector or of another artist, an author's *replica* or a *replica* with variations. Historical investigation includes the studies on authenticity of those materials and studies on the historical-artistic importance of the work.
In parallel, the research also focuses on extra-film materials like production documents, brochures and advertising, photos, censorship visas, correspondence and so on.
Once found the copies, it is necessary to define a restoration project considering the economic possibilities and the results of the availability research, but also evaluating the film elements, their general conditions and the problems of decay.
At this point, a careful comparison of the copies will help to create the reference document in which is indicated from which source has been took each shot, which changes have been made and which parts have been rebuilt. In this step, the restorer may produce an element as close as possible to the original and several factors must be evaluated to make decision valuating the cost and risk of repair.

5.1.2 Analog restoration

This phase consists in making all the copies selected in the best physical condition to be duplicated, to avoid film breakings during the digitization or the analog printing process. The first steps in film analog restoration are the repairs or substitution of damaged splices and perforations using adhesives, cement and tape splicers. In fact, the splices between film lengths degrade over time and eventually fail, even under optimum storage conditions and must be repaired by manually scraping away the adhesive residue and remaking the splice (Enticknap, 2013).

The analog restoration can take several weeks because this phase includes also chemical operations that can take long time: e.g., sticky films require incubation periods with silica gel to reduce humidity and consequent slow and controlled reintroduction into the atmosphere.

Once the copies are repaired, it is possible to proceed in different ways, according to the state of the material and the output required for the project (Enticknap, 2013).

Part of the analog restoration are also the operations of film cleaning, which could include both the simple use of an organic solvent to remove contaminants from the film surface using a pad of cotton wool and the automated application of chemical substances, to leave the permanent, protective residue on the film. Anyway, this second procedure could affect the film irreversibly, so today there is the tendence to avoid the application of chemical treatments.

An alternative commonly used non-invasive cleaning technique is the ultrasonic film cleaning, which allows the cleaning through the ultrasonic-induced agitation of the solvent separating contaminants from the film surface and dissolving them. In addition, the particle transfer roller (PTR), can be another commonly used technology to clean films that consists of several cylindrical rollers coated with a mildly adhesive, polyurethane-based substance placed in a film path, usually between the feed reel and the point at which an image is read in a projector, printer, or scanner. The surface of the roller is formulated to be adhesive enough to transfer contaminants from the film surface to the roller, but not sticky enough to impede the film motion.

In a photochemical workflow, the master element consists of physically assembling sections of different film elements together, from which the restoration master element will be created by printing. In a photochemical workflow, it is necessary to ensure that all the footage components within the assembled master element are of common polarity either a positive or a negative image.

Image enhancement by photochemical process usually includes the mitigation of scratches and the removal of dirt and artefacts. In a wholly or primarily photochemical restoration project, the main duplication stage begins when technical selection, cleaning and scratch diminution treatments and master element assembly have been completed, and the assembled reels exist with the order of shots as they are to appear in the restored film. The

duplication is carried out using a printer, which re-photographs the image on an existing processed film element onto unexposed, new film stock to create a copy of the assembled master element, in some circumstances changing its visual characteristics in the process.
In film restoration, the printing process can incorporate a number of techniques intended to change the aesthetic properties of the image on the destination film stock to solve the perceived effects of physical damage or chemical decomposition to the source element which cannot be removed or mitigated by working directly on the film itself such as the shrinkage of the film base, severe scratching, grading, sensitometry and densitometry, or color dye fading (see Section 6). In the case of an analogue restoration workflow for the image, the result will be either a new negative or fine-grain positive element, depending on the polarity of the assembled source element being printed (Enticknap, 2013).

5.1.3 Digitization

In the film scanning phase, each frame of the analog film is converted in a digital image through a gate, equipped with a LED source that digitize each frame using defined parameters. At the end of the process, the digitized film is returned as uncompressed file usually in DPX (Digital Picture Exchange) format, designed specifically for restoration. This format, in fact, encodes information about the gamma of acquisition and incorporates a *lookup table* (i.e., calibration data that is used to ensure that the color space in the scanned film looks consistent in all the display devices used in the workflow). The DPX format also enables the creation and storage of metadata information about the file.
A remarkable advantage of the digital restoration is that the shots do not have to be scanned in the order they appear in the finished restoration, and non-linear editing can be done on a software timeline after scanning and post-processing, and the source elements from which the restored film will be constructed can be scanned separately.
The scanning resolution is a trade-off between the detail of image information captured (resolution and color depth at which the individual frames will be scanned) and the volume of data that will need to be processed (for grading and color correction) and stored, and thus the overall cost of the project. Today, the scanners used for film restoration uses standard resolution of 2K up to 4K. As a general rule, 2K (with a width of 2,048 pixels) is generally considered sufficient for scanning film frame sizes up to 16 mm and for digital cinema projection on smaller screens (Fossati, 2018). Whereas 4K

(with a width of 4,096.80 pixels) is regarded as the norm for 35 mm film and projection on larger screens (Dagna, 2014).
In parallel with the development of innovative and new systems of acquisition, at both national and international level, many guidelines and regulations have been developed and adopted by archives, libraries, and laboratories (FADGI., 2015), (Van Dormolen, 2012).
Nevertheless, in the digitization pipeline, an evaluation of the instrument performance is rarely considered, as well as an objective evaluation of the results. In fact, digitization guidelines rarely contain information on instrument calibration, and in many practical cases film scanning is performed in uncontrolled conditions or using automatic color correction and adjustments introduced by the scanner software. In this context, the lack of proper systems of performance evaluation makes impossible to measure and assess the influence of the system processing in the final acquisition, and an excess of automatism can be dangerous, when the digitization purpose is a faithful digital reproduction of an analog film (Plutino & Rizzi, 2020).
Digital restoration: After the film digitization, the following step is the digital restoration. Today, this phase is done through specific software, which allow for a manual, semiautomatic, or automatic workflow, supported by a thorough control and a frame-by-frame correction carried out by specialists in this sector. In this way, the digital restoration phase can take several months, and specialized professionals are required.
These software exploit dedicated algorithms able to identify and remove all the undesired elements in the film that are impossible to be removed through analog restoration (e.g., strains, flickering, graininess, dust and scratches). However, despite the great potential of digital restoration, these algorithms are not foolproof and user supervision is always needed. In fact, the instruments for defects identification are significantly less efficient than the human eye. Consequently, one of the biggest requirements of digital restoration systems is the capacity to work automatically, but the archives or restorer's ethical stance demand also a transparent restoration process. In fact, the restorer must be able to check the results of the software intervention, ideally by comparing frames before and after every step of the process. The restorer has the choice to let the software automatically search and remove damage according to the chosen parameters, restrict the application of the tool to certain areas, such as to the single-frame damage only and, carry out manual retouching (Wallmüller, 2007).
The use of automated restoration tools is, therefore, an economically attractive possibility. These tools will look for similar defects in multiple frames of scanned film frames and apply a fix automatically when they find

them, but the software defect identification is not infallible and is less accurate than the human eye (Bellotti, Bottaro, Plutino, & Valsesia, 2020).
Generally, software-based image restoration tools fall into seven broad functions: polarity correction, mitigation of dirt, adjustment for consistency of stability and illumination, brightness, contrast and color correction, recreation of original post-production effects and achieving consistency in the overall aesthetic.
The digital restoration step in the film restoration workflow involves not only the restoration *per se*, as described above, but also the color correction.
Although the general workflow and the available software are still very similar, the specific tools for resolving color issues have clearly improved in the last decade. In line with the general development in the field, restoration software packages have included some basic color correction applications which can be used for tackling smaller problems. Furthermore, with a faster processing and rendering time, color restorers can work efficiently with high resolution (typically 4k) material. In general, for all color restorations, the same tools are used as those used for color grading in post-production (Fossati, 2018).
As well as for all the other steps in the restoration workflow, also for digital restoration the used instruments and hardware are fundamental, in fact is mandatory the use of a high-quality calibrated monitor to edit and show the results of the restoration process. In some cases, in large laboratories the results are also projected in a standard calibrated cinema.
Nevertheless, the dependency of digital film restoration on consumer software often can lead to the tool-dependency of the restorers. This means that the restorer in his carrier become an expert in the use and application of a single editing software, and this led to the tendency of accepting passively all the solutions provided by the software producer without knowing important details about how them have been produced or demanding for new solutions. This situation led to the lack of research in alternative solutions for film restoration and thus, film restoration technologies are left in the hands of industries and companies which produces general image and video editing solutions, without a proper focus on restoration (Plutino & Rizzi, 2020).
Furthermore, since in film restoration a proper reference is missing or has been subject to decay, is even more important to find new solutions and tools to study, analyze and restore film colors. In fact, even today, a technical colorimetric characterization of films, is quite always impossible (Plutino & Rizzi, 2020) (Mazzanti, 2019).

5.1.4 Conservation

The result of the entire photochemical or digital process will be a new master film element or digital asset, one that is intended to serve the purposes of maintain its integrity in long-term storage and of serving as the source element from which all subsequent access copies are made. For what concerns the long-term durability, an analogue final output is considered preferable. In fact, if stored in appropriate atmospheric conditions (i.e., cool and dry), a new polyester base film element has a useful lifetime measured in centuries (Enticknap, 2013), (RTI I. P., 2021). Despite this shared knowledge, many archives and restoration laboratories cannot afford the expenses of an analog film printing and decide to preserve the digital format.

On the other hand, for what concerns the film accessibility, the possible solutions depend on the most diverse needs. If the image restoration was photochemical, the final negative or fine grain positive will itself be scanned, and the resulting digital version will be used as the source from which to transcode the versions required for distribution. If the image restoration was digital, software available today enables to reduce the resolution or other quality characteristics while copying a digital file so it makes sense to plan a digital restoration project such that the final output file will have the highest quality needed for access, or higher.

The most diffuse technologies to preserve digital files are the RAID (Redundant Array of Independent Disks) and the LTO (Linear Tape-Open). Anyway, the obsolescence of the digital format is a key factor that contributes to the common state of conservation practices for which the preservation on analog film is often cheaper than its digital equivalent. In fact, all the digital technologies require an active approach, continuous maintenance and renewal of the software and hardware, and this led to a strong need of constant data migration.

The archival issues of the long-term conservation masters are an open problem in film restoration and archiving domain and, today, the archives are still looking for a trade-off between analog and digital conservation.

In this last step of film restoration workflow, together with the conservation, the cataloging of the restored film is included. Nowadays, the cataloging boards and guidelines give particular attention to the documentation of the analog process and just a few of them also consider the digital restoration process. In fact, many cataloging sheets, databases and guidelines, report just marginally the intervention made during the digital restoration, it is not satisfying (Dagna, 2014).

Among the few points generally accepted in the restoration workflow, there is the ethical practice of reporting in details all the interventions and decisions made on the film during the restoration, to create a complete record. That aims at giving the future end-users the reversibility of all the operations: it is commonly done for all the analog intervention, but not for the digital step, where the lack of documentation is one of the most important issues in the restoration workflow, because often it is not only impossible to reverse a digital intervention, but it is also impossible to know which enhancement or modification has been made on the film.

5.2 Simulating early film colors

The color dye fading in the photochemical restoration is usually resolved by the Desmet color method that allows to replicate the tinted and toned effect used in a film. The technique was developed by Nöel Desmet from the Royal Film Archive of Belgium and involves printing a black-and-white negative on a color print stock and the colored tints and tones are replicated by exposing the print stock using a combination of red, green, and blue filters on a continuous contact printer. In some cases, the color is replicated by *pre-flashing* the raw stock with no negative between the light source and the color print stock. Other colors are replicated by varying the light filtration with the black-and-white negative in contact with the color print stock (NFSA, 2021).
To reproduce a print only colored by tinting, the developed black and white inter-negative is first printed onto a modern color print stock, then the same film stock is flashed with the appropriate colored light (complementary to the desired one) or with a neutral light filtered through specific filters.
To reproduce toned prints, the developed black and white inter-negative film is exposed onto a color print film using a colored light source rather than a neutral one. As the light passes more easily through the light parts of the negative image, the result will present color only on the dark parts of the positive image, simulating the original toning.
Combined tinting and toning effects can be reproduced using the same process used to simulate the tone but adding a second printing pass to color the light parts of the image, simulating the original tint.
Also in digital restoration, the Desmet method can be used to simulate early cinema colors such as tinting and toning. The Digital Desmet method has become widely used and its results have improved significantly in recent years. The digital version of the Desmet method is in many ways similar to the photochemical one. To simulate the tinting, the method is carried out on the black-and-white image and, only at the end, a color layer is added to the image; to simulate the toning the blacks in the image are replaced by a color. It should be mentioned that analog techniques for recreating tinting and toning effects are still quite practical and can also give very good results.

Similarly, in the case of hand-colored and stenciled films, digital restoration has proven to be quite satisfactory in simulating the original tints: does not only allow for great flexibility in determining each separate color that was originally applied with an aniline tint on a black-and-white image, but it also provides a neutral reproduction of the underlying black-and-white image. The restoration of later chromogenic color films has become common practice in the field as digital, unlike analog methods, allows restoring faded films more easily and efficiently. For all color restorations, the same tools are used as those used for color grading in post-production (Fossati, 2018).

6. Supplementary materials

In this chapter we briefly we introduced the story of cinematographic technique, we presented the main features of film as a container and as content and explained the general workflow of film restoration. Since many images and photos of different film coloration processes are covered by copyright, we have not the possibility to report them. Nevertheless, here we report different websites where it is possible to find many descriptive images of the topics discussed in this chapter:

Timeline of historical film colors by Barbara Flueckiger: https://filmcolors.org/

Motion picture film processes by RTI-Image Permanence Institute: https://www.filmcare.org/identification

Technicolor online research archive by George Eastman Museum: https://www.eastman.org/technicolor-online-research-archive-0

Online open access Resources by FIAF: https://www.fiafnet.org/pages/E-Resources/FIAF-Summer-School-Resources.html#_Toc517876626

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