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"The Stuff That Dreams Are Made of"—Restoring Cinema Colors: A Roadmap for Real Research

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Abstract: Since 1895, through the analog and the digital eras, color is among the many narrative and aesthetic tools cinema language used in its creative process to shape a unique, multi-sensorial experience for its audience. Over these 120+ years, endless cinema color techniques, technologies, aesthetics, and ideologies came and went. One thing that stayed the same is that color in cinema, more than a technology, is a complex system made up by many components: filmmakers' ideas and intent, negotiations with the audience, technologies (such as film stocks, chemicals, cameras, printers, developing machines, projectors), and laboratory processes and practices. Taken individually, none of these elements tells the whole story of color use and experience in cinematographic works. This complexity adds to the fact that much of film color technology history is not recorded in books, journals and patents and is often forgotten as so much of it relies on individuals' practices and memories. Consequently, a novel and more comprehensive theoretical and methodological approach is needed in order to make it possible to preserve and restore cinema colors, that is, to faithfully recreate their original chromatic effects in a modern, completely different environment.

Keywords: color cinematography; film technology history; film history; film restoration; history of color cinematography

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1. Introduction: To Know That We Do Not Know

"Cinema has never had a phase when it was not in color: colors were there, immediately. Immediately as a deliberate addition, a supplement, contingent by nature, thus a fortiori implying intent, and purpose" [1] p. 30 (my translation).

Not only is color present from day one in the history of cinema, but its role has always been much more complex than a mere device to improve the "realism" of cinema experience. Cinema was always very much aware that nothing is less "natural" than cinema colors. Rather, it derives narrative, emotional, and aesthetical meaning from its unnaturalness and that interference zone generated by the chasm between cinema's inherently unnatural colors and the viewers' own perceptions of, and cultural references to, the colors of the real world. In other words, cinema color (and black-and-white, which since 1895, cinema treats as a chromatic choice and should be interpreted as such) has a wide range of functions, effects and meanings going well beyond the mere intent to technically reproduce, record, and simulate the real world and venturing into the realms of language, narrative, aesthetics, culture, and ideology, as many scholars posited, including Tom Gunning—here on early cinema: "Like the cinema, the color may have become omnipresent, but still had the ability to disturb cultural hierarchies through its association with the emotional and sensual rather than the rational and ideal" [2] p. 252.

From all this, a couple of considerations derive. First, it is not really possible to study or discuss cinema while ignoring color or considering it "just" a technical addition. Color was never a step on a continuous line of technical "improvements" from a "primitive era" to an advanced one. From a systemic point of view, black-and-white was cinema's only option for roughly a decade, around the 1930s. In the other 115 years of cinema history the technology of color changed constantly in a mutual interplay between creative intent and technical possibilities and limitations—the keyword here being mutual).

Secondly, it is not possible to understand how in practice cinema makes use of that interference zone I referred to earlier without being able to evaluate, i.e., to experience, watch, and analyze the characteristics and the effects of the many color environments that came and went. I suggest here the term 'color environment' to include all the factors that concurred to define color in a given moment of film history: technologies, techniques, practices, linguistic and ideological contexts. In short, this means that studying color cinema (or color in cinema, or simply cinema) implies to experience, watch, and analyze film works in conditions that represent as accurately as possible those a given work was conceived for. In turn, achieving this requires knowing how to correctly represent past color systems under current, completely different viewing conditions (new technologies, displays, and contexts)—which is in fact the proper definition of color restoration when applied to cinema.

In practical terms, an imperative precondition of color restoration in the current digital environment is a comprehensive characterization of each of the hundreds of color environments that existed in film history. In fact, only by means of a full characterization of each color environment we can assess whether or to what extent the colors of the work we are confronted with correspond to the ones the work was conceived for. Once we ascertain that for whatever reasons—such as image digitization, use of current digital displays, projection of analog originals on modern projectors and screens, or simple color degradation due to time (aka color fading)–the chromatic experience differs from the one at the time of creation, only a full characterization of both can tell us in what and how much they differ from each other and, most importantly, whether and how one can be mapped into the other.

As essential as they might be, such characterization, modelling, and mapping of the characteristics (chromatic response and absorption, gamut, etc.) of past and present cinema color environments simply do not exist today, at least not with the granularity and level of detail that would be necessary.

Worse, even a coherent methodology is lacking, from a definition of what needs to be analyzed to the factors to be taken into account and down to the actual tools, instruments, and procedures for analysis. While pleading the case of the urgent necessity of this approach to the study of cinema color(s) and hoping that sufficient research efforts address this endeavor, we need to start by defining the factors and variables that must be taken into consideration. Therefore, we dare propose here some reflections for a roadmap of research and a methodological approach.

2. In Principio Erat Color—A Short Walk through History

In order to better understand the categories that need characterizing, modelling, and mapping and how they apply differently to various systems, it might be useful to reacquaint ourselves with the history of cinematographic color processes—at least in broad terms, or by geological eras, so to speak.

2.1. Applied Colors (1895–Mid to Late 1920s)

Already at its birth with the Frères Lumière and then G. Méliès, cinema starts applying dyes to B&W positive images, where the silver image provided density and modulation. It did so by appropriating techniques belonging in the photography studio or the textile and printing industries: hand-painting, tinting, toning, mordanting, and stencil coloring. At least until the first post-war period, this was performed in a very low-tech and labor-intensive environment. According to the practice at the time, every shot or scene was separately printed onto B&W film and fully processed before applying coloring. The resulting separate, colored positive segments were finally assembled following detailed instructions (a process known as "positive cutting").

Until the mid-1920s, techniques and equipment in use allowed for almost no process controls, and standards barely existed yet. Cameras were hand-cranked, so exposure time was a guessing game; all "wet processing" (developing, as well as tinting and toning) was done manually, with film wound on waterproofed wooden racks immersed into tanks containing the various solutions (developer, fixer, or coloring processes); agitation came from simply lifting and dropping the racks into the tank, no automatism existed for replenishment or temperature control. Once fully developed, the negatives and positives were unwound off the racks, re-wound onto large wooden drums and dried by mean of hot air. Positives would then be sent to coloring, with tinting and toning performed in very much the same way as processing. Operators were given general instructions about the time of permanence in each bath, but mostly they visually judged when the film was "ready"—i.e., had reached the right silver or color density. Printers had primitive and unreliable exposure controls so that negatives were usually grouped by either by similar density, or by color process—all the over-exposed ones on one small reel, and all the yellow tinted shots on another, and so forth. The absence of automation, standards, and controls had at least one advantage: it allowed for the widest range of corrections. If for instance a piece of film was under- or over-exposed, it would suffice to keep it longer in the developer, same if the developer was depleted or its temperature too low. Finally, after any coloring process or combination thereof, the resulting separate, colored positive segments were joined together following detailed instructions (aka positive cutting).

This workflow was typical all through the "applied-colors era" and its complexity allowed for the wide degree of flexibility and the unsuspected sophistication required by the cinema industry and market at the time. For instance, the practice of "positive cutting" was soon perfected enough to allow for one laboratory to produce multiple versions of the same work in parallel. Every shot and scene of the film was processed and colored separately and only assembled together with its intertitles at the very end by "positive cutters" (mostly underpaid young women) who followed instructions written either on the positive film segments themselves or in shot lists. It was therefore extremely simple to create multiple versions—differing in language of the intertitles, in the narrative continuity or in the actual coloring by simply switching shot-lists. For richer discussion and analysis of these practices, I shall refer to my previous article on Film History [3].

What must be emphasized in this context is that any information we find in literature or documentation—including test-films—regarding processing parameters employed at the time for B&W development or coloring processes—such as temperature, duration, chemical formulas and concentrations, pH, and even type of dyes, etc.—is almost meaningless, or at best merely indicative, as objective, regular, scientific, or analytical control were not carried out in the everyday practice of the time. Therefore, the only way to characterize and map the characteristics of any process employed in those days is to analyze the largest possible number of actual extant films with a statistical approach.

Although cumbersome and labor-intensive, these coloring processes rapidly became ubiquitous. Very soon, nearly all films were "colored/a colori/en couleur" (as they were advertised at the time) with varying levels of complexity and very sophisticated chromatic effects obtained thanks to dozens of dyes and combinations of tinting, toning and stencil coloring. This last process was also able to reach unexpectedly high levels of realism. In a few years, color had turned into a key element of cinema's language, aesthetics, and strategies to become dominant in shaping the life and experiences of millions who, in those years, had otherwise limited access to anything color.

Along the 1920s, applied colors were slowly pushed aside by a combination of factors. Film language and aesthetics were changing, influenced by improvements in B&W picture quality, and by new narrative and editing devices. The increase in the films' average duration, along with requirements of the post-war globalized cinema market made higher productivity necessary, thus forcing labs to automatize and streamline their processes—manual processing was being replaced by continuous developing machines, while printers became semi-automatic. Finally, when at the end of the decade the advent of sound-on-film made positive-cutting impossible, manufacturers tried offering positive film stock supposedly compatible with soundtracks that was pre-tinted in a small number of hues—dyes were in fact applied in a sort of lacquer on the base rather than by imbibing the emulsion.

However, by then cinema had moved on from applied colors.

2.2. "Natural" (i.e., Recorded) Color Systems (A)-Additive—The 1910s

Not yet of age, cinema already started researching ways to—as termed at the time—"record the colors of nature"—as opposed to simulating them by applying colors to B&W images. Previously, cinema had opened to its spectators a window on the world, particularly for those who could hardly afford a tramway ticket. It had brought color into people's otherwise colorless everyday. It was well on its way to become the real Gesamtkunstwerk encompassing theatre, visual arts, music, photography, and literature. Its fathers, the Lumières, had invented color photography and demonstrated 3D and immersive projection. Edison had added sound recording and synchronization. Soon cinema was to be the first to amplify sound for the masses. So, it was only logical for everybody to assume that cinema was destined to add capturing and reproducing "all the colors of the world" to this list of world-reshaping inventions.

Around 1910, additive synthesis was the obvious choice for recording color. With the concept being already known to photography and performed on Magic Lanterns, all the early results in cinema came from there: Friese-Greene, Gaumont's Chronochrome, Kinemacolor, and the very first Technicolor system. All attempts were based on the simple principle of filming two or three B&W separation negative images through fixed or rotating filters, and to recombine the resulting positive images in projection by subsequent projection through rotating filters (Kinemacolor), or image superimposition on screen (Technicolor1, Chronochrome). Friese Greene's system was the sole exception: he hand-tinted alternate frames rather than using filters.

Ingenious as they might sound, additive color systems failed to have a real, lasting systemic impact on film history, and none did make it into the 1920s (except for some zombie returns few decades later, like Francita). Few films were made per process as it soon became clear that audiences were not excited enough by the idea of "natural colors" to overcome the many obvious shortcomings these systems suffered from. First, film emulsions were not really fully panchromatic yet and, as we saw previously, film processing and printing techniques were far from precise, leading to doubtful color separations and consequently reproduction—even more so as most were two-color systems. Inventors were well aware of this—so much that Kinemacolor advised cameramen to use different sets of filters depending on the subject at hand. Furthermore, subsequent capture through rotating filters inevitably led to serious color fringing due to temporal parallax. Chronochrome had solved the problem of temporal parallax by exposing three frames at once through a special lens holding RGB filters, only to experience color fringing due to spatial parallax. By inventing the prism divider—an optical device that allowed the concurrent exposure of two frames through the same lens—Technicolor1 solved all parallax issues at once, only to find out that superimposing the two positive images in projection was tricky at best. Herbert Kalmus (Technicolor's co-founder) apparently commented about his additive system: "I concluded that the operator would have to be a cross between an acrobat and a professor" [4] p.12. Last but not least, additive systems were uneconomical: they required dedicated or deeply modified projectors—mounting special filters or lenses, running at twice or thrice the usual speed—and filming and printing obviously required two or three times more film stock.

In a blink of an eye, additive was out and for its return, cinema must await electronic and digital imaging.

2.3. "Natural" (i.e., Recorded) Color Systems (B)-Subtractive, Non-Chromogenic (Mostly Technicolor2 to 6: 1920s–1980, Semi-Revived 1990s)

Capture: separation3 B&W negative film images. Reproduction: positive prints with subtractive-color positive images obtained by dye-transfer (aka imbibition process) onto "blank film" (with or without "key" B&W image).

By the late 1920s, just a short decade or so after the failure of additive systems, the landscape of cinema technology had changed deeply. The 35 mm format was fully standardized (as was the newly born 16 mm). B&W panchromatic negatives were improving fast and now dominant. Cameras improved in their mechanics and optics and were increasingly motor driven. The same was true for projectors, whose mechanics, lenses, and light sources also improved. Continuous developing machines were more commonly in use—thus allowing and at the same time imposing stricter process controls. Film printers were increasingly automatized, with more precise mechanics and consistent exposure management. Standards were written and maintained by organizations like the Society of Motion Picture Engineers, founded in 1913, whose official name was then SMPE, to become later SMPTE—in order to include television. The Academy of Motion Pictures Arts and Sciences (born 1927) whose many missions also included research and training also played a key role in this context.

This new landscape fostered the advent of sound, which in turn drove and accelerated the transformation and further broadened its impact. In sum, the whole activity of filming, processing, editing, printing, and projecting films was fast becoming more controlled, automatized, and standardized, making it look more like a modern industry than a homemade craft. More Henry Ford than Antonio Stradivari, so to speak.

Rather than being forgotten, the experiences and research of the past—in our case, those referring to applied colors and additive color systems—made up a vast legacy of know-how, techniques, and technologies susceptible to be re-used, combined, or expanded if needed to achieve new goals.

For instance, although the additive path had proven a dead-end, extremely useful lessons had been learned from its failure. First, 2-color separations were "barely good enough", and 3-color would be ultimately needed. Secondly, recombining two or three filtered images in projection led to numerous, inevitable problems, a hard truth that ruled out additive synthesis altogether. In sum, subtractive synthesis—with CMY-color images somehow physically recombined on one piece of film and in the same frame—was clearly the obvious way to go.

So, just when cinema—for the first time since its birth—was going all B&W, the constraints, and parameters to solve the "recorded color problem" were clearly defined. It was only logical that in order to bring color back to the screens, cinema was to turn first to its recent past. Tried-and-tested technologies and processes could now be perfected thanks to the new industrialized and more scientifically controlled environment. After all, additive systems had shown how to produce color separations without incurring in parallax artifacts, while applied colors techniques had taught how to turn a B&W positive image into a colored one. Possessing both the know-how and many relevant patents, Technicolor was the research group best positioned to win the race—and win it did.

Adrian Cornwell-Clyne's "Colour Cinematography" is still the book that says it all about cinema color technical history up to 1951, containing as it does a huge wealth of information, references to patents, publications, and less obvious sources. Most importantly, it conveys the opinions and feelings of an attentive and competent author, an interested witness of cinema color history in the making. No wonder that his is by far the best description of what Technicolor dye transfer process really was:

"This famous process owes more to engineers than to chemists, seeing that to work it successfully nothing new to photography had to be made, all its elements were ready to hand, nothing new had to be invented that was not mechanical, or that was more than refinement upon existing practice. Its sponsors were faced with innumerable problems, some of great complexity, but in nearly every case precision engineering provided the answer. Why was this? Because the film was printed not by the action of light upon a sensitive substance but by the mechanical transfer of dye from a matrix in relief—a true type of printing" [4]. p. 451 (my emphasis).

In other words, subtractive, non-chromogenic color processes that dominated cinema for five decades belonged in truth more in the 19th than the 20th century. Additionally, this, was in many ways its first and greatest advantage. Once it solved the mechanical complexities mentioned above—primarily the problem of dye-transferring three colored images in perfect alignment onto a single piece of film while precisely calibrating the density and contrast of each color image independently from the other two—the Technicolor process offered many advantages.

High levels of color saturation were guaranteed thanks to capture on three separate B&W negatives (each having different, appropriate spectral sensitivities), and to the fact that the CMY image components were not obtained by chemical reaction but by transferring individual dyes in a sort of relief-printing. A process in which positives printed from the three RGB records were specially treated so that their silver images were transformed into chemically engraved actual bas-reliefs, where higher image density resulted in a greater thickness, which in turn transferred more of the dye onto the blank film proportionally to the depth of the bas-relief, thus acting literally like engraved printing plates—so much that the positives were called "matrices" by Technicolor. Color density and contrast was further regulated by varying the temperature during transfer, and the duration of washing-out the excess dyes. Dyes were as stable as their chemical composition allowed because they were not produced by any complex (and potentially unstable) chemical reaction, unlike what happened in the chromogenic processes—whose dyes inevitably fade.

High levels of color saturation, and the use of the so-called "key image"—a low-density silver image printed on the positive "underneath" the CMY dye-transfer images—led to detail-rich shadows and blacks, whereas Eastmancolor (particularly in certain decades) was accused of showing "muddy, or murky" shadows.

Furthermore, Technicolor employed only B&W film stock, which was easier to process than any monopack color film, and much cheaper. This made the process very cost-effective, notably when a high number of prints were made in a short span of time—initial setup was the most time-consuming and costly part of the process, but once done, cost-per-print was rather low compared to monopack color film printing.

Lastly, while keeping the very core of the process—the dye-transfer—largely unchanged in its basic principles and mechanics, Technicolor was flexible enough to adapt over the years, by devising workflows that avoided the use of the impractical 3-strip camera and allowed the use of chromogenic monopack negatives in filming. First came a workflow for filming onto Kodachrome (a 16 mm monopack color reversal preferred whenever a small, manageable camera was advisable): 35 mm blown-up separations were produced, from which standard dye-transfer prints were then made. When Eastmancolor negative came, a similar workflow specifically calibrated for it came rather fast, allowing dye transfer prints to continue being produced until 1980 (when the last dye-transfer machine stopped operating at Technicolor's Rome plant). The process was rumored to survive in one form or another in China, and had an unsuccessful, short-lived second coming in the 1990s (more on this later).

Technicolor was a proprietary process, with no real need for transparency. Whereas other manufacturers like Fuji or Kodak (e.g.,) would publicize the latest twist—tiny as it might be—in their emulsions either for marketing reasons or to enable customers to use them at best, Technicolor had no reasons to do the same. On the contrary, it had a vested interest in reasserting the stability represented by the magic of a brand name that had become a synonym of color per se. Therefore, the amount of information available from Technicolor about both deliberate changes in the process (e.g., modifications in dye bath formulas) and accidental variations (e.g., excessive temperature in the so called "table") is limited. What we do know is that dye-bath formulas differed along the years and in distinct locations (L.A., London, Rome). We also know that the process was incredibly complex and delicate, with many critical factors playing a role in the end-result: temperature, time, and agitation in the dye-baths, temperature in the "table", and temperature and duration of the "wash-back" phase—the list was potentially endless. These factors and variables were sometimes used to obtain certain effects creatively, that is, by choice. But more often they happened by mistake—due to mechanical or chemical failure. The difference against the Eastmancolor-type of process is that in the latter we possess a rich documentation telling us not only that temperature in the developing bath was critical, but also detailing precisely what the effect of—let us say—half a degree Celsius less had on the blue curve. This is not true for Technicolor: "The greater the temperature the greater the contrast. There is an increased colour density in the shadows, giving in severe cases "off ratio" defects [4], p. 469. This is how vague the information we have is.

As all those who studied original Technicolor prints for restoration purposes know very well, the Technicolor look did change significantly along the decades, at the same time shaping and being shaped by cinema aesthetics. Gone with the Wind (1939), Written in the Wind (1956), and The Godfather (1972) do have different colors because they do belong in different color environments—despite being all Technicolor positives.

The key challenge for a study aiming at a precise characterization of Technicolor's chromatic profile or mapping—the same as for any other color system, as a matter of fact—is to define a methodology strong enough to operate at two levels at once. On one hand it must be able to define a "normalized model profile" (a standard, theoretically abstract profile, if you will) to map the differences between the types of Technicolor informing each of the above-mentioned works. On the other side, it must be methodologically strong enough to be able to account for the actual variations within each "normal model profile", in other words between two coeval Technicolor prints of Written in the Wind.

"The class of colour obtained is recognizable Technicolor colouring. Indeed, in a way, it has the same result as the specialized technique of a painter which is the outcome of personal methods of pigment mixture and brushwork, the subtleties of which often defy analysis, but the effect is unmistakably apparent in a given artist's work" [4], p. 506, (my emphasis).

We cannot but agree with Cornwell-Clyne that Technicolor has a very recognizable "look and feel" for the spectators. However, he is of course wrong in saying that "pigment mixtures defy analysis." They do not: not anymore; in Fine Arts restoration, they do not.

Today, I am here to plead that something similar to 'pigment analysis' is carried out for film restoration—at last, after decades of unsystematic approach!

2.4. "Natural" (i.e., Recorded) Color Systems (C)/Subtractive Chromogenic Monopack 1930s–Today)

Various "families" from Kodachrome reversal process to Agfacolor and derivates, finally onto Eastmancolor, and derivates. Capture: 3-layer monopack Neg/Pos or reversal with RGB images obtained via CMY layers, and (Kodak families) integral color masking. Reproduction: reversal or positive 3-layer (CMY) monopack, integral 3-layer color film.

Unusual, complex, and rooted in another century as it might be, Technicolor provided cinema with a quite effective, resilient—and visually stunning—solution to the problem of recording color on film and bringing it to cinema audience. However, the solution was strictly limited to one provider and one market (the US high-end productions). In a sense, it felt like a one-shop, pre-globalization handicraft when compared to the system that cinema had built around B&W. By then, the latter was a highly standardized, mass-production, high-output, fully globalized industry where anybody (big-budget production or amateur) could buy a camera (any camera), a roll of film (any B&W film), expose it, and have it processed, printed, and projected (or commercially distributed) anywhere in the world. In that respect, the whole cinema industry felt that something was amiss, that it needed to build for color the same fully integrated ecosystem it had built for B&W, that it needed something else than Technicolor.

In short, cinema needed a true color negative/positive system.

With this slightly different and more precise goal in mind, researchers the world over (pushed by the US industry at Eastman Kodak, and by Goebbels at the infamous IG Farben) went back to the drawing board and started over from scratch as if the previous three decades of color cinema had not taken place. To any color scientist, it was obvious that this meant going back to Ducos du Hauron who, as we all know, in 1897 introduced the concept of a color multilayer emulsion—which he called the "Polyfolium Chromodialytique" [5]. From there, they progressed to the research and patents (ca. 1907–1914) by Benno Homolka (who almost by accident discovered the first true color developer) and Rudolph Fischer who applied Homolka's discovery to the concept of multi-layer color-coupler development, only to hit the then insuperable proverbial wall, which consisted in the dye-couplers' stubborn propensity to wander around from one emulsion layer to the next.

Once Kodak and IG Farben had discovered how (in subtly different ways) to enchain dye-couplers to their own layer, integral tripack- or monopack-color film was born, with Kodachrome and Agfacolor (both in the 1930s). The very fundamental difference in concept between Kodachrome and Agfacolor being that in the former dye-couplers were added in the developer bath, while in the latter they were already inside the emulsion.

After the initial excitement—and as soon as the disruption of the war was over—monopack negative/positive color systems were evaluated more closely, and the awful truth became evident: they were not suited for cinematography—at least not without major improvement. Cornwell-Clyne is as precise as he is merciless in his analysis: "The weakness of processes employing an original record in colour lies in the difficulty of making duplicate master negatives without obtaining unacceptable degradation or distortion of colour and/or loss of resolving power. In general, as is now well recognized, magentas have excessive absorption of blue and, to a lesser degree, of green, while cyans also have excessive absorption of blue and green" [4], p. 388 (my emphasis).

Furthermore, referring to cinematography as a Negative/Positive process is "sensu stricto" correct, but it tends to overlook the fact that cinema was always a global industry based on the efficient and cost-effective distribution of films across countries and cultures—so much so, that as early as 1926, Kodak had to introduce the first film emulsion specifically designed for duplication. Since then, rather than just a negative/positive process, cinema is actually a negative/duplicate positive/duplicate negative/positive process (that is, a multigenerational system). For the overall system to work, the qualities—contrast, grain, density, sharpness, and color when applicable—of a positive printed from a camera negative and those of a positive printed from a duplicate negative must be ideally identical, and realistically "close enough"—the extent of "enough" varying with date, place, and production costs.

By the late 1940s, cinema was used to such a system working like magic for B&W, so much that any color process was expected to deliver just the same smoothness. It is in fact intuitive that any distortion, deviation or degradation in image quality encountered in a Negative/Positive (mono-generation) process would be amplified exponentially in a multi-generation process—its end-result consisting in the "compound-interest" of each step's distortions multiplied by those introduced by the next, and so forth. Intuitively again, this issue is less critical for reversal films (which are not primarily meant for direct printing), and for films of which so few prints are to be made that they can be all printed from an original negative—as it was the case for embargoed Nazi Germany.

However, for a new color system to be considered successful in the newly global post-war world, a perfect outcome in a multi-generation workflow was a prerequisite, a "condicio sine qua non". It was also the very reason why Agfacolor proved to be not good enough, same as other interesting, but ultimately irrelevant systems like Gasparcolor, or Dufaycolor.

Agfacolor technology and its derivates was not the solution, not yet.

Early years in the monopack world were spent concocting solutions to counterbalance the absorption distortions of the monopack film. Negatives were printed with physical masks—a film to be sandwiched between negative and the positive, and whose carefully calibrated density would act as a filter correcting the chromatic distortions—not an ideal or practical solution. Kodak had researched the topic of 'internal', or 'integral' masking for few years (patents exist already in 1940), but it is only at the end of the decade that the technology of integral color masking was mature enough to be introduced—first in the Ektacolor negative, and finally "for professional motion pictures" in the Eastmancolor 35 mm negatives.

This marked the beginning of the last chapter in the history of analog color cinematography: Agfacolor-derived unmasked color materials would still enjoy a short life, but Eastmancolor would soon come to dominate, either produced directly by Kodak or licensed to other manufacturers.

From 1950 to yesterday, cinema has one color, and one only: Eastmancolor.

All gone overnight were the dozens of ingenious, weird, improbable color systems that were patented, announced and rarely—if at all—used in those years of frantic search (the 30 s and 40 s). Forgotten were the lenticular, reticular, silver dye-bleach, additive or subtractive systems, a smorgasbord of systems and names (Dufaycolor, Gasparcolor, Kodacolor, Keller-Dorian, Agfacolor lenticular, ThomsonColor, and Polavision) as large as utterly irrelevant from a macro-historical point of view—belonging more to a "cabinet of curiosities" than to History.

Differently from Technicolor, which operated very much in its own niche—being filmed mostly with Technicolor own three-strip cameras and negatives and positives produced only in Technicolor plants—, the advent of Eastmancolor had a systemic impact on cinema at large—comparable in its far-reaching effects only to the revolution caused by the advent of sound. In many ways, cinema was forced to switch to a new paradigm that impacted every step of cinema's workflow, everywhere in the world. Color film brought chemistry back to the forefront—the chemistry of color processing was highly standardized, but also obviously much more complex than that of B&W. Variations in the many parameters of B&W processing (such as time, temperature, turbulation, wash, rinse, drying) had always had effects on the final results—contrast, density, sharpness, and grain. However, there always existed ways to correct these variations in the following steps of the workflow, so much that laboratories often operated with their own standards and procedures. They even used their own homemade processing baths-formulas, which were supposed to give better results (less grain, or a smoother tonal curve) than the competitors'. Unfortunately, Eastmancolor had three curves to keep under the strictest control, bar disasters due to mechanical (speed/time, turbulation) or chemical (wrong replenishment rates, contamination, carry-over, insufficient washing, imprecise rinsing) issues. Literally just about anything had the unpleasant tendency to affect differently one layer (i.e., one color) from the next. In other words, too often out-of-standard processing tended to lead to mismatches of the three curves that made a negative virtually unusable. For instance, if the overall density was too high but the curves were still aligned, the problem could be corrected by adjusting (increasing) the exposure in printing. However, if the effect was—as it was almost invariably the case—that one curve was twisted differently from the others, the result would be a color mismatch: e.g., shadows too blue and highlights too magenta. Such a defect could not be solved at the printing stage—the negative was hopelessly flawed. A filming problem could lead to "color-breathing"—subtle but visible variations in one color from one frame to the next—again, no solution. A simple enough malfunction in the printer, and every few shots one could be too green, or a vertical blue line would appear. Another negative to the garbage bin! The list was virtually infinite.

If process variations to be taken into account in the monopack color film environment are multiplied by the '1-film-3-layers factor', they are further exponentially multiplied due to the multi-generational character of the workflow—in which the outcome of every sub-process affects positively or negatively the following ones up to and including the very last: the theatrical projection. One can easily imagine what happens if the intermediate positive is both overexposed and it has a too-high contrast in the Red curve, and then it is printed onto an intermediate negative where the Blue curve had, for whatever reason, "gone amok". It is only the compound-result of these two defects having taken place in two separate workflow's steps that makes the printing of high-quality positives impossible.

In short, throughout the whole workflow (from cameras to printers to developing machines, to the chemical control laboratory), the precision of mechanics, optics, and chemistry had to be improved enormously. Electronics started replacing electromechanics. Controls became obsessive. In other words, the whole chain went through a further, more profound step towards standardization and industrialization, many times stronger than what cinema had witnessed in the 1920s and 30s.

From our standpoint—that of imagining an approach to characterizing color systems in order to map them into the current color environment—the Eastmancolor era (1950s to 2011 ca.) highlights an interesting dichotomy. On the one hand, all the processes, the equipment, and the materials (from film stock to chemicals) used become highly standardized, complete with the richest accompanying literature ever produced. On the other hand, the high complexity of the overall workflow and of its sub-processes, and the sophistication reached by film materials expose them to a greater extent to any type of factors that might be out-of-standard, thus increasing exponentially the number of deviations from the norm, which can negatively affect any film element (negatives, positives, intermediates, etc.). Simply put, each process as well as the overall system became so complex that almost anything in the chain could "go wrong". And, take the word of somebody who inhabited a film lab for three decades: in any given week, something always did go wrong, at least once (!).

When Eastmancolor was finally introduced, there was indeed a sense of "end of history"–a 'that's-it!' feeling that cinema had reached the top of the mountain: the recorded color problem was definitively solved! So much so, that the usual Cornwell-Clyne already in 1951 writes: "It is difficult to conceive that there will be any sensational advance on chemical lines during the next few years. On the contrary, one good reason for expecting invention to shift its point of departure once more from the chemical to the physical is that the technique of television in colour will in due course bring about entirely new electrical methods of both recording and reproducing coloured images [4], p.V. (my emphasis)

As we now know, the Major was spot-on, yet again...

2.5. Digital Intermediate Workflow (1990s–ca2010)

Capture on monopack camera negative > scan (first and mostly 2k, then 4k) > complete digital postproduction > film-out onto monopack color camera negative or intermediate film > monopack color positive prints made from the resulting negatives oft-termed "digital negatives").

In retrospect, the 1990s was an interesting—if confused and confusing—decade for color cinema, with too much happening at the same time in laboratories hundred meters or thousands of kilometers away from each other. The fact that a history of the period is still to be written is regrettable, as so much of the current Digital Cinema technology was informed by events and ideas from back then. If such history exceeds the scope of this article, a few key matters are still worth mentioning as they deeply influenced ensuing events.

First, a look onto the photochemical side. Here for a few years, Technicolor 'threatened' to return, with various plans and attempts to resuscitate the process leading to few trials and prints being made. Although an actual, impactful return never materialized, the idea itself had some important consequences. Directors and cinematographers—many of whom might have never seen a real Technicolor print—who were shown the new Technicolor tests were awed to see how saturated the colors were, and how much details were retained in the shadows when compared to a standard Eastmancolor film. Few questioned which images looked better. Kodak felt threatened—or perhaps it was just pushed to improve its products according to the general feeling—and responded with a range of new emulsions meant to be more stable and to improve contrast and saturation. Additionally, with the intent of increasing contrast in positives, the so-called bleach-bypass practice was introduced in color processing. Practically, by bypassing the bleach bath, some silver was retained in the image together with Eastmancolor's dye clouds—an idea somehow similar to what Technicolor used to do 50+ years earlier when it added a low-density B&W "key image" to the CMY dyes. Bleach- bypass was a variation applied to an otherwise standard processing, and only to selected prints—it was also attempted on negatives, although with dubious results. Unfortunately, there is no way to know today whether a given film or print made at the time was meant or not to undergo the process. Being more fashionable than convincing, bleach-bypass had a limited use and a short life, while the whole Technicolor idea slowly withered away.

However, an important seed had been planted in the minds of many. After five decades of unchallenged domination, Eastmancolor's qualities were questioned—perhaps there were ways to improve its images, maybe there was a 'life after Eastmancolor' after all.

Secondly, and even more disruptively, Cornwell-Clyne's 1951 prophecy was coming true. After having taken over TV and video, digital imaging was finally worming into cinema. The turning point was probably in the late 1980s, when Kodak announced its High Resolution Electronic Intermediate System [6]—a closed-loop HD-scanner > workstation > film-recorder system designed to import 35 mm color negative film images, process them and finally export them back to film. The system offered a glimpse into how digital image manipulation could revolutionize cinema, starting first from SFX—because of how slow and costly the process was. Later, others (e.g., Quantel's Domino system, 1993) joined the race. Digital tape formats for film images were then standardized (such as the 'infamously' impractical D16). By then the question was no longer "if", but "when" cinema would go digital. The only issue left was in fact quantity: of data, of processing power, of seconds to process one frame, etc. In other words, by the mid-1990s the question had become "When will we be able to process a whole feature-length film rather than commercials and seconds-long SFX?". The answer came in 1998, when the very first feature film entirely post-produced digitally was produced and released, using a workflow perfected at Digital Film Lab in Copenhagen (of all places!)—a workflow that was later generically referred to as "Digital Intermediate, or DI". DI ended abruptly in the early 2010s when 35 mm film distribution virtually disappeared. Sadly, little about DI was written and published at the time, as too much was happening too fast, first in Europe (mostly in Copenhagen, then in Soho, London) and only later in the US—a fact that of course nobody wants to admit now (!).

DI was always a small-shop, almost homemade craft (back to what cinema was in the 1910s!). Every production and postproduction house had its own "*superior and unique*" workflow, differing in equipment, software, and image processing techniques—for instance, secret, proprietary, and almost magical 3DLUTs. This is the main reason why it is impossible to outline a 'typical, or standard' DI workflow. Figure 1 is the best attempt (at least that I am aware of) of visualizing a 'generic' DI workflow—complete with optional routes and steps—as it stood in the mid-to-late 1990s.

On the plus side, color science entered the post-production labs, but too often the process was still dominated by "visualmatching" across numerous, dramatically different displays: film projection, CRT monitors, and early digital projectors. All of a sudden, the buzzwords that everybody muttered with awe were 3D-LUT, colour space, and gamut!—obviously, very few knew or understood what they really meant.

In truth, all Digital Cinema technologies (scanners, film recorders, digital projection, color imaging software, etc.) find their origins, concepts, and design in this phase. They were produced by a handful of manufacturers—mostly European—who also acted as real research centers by developing most of the science and technology that later morphed into the current all-digital cinema workflow. These manufacturers also produced a wealth of documentation and research about the relationship between analog film and digital imaging, and the related color science—most of which is still useful once the changes on the "digital side" are discounted. DI developed methods (both SW and HW) to measure and calibrate not only electronic displays but also actual analog projection—a whole area of research and expertise that was made obsolete and forgotten by the all-digital workflow.

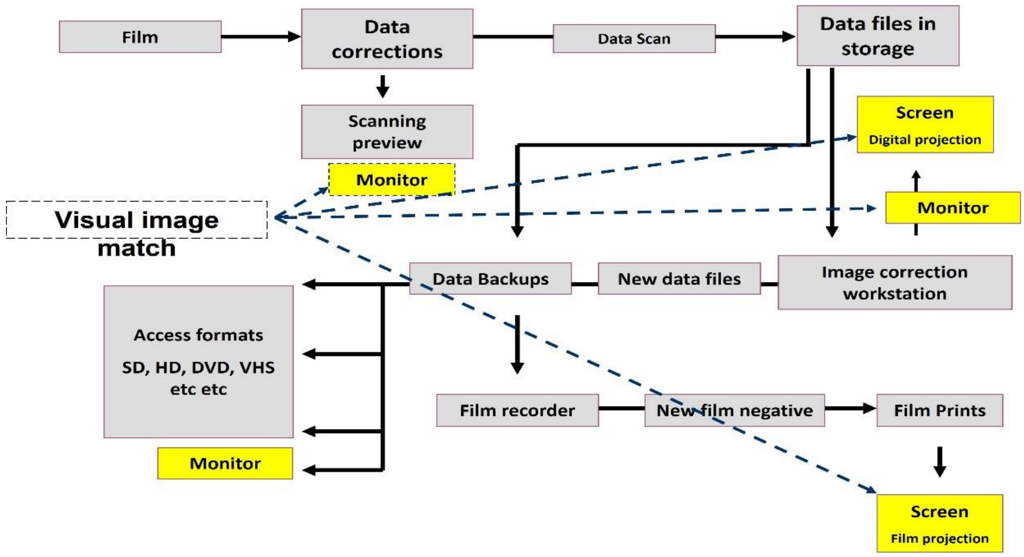

Figure 1. How a 'generic' DI workflow looked like in the late 1990s, with points of visual match highlighted.

For the very last time in history, the DI years saw photochemical film as paramount from all standpoints. Film was indeed the golden rule, the ideal reference image, the alpha and omega—quite literally, as DI's input and output were actually on film (!). All characteristics of analog film images (including their artefacts) were meant to be reproduced exactly in the digital environment—just as they appeared on film.

Conceptually, DI was not meant to produce new, or different, digital images—for instance, grain-free, or wider-gamut, or higher-resolution when compared to film. On the contrary, DI was seen as a mere tool to push analog film potential to its limits by means of more precise and powerful color management but always within the boundaries of the analog film color environment. The ideal DI setup strove to be perfectly transparent. The end-result, once recorded back onto negative film and then printed onto 35 mm positives, was to "look and feel" 100% just like a positive derived from an all-film workflow. All procedures, techniques and equipment were designed to that aim.

Scanners and film recorders were precisely calibrated in order to best respond to the camera negative used at the time in production, just as a software was written with analog images in mind—nothing less, and nothing more. This means that scanners and film recorders were designed and kept precisely calibrated—in exposure, light source, internal image processing, filters, optics—to match the color camera negative of the time. As a practical consequence, most film recorders (and all the good ones!) were not able to record back onto B&W material. Scanners had serious troubles scanning B&W, or non-Kodak negatives, or Kodak negatives older than a few years. Additionally, one had to forget altogether about scanning unmasked negatives, reversal films or positives, or non-standard, non-monopack chromogenic color materials!

This is a key point to understand and retain—as the whole spectrum of technologies and knowledge that is still in use today when it comes to scanning and then restoring analog films descend straight from that DI environment, those ideology and aesthetics. The same goes for digital cameras, and ultimately for digital projection as well.

In sum, all current D-Cinema technology stems straight out of a conceptual, ideological, and aesthetical paradigm based entirely and uniquely on photochemical film's characteristics—its so-called look-and-feel. To be e even more precise, it is based on the "look-and-feel" the Eastmancolor-type color film negative/positive system had reached in that precise moment of time—the mid-to-late 1990s to the early 2000s.

Lastly, the relatively fast embrace of the DI process by directors and cinematographers was mostly due to a degree of creative freedom unimaginable in the context of analog-only film postproduction, but it was also connected to that idea of exploring ways to "go beyond

Eastmancolor" we referred to earlier—at least in part. Without the need of weird, little-tested techniques (such as the bleach-bypass, or the new Technicolor) it became somehow possible to stretch the limits of Eastmancolor towards a new aesthetics. In this sense, DI marked the actual beginning of the end of the photochemical film colors environment. Counter-intuitively, this happened when the latter had reached its zenith.

2.6. Full Digital from Capture to Projection (Dominant 2010–....) or, Happily Back to Additive!

Cornwell-Clyne's prophecy was fulfilled around the year 2010—the exact date varying according to the countries—when film distribution turned altogether away from 35 mm analog prints. The switchover in the cinemas was extremely fast and disruptive, but behind the scenes, the many years of DI practice smoothed the impact.

As mentioned earlier, the DI environment featured an input and an output that were totally different from anything happening in-between. This led to a unique need to master the relations between analog film images and their displays, and digital images and the way they were displayed. As a deep understanding of displays and the relations of their different gamuts and color spaces was key to processing digital images, the DI process imposed to expand the field of research to include analog cinema world. All of this became less important in an all-digital cinema system as the one we live in today.

To some extent, the advent of D-Cinema had the major (dis)advantage to simplify things enormously. D-Cinema images are now processed in a coherent, all-digital context where analog-film imaging plays no real role—the capture-on-film might retain some mystique, but conceptually and systemically it does not matter in the least. Even though film negatives are still used in capture (albeit rarely), what really matters is not the "look and feel of analog film" anymore, but a new digital aesthetics where film characteristics like grain, or flare become devices employed to merely remind of film, as they ceased to be the reference—key characteristics that the process must retain.

For the very first time since 1895, within D-Cinema dyes are no longer responsible for creating colors on a cinema screen. With DI gone, cinema is not really concerned anymore with the ideological view that it must somehow re-create or simulate analog cinema colors.

To complicate things further, in the meantime the original template behind the founding D-Cinema paradigm—i.e., the photochemical film—has totally disappeared from the audience's viewing experience, hence the profound changes to the aesthetical and theoretical status of analog film. In fact, after more than 120 years, analog cinema colors (along other analog-film characteristics) ceased to be the unquestioned, un-, or semi-conscious chromatic reality of the unreal brought by film works to cinema viewers. Analog cinema colors and other analog-film characteristics are not part of the viewers' daily experiences any longer and consequently they cannot function anymore like direct, conscious references. The constant hints to these characteristics—in D-Cinema, and increasingly in the Art world, on TV, in VR or videogames and such—cease to be quotations and become references to a collective memory, not to an actual presence. The farther the analog film experience recedes in the past, the more it becomes the collective memory of a lost dream—as deep-seated in our mind and blurry, as memories of dreams are, after we awake.

The Ludovisi Gaul is a famous marble copy of a long-lost Greek bronze original. As such, we can only look at it—with its totally different texture, and color(!)—and guess about the effect of the original's color and texture, which are no longer available to us.

To dare an analogy, D-Cinema suffers from a sort of "Ludovisi effect" as it tries to be a copy of something gone forever—in this case analog film. From a film theory viewpoint D-Cinema is ultimately a "Ludovisi-cinema".

Unfortunately, during the 115-year history of the dyes' reign, research was primarily focused on either mastering the then dominant color system, or inventing the next one. Before the DI era, there were few reasons to analyze how all analog color systems related to one another and when it happened, the analysis was limited to the usual cinema approach—the visual evaluation. Information about cinema color systems and their chromatic characteristics (gamut, or dye absorption, etc.) exists, but it is unorganized, scattered, unsystematic, in most cases not fully compatible and, most importantly, it is very far from being complete. Very little data, if anything at all, exists for the period prior to the era of chromogenic processes, when cinema started dealing with color science. So, on the analog side of the issue the amount of research required to "scientifically" characterize and map cinema color processes, is quite significant. Were this research to be conducted, it should combine a first phase of gathering, processing, and normalizing the existing data in order to start analyzing them, with a second phase of "fieldwork 2.0", aimed at gathering further data from the extant witnesses of the various processes (i.e., the extant films). On the digital side of the issue, the situation is definitely better, except for the fact that the technology is alive and therefore constantly mutating, with current technologies and research thereof literally running ahead. On the contrary, the analog ones are slowly fading away (also literally, in case of the films).

3. A Question of Granularity

This concise, high-level, macro-history walk through the eras of cinema color/s was hopefully useful to structure the discourse by identifying key concepts, major shifts and underlying dis/continuities.

On the other hand, a serious approach to the type of research necessary to extend our knowledge of cinema color environments by characterizing past cinema color processes—so that we can, among other things, map them effectively into modern systems and displays—implies a greater level of granularity in order to study not only the hundreds of color systems that existed, but also all the variables and factors relevant to such a characterization within each system. In short, we need to consider a picture that is even more complex than normally presumed, at least in most of the existing literature.

4. Granularity 1: How Many Systems?

Proposing a precise figure for the number of color systems and processes in cinema history is the first, difficult hurdle. First comes the issue of how we count precisely. Are we counting actual patents, or just mere mentions in literature—knowing that some could be just ideas, never put in practice, or with which no films were ever made? Additionally, to what extent, if at all, do we group contiguous processes and systems? Does Technicolor count for one or for six, or even more, counting the changes (e.g.,) in dyes-bath formulas? More seriously: how many applied colors do we tally? Does each formula for tinting and each for toning count as one separate process or do we group them differently? Additionally, what about their combinations, mordanting formulas, pre-colored film stock? The list is daunting. Similarly, to what extent, if at all, do we group different emulsions based on the same macro-system (e.g., Eastmancolor)—by manufacturer (Fuji, Kodak, etc.), or by family (EXR, Vision, etc.), or both?

Whatever the precise criteria defining any comprehensive list, we must think in terms of many hundreds of entries, not dozens, as a simple list of dyes and processes used in the applied-colors era runs up to more than 300 and counting.

It is very probable that the correct answer to this question can only come at the end of a proper, thorough research, not at its start. In other words, it must be based on objective characterizations that can tell us where the demarcation lines lie between one system and the next, one emulsion and the next. Before characterizing them with a sound methodology, how can we tell how different three randomly chosen dyes were: "Acridine Red 3B", "Anisoline" and "Safranine A"—spoiler alert!, they were all defined as "Red")?

5. Granularity 2: How Many Variants to Consider?

Another key methodological question is how to define and then approach variants and variables within each system. The easiest example of course is the above question concerning different emulsions from one specific system and/or one manufacturer. In most cases, manufacturers kept track, at least internally, of any significant changes in their products and often they publicized them. However, this is not necessarily a rule. When the

Allied were trying to evaluate Agfacolor's value as a technology, they were surprised to find significant differences between film materials processed in Germany and in occupied Czechoslovakia: had IG Farben toyed with color couplers while being bombed? Or was it just due to differences in processing? Whatever the reason, the "Czech Agfacolor" was judged 'better'.

As this episode shows, it would be reckless to rule out subtle changes to the chemistry of color film stocks even when not advertised. Even less transparent would of course be the case of proprietary processes like Technicolor. We know that the fundamental principle of the process did not change much in separate times and plants. However, we also know that in some instances, different dyes were used, and we cannot exclude that more changes took place, as Technicolor had little interest to advertise such internal decisions. So, can we really base our characterization on just few Technicolor prints per sub-process? Which print? How many? From where? From when?

Furthermore, the opposite could be true: after closer inspection, it is very much possible that we discover that differently branded emulsions (from one manufacturer or even across manufacturers) might turn out to be very similar in their chromatic responses, or gamut. We simply do not know—not yet at least. We just know that basing all research on available published data can be misleading.

6. Granularity 3: How Many Other Variables and Factors to Consider?

We come now to the least discussed among the many issues that should instead be considered at length when it comes to characterize, or map, the actual chromatic characteristics of cinema colors (a broad term meant to include overall systems, processes, and techniques).

For several reasons—the most relevant among them being the easy availability of data from published sources—research on color systems and technologies has always been focused primarily (almost uniquely) on characteristics of commercially manufactured film emulsions, and more precisely on standard or nominal characteristics—i.e., defined and published by manufacturers or inventors. Wherever the relevant element of the system was not a film emulsion but a process—as in the case of Technicolor, some applied colors' techniques (stencils), or additive systems (Kinemacolor)—research too often limited itself to a description of the mechanics, the principles of the system. This is due to the very reasons mentioned earlier, in other words the ready availability of literature—what in other contexts is defined as "secondary sources"—except that in our context they became the only sources. In practice, data that are mostly studied and referred to are 'official', nominal data, not experimental, real-life data derived by analyzing actual real-life products and equipment and their components—e.g., Kinemacolor's filters, absorption of tints and tones as they are actually on film, and so forth.

Furthermore, other two key categories of data were until now largely underestimated, if not totally overlooked, as they are not well-known and are complex even to define: system complexity and process variables. System complexity can be defined as the interaction of cinema production and postproduction workflows (in their concrete instantiations along film history) with the specifics of all components employed in each of their sub-processes—or steps. Intuitively, each sub-process in the workflow can be characterized as the result of the interaction of all components needed to perform it. The results of two identical processes that make use of different components will give results that differ from each other at least to some extent—the resulting differences are defined by what we call process variables. Hopefully, the breakdown of a generic film workflow will make the concept clearer and more concrete. In very simplified terms, a typical workflow for a film produced in the 1920s include the following sub-processes (those in square brackets are not discussed in full):

Step 1: capture/filming/shooting >
Step 2: negative processing >
Step 3: [workprint printing and processing, editing, negative preparation] >

Step 4: positives printing >
Step 5: positive processing >
Step 6: [positives coloring] >
Step 7: [intertitles production and coloring. > positive cutting] >
Step 8: public screening.

Step 1: filming requires cameras (with certain characteristics, giving certain results driven by their variables—e.g., in terms of steadiness, constancy of speed/exposure, evenness of field, lenses aberrations, etc.—plus a camera negative with an emulsion with certain photographic characteristics. It will also require certain skills and employ certain procedures, typical of the time. The result of the filming subprocess is a roll of exposed negative whose actual characteristics derive from those of the film emulsion multiplied by those of the camera and of the operator. This exposed negative becomes then the first component of the ensuing process, Step 2: negative processing. This too needs know-how and procedures, equipment (racks and tanks, or a continuous processing machine), a setup for drying the film, as well as the chemicals employed in the baths. The result of Step 2 will be a fully processed negative that will be used in the next step, Step 4. Similarly to the process of filming, where the specific characteristics of the exposed negative are informed by the characteristics of the negative film used, of the camera (and the lenses, and the filters, etc.), and of the cameraman, the characteristics of the fully developed negative coming out from Step 2 will depend on the characteristics of the result from Step 1 "multiplied" by the characteristics of the equipment, chemicals, baths, staff, etc., employed in Step 2. The characteristics of the positive image resulting from Step 5 will be informed by the summation (or compound interest, if you will) of all preceding steps multiplied by the components belonging to that step. Similar considerations apply for each Step, until the very end—Step 8: projection (positive film + projector + theater + screen). (See Figure 2).

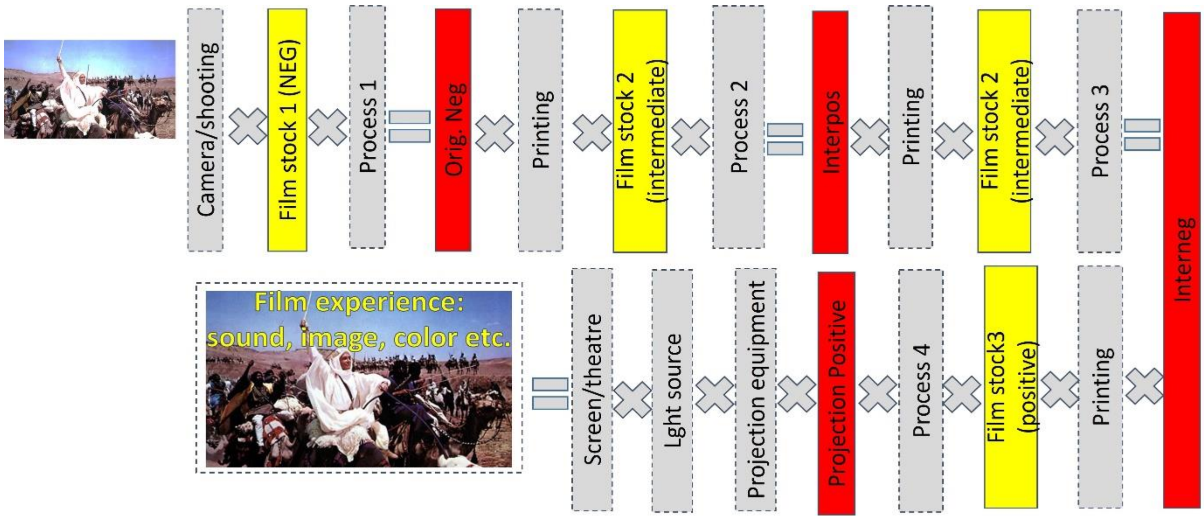

Figure 2. System complexity and variables: typical system workflow for a generic film production 1920s ca. highlighting processes, type of film emulsions used, and resulting materials.

Each component used in each sub-process (like cameras, printers, emulsions, processing machines, but also procedures and skills) have specific characteristics that affect each process' results—and ultimately, they influence the complete workflow's end result in different categories (evenness of field, constancy of exposure, contrast, sharpness, density, graininess, density, contrast, color, etc.); the actual characteristics that the end result assume in each category are what can be defined "overall process variables".

Process variables are never completely random, or unprecedented and uncontrolled, but they rather depend on the characteristics of each sub-process' component. For instance, because of its mechanical precision, a 35 mm camera from the 1940s will be characterized by a fairly small range of variables in terms of irregular speed or shutter de-sync. Compared with one from the 1960s, a continuous processing machine from the 1930s was less precise mechanically and chemistry-wise, and consequently more likely to have a wider variables' range. Certain categories of equipment will have different effects. An optical printer will inevitably increase the contrast and grain of the printed film more than a contact printer. Still, any type of printer from the 1950s has a wider range of variables than one from the 1990s.

Eastman Kodak and other manufacturers issued a wealth of information about all sort of variations that could affect any type of processing: from mechanical accidents to chemical contamination, insufficient turbulation or replenishment. In short, process variables are reasonably documented and foreseeable, and they tend to happen within a certain predictable range depending on factors such as type of equipment or process, level of quality controls, and of course the type of film subjected to the process—the same variation in temperature has very different effects on a camera negative than on a positive, which is usually more resilient.

As process variables are well described in literature (either published or internal, unpublished), they can be defined and predicted. Most importantly they can be empirically measured on the actual products of these workflows—the films. Just to give few examples: there are enough so-called studio prints—the best possible positive prints produced by a given studio for a premiere projection—in the archives to measure and characterize what a "top" print would look like in different years of, let us say, the US production. The same is true for an 'average distribution prints' of the same title, and/or for one or more markets. Once a methodology apt to characterize a given color system in a given year or period is defined, it will be easy to not only create a standard, nominal model for that specific color system, but also define the ranges of variations—and the differences from year to year and lab to lab—by applying statistical methods on a sufficient number of samples. Thus, a real-life model could be defined, which would be much more useful than a generic "taken-from the-official-datasheet" model, which would apply in very few cases only.

It should be rather obvious how system complexity and process variables are related and interconnected, although the precise extent of the interrelation is complex and cannot be given for granted. So, we can in principle assume that a more complex system has a wider range of variables, which is true, but it is also true that innovative systems and workflows tend to "start simple" and slowly add complexity. In this case, a brand-new workflow for an untested new film emulsion can be very simple—have a rather low complexity—but still have a wide range of variables—because it is untested. When launched, a new color system, or type of film, is normally introduced in the negative/positive form, which represents the simplest form of workflow. For instance, this actually happened in the case of the first Eastmancolor neg/pos pair. Only later, after the new system was tested and accepted, intermediates (interpositives and internegatives) are introduced, and the system saw its complexity increase. However, in this scenario, despite the higher system complexity, the overall level of process variability decreases as the system matures. This was exactly the dynamic for B&W—which started as a simple neg/pos system, basically handcrafted (hence with huge process variability), then it increased its system complexity in the 1920s, when sound and duplicating films came into use. However, by then it was becoming more standardized and industrialized, hence showing lower overall process variability.

In conclusion: system complexity and system variables are normally in lockstep. On the one hand, higher complexity implies wider system variables—because of the sheer number of sub-processes. On the other hand, process maturity and overall technical evolution—increased sophistication of technology and experience, which we can define jointly as system maturity—can have mitigating (and even reversing) effects on the direct proportionality linking system complexity and its variables.

Far from being purely speculative and philosophical, these considerations can have a major impact on the actual definition of a working model for a specific color system as they enable models flexible enough to account for changes in the expected range of system variables along a specific color system's timeline. In practical terms, they define a model capable of characterizing the process variables in the Eastmancolor system when first introduced in 1950 (as Negative film 5247 + marrying Positive film 5381 only) but also later in 1956 when by adding the first color intermediate film, the original neg/pos pair turns into the typical Eastmancolor triplet: Neg5347 + Intermediate 5253 + Positive 5381.

For the model to be able to characterize this color system in both its 1950 and 1956 versions, it must correctly take into account system complexity and process variables as effectively influenced by the system (im)maturity in 1950 and increased system maturity in 1956. A generic, nominal model would fail to map the differences between the two versions, thus risking being of little use. In fact, empirical experience shows that process variations in 1950 are greater than in 1956 despite complexity going in the opposite direction. The precise extent of this narrower range of variables is exactly what needs to be measured with scientific, numeric precision. In short, this is what we do not have yet and what we advocate for here, instead of what we have now—which is at best make-pretend research projects, and background, distracting noise.

7. A System, Not Just Films

Workflows and processes changed vastly along cinema history. Lumières' Cinématographe served as a camera, a film printer, and a projector; for quite some time the same emulsion served for negatives and positives—quite a long way to the high-tech plants of hundred years later.

Most consequential for the history of color film was the introduction of duplicating steps into the workflow—meant to produce duplicates negatives necessary to make distribution easier and more widespread. The need was present from the start, and stop-gap strategies were in use until dedicated emulsions became available, starting in the mid-1920s. From then on, original negatives were used to print duplicate positives, and from these, duplicate negatives were made which could be shipped around the world to strike release positives. As discussed earlier, for any color system to be effective, it had to include a successful duplication route. Chromogenic emulsions were inherently difficult to duplicate without distortion, making specifically and carefully designed duplicating emulsions a necessity. In simple terms, just like a positive film emulsion, a duplicate emulsion (aka intermediate, negative or positive) must respond as precisely as possible in terms of chromatic sensitivity, contrast, density, resolution, and grain to the densities and chromatic absorption of the element it is printed from—in other words, the chromatic sensitivities of the three layers of the intermediate must mirror the chromatic absorption of the layers in the camera negative. In practice, this means that whenever a new camera negative is introduced, duplicating emulsions (intermediates) need to be adapted to the new negative's characteristics.

As mentioned earlier, it is incorrect to conceive color cinema post-Eastmancolor as being in real-life a negative/positive system—where the introduction of a new negative simply imposes the introduction of an adapted positive. Rather, it should be conceived as a negative > intermediate positive > intermediate negative > positive system—where each generation of negatives (think of Kodak's original Eastmancolor, then EXR, later Vision families of negatives) requires adapted positive and intermediate emulsions. Together, these three film emulsions form a sort of inseparable "triplet".

Because of its relative simplicity, B&W was able to function throughout film history with very few changes in its duplicating materials. However, that is clearly not true for color monopack.

Walking through the history of Kodak's Eastmancolor family, it becomes clear that a pattern repeats itself regularly: first a new negative is introduced, then it is followed by others of the same "family" (e.g., EXR, Vision,..) characterized by the use of similar technical solution (e.g., T-grain emulsions for EXR), but offering different speeds, or tungsten/daylight calibration, etc. Then, a few years later, as soon as the "negative family" is stabilized, a new intermediate comes to complete the triplet; commonly, one intermediate emulsion is calibrated for a whole negative family. Progressively, intermediates linked to previous triplets are discontinued. In order to achieve the nominal, optimal results from a given negative, this must be used within its own triplet. Mixing different negatives and intermediates does not work well chromatically—which creates system incompatibilities even within one manufacturer and one color system—something that cannot be overlooked and that is more common than usually expected.

In conclusion, it appears that there is more to cinema history and to the history of cinema colors than a succession (usually depicted as progress) of different technologies, discoveries, systems, and emulsions. If this were the case, things would be much easier: it would suffice to characterize a certain type of dye or film, by analyzing extant examples, or by studying the literature—the latter being what has been done until today.

However, as it becomes soon apparent even from our cursory look into history, the reality is significantly different. From the very beginning, cinema must be conceived as a complex system composed of multiple processes and sub-processes, and their components—including every technology, equipment, chemicals, film stocks, knowledge, procedures, as well as economics, aesthetics, ideology, and politics). These components were all interacting with each other at different degrees of complexity.

This cinema system mutated continuously over time along multiple parallel or intertwined trajectories (per category of components and factors: equipment, film material, and so forth).

Taken at any point in history, the system is coherent in itself, and its results (the cinematographic works it produced) were coherent with the actual characteristics of the system in that specific moment of time (and space). The changes the system underwent constant, slow, parallel or diverging as they might have been, can be so profound that for all practical purposes relating to specific fields of analysis, points of discontinuity can be defined to identify the borders of specific, discrete "eras" or "periods" that are effectively "impermeable" to each other. In other words, films produced in one era are no longer coherent (compatible) with those from another.

Furthermore, what we define as one continually mutating system, when it is analyzed from a more specific perspective, or through a narrower spectrum, or set of characteristics—e.g., color history, or sound history, or language, evolution, censorship, social attitudes, concept of 'realism', whatever...—can be more precisely interpreted as a succession of separate systems, each coherent only within itself, but not with what comes before or after. A film produced in the silent era is not coherent with the sound era; nitrate with safety film; before and after feature-length, Cinemascope and Widescreen; 'realism' after Rossellini, representation of time after Akerman, B&W before and after Technicolor, analog in the D-Cinema era—the list is infinite. The point being that the definition of system discontinuities depends on the level of detail, and the spectrum (i.e., the selected categories) of the analysis

So, remaining within our narrow perspective, the six eras of cinema colors that we described above can be defined as system discontinuities from the perspective of their color environment, each of the six eras being a system coherent only in itself and incompatible with the others. What was produced in the 'applied-color era' is not compatible with the Technicolor era, nor it is with the Eastmancolor world. The films of one era were conceived, produced, shown, and judged within their coherent system and are therefore incompatible with any other—even more so from the perspective of their technical reproduction.

8. Conclusions: What Film Restoration Is, and What It Needs

In this sense, film restoration becomes "the process of defying the separation between two incompatible cinema systems, by means of a methodology-grounded practices that (tries to) transduce a cinematographic work belonging to one system into another system the given work is not coherent with".

A stencil-colored film, or a Technicolor print cannot be accurately reproduced onto Eastmancolor, or into Digital Cinema—not just because the film emulsions or dyes have changed, but because the entire system—laboratories, processing, editing, printing, theatre, projection, language, audience,..—has, thus becoming a separate, incompatible system.

What is needed to cross system boundaries—i.e., to restore a film—is exactly what we are discussing here: we need models characterizing precisely enough all the features (e.g., dye absorption, saturation, gamut, densities, and contrast) of the work from one system so that we can re-map them into something else, which is coherent with the current, radically different, and incompatible system.

Simply put, the challenge in front of us is "just" this: "What is the methodological approach to characterize the results of a complete, actual system and not simply of one of its components (e.g., the film emulsion), so that we can then map them into the current system and its displays?"

There is primarily the matter of the techniques and instruments for the analysis of the actual images on film, but also of the projection environment. Furthermore, there is the issue of how to account for the variables within the system. We know for a fact that any piece of film we analyze is the result of actual system variables (as defined above) that may (or not) have affected it to an extent that makes the film at hand non-fully representative (or perhaps only partially representative) of a given color system.

In sum, on the one hand, a characterization precise enough to allow the needed mapping into modern displays must take fully into account what we defined earlier as system complexity and process variables-without which the characterization would simply not be useful. On the other hand, the adopted methodology must be strong enough to precisely identify the effects of process variables so that they can be "calculated out" of what we can define as a "standard model for color system X or Y".

In practice, this means that the process of characterizing cinema colors cannot be limited to literature, but this must be combined with an analysis of reliable surviving witnesses, in other words prints that we know represent the color characteristic the work was intended for—they are not faded, or suffered distortions due to process issue so that it has, for example, totally twisted RGB curves. Luckily enough, the number of existing prints—and related negatives—conserved by archives the world over makes this endeavor possible—methodologically complex and practically demanding, but possible.

What is needed is a comprehensive methodology for both theoretical and applied research whose aims, features, and constraints we hope to have at least broadly outlined here, while striving to sketch a roadmap for the research that is a prerequisite to such a methodology. Today this type of methodology, research and approach are still missing—despite the millions thrown at improbable research projects in the last decade.

The agenda for theoretical and applied research is in front of our eyes, as it is the need for a more "color-science-based" approach to cinema color mapping across systems—that is, color film restoration—so that scholars can study and audiences enjoy cinema colors on reliable, accurate reproductions—at last.

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