

Introduction to Light-Emitting Diode Optics for Motion Picture Film Scanners

Jeffrey Lauber

Introduction

As cinema makes its fated way towards an all-digital world, manufacturers of motion picture film scanners find themselves increasingly motivated by a desire to accurately render film's images in digital form. Whether for archival digitization, digital film restoration, or digital intermediate production workflows, ultra-high resolution, far-reaching dynamic range, and natural color representation have come to be regarded as the ideal standards of both industry and audience. From the telecine in its earliest forms to top-of-the-line contemporary film scanners, these motivations have been at the forefront of digitization operations. The introduction of light-emitting diodes into film scanning technology is arguably one of the most important innovations in this regard. Since first arriving on the market in the early 2000s, LED-based optical systems have come to be a widely-sought feature of film scanners for their versatility, efficiency, and consistency.

This paper will trace a brief history of film scanners from telecine to present to illustrate the ways in which innovations and limitations of the film scanner's predecessors ultimately led to the inception of LED-based optical systems in its technologies. It will then outline the numerous implications of LED-based optical systems for digitizing motion picture film, especially as they pertain to archival film. Finally, it will address the ways in which LEDs function within the film scanner's optical process at large, drawing on contemporary products for practical examples.

From Telecine to LED-Illumination Film Scanners

Long before the film scanner made its debut in the film world, its two most immediate predecessors had been in wide use in archives, film production, and the home entertainment industry. With the rapidly growing consumption of television, and especially with the advent of color television, the 1950s saw a growing awareness of a market in need of exploit. Though Hollywood had already been producing motion pictures for decades, it wasn't until the 50s that television came to be recognized as a valuable medium with which to bring the movies home. The television industry found itself in need of a machine which could convert celluloid-based motion pictures into television-capable video signals, and from this need the telecine was born.

Though the telecine would eventually improve to the point of being somewhat similar to film scanners, these two technologies bear a number of fundamental differences. The earliest telecine transfers utilized the effective, though rather unsophisticated, method of pointing a film projector directly into the lens of a video camera, thus recording the image in a magnetic signal which could be used for broadcast and home video. More advanced versions began using methods somewhat akin to the cathode-ray tube technology of television itself; the first flying-spot scanner used an electron beam, projected at a phosphor-coated envelope, to produce a pixel-sized beam of light which was scanned horizontally across a frame of film as the film moved through its path.¹ Even later versions used a xenon bulb to project a single array of light through part of a frame of film and onto a charge-coupled device (CCD), which develops electrical charges relative to the amount of light it receives and converts that charge into either analog or digital signals depending on the desired output.² These developments resulted in outputs which

¹ Jay Holben. "From Film to Tape: 'AC' Takes an In-Depth Look at Some of Today's Top Telecine Hardware: Part 1 in a 2-Part Series." *American Cinematographer*, May 1999, 109.

² *Ibid.*, 116.

were increasingly high in quality and more accurate in reproduction so that, by the late 1970s, Hollywood had started to widely adopt these systems in their studios for production and home video.³

Widespread use and highly improved technology of the telecine, paired with an ever-increasing use of digital technologies in production environments near the turn of the century, led to the development of the second predecessor to the film scanner: the datacine. The first widely used datacine was the Spirit DataCine, introduced by Philips Digital Video Systems Company in 1996. Datacines, for the most part, operate in a manner similar to that of telecines, but whereas telecine output is a continuous electronic video signal, the datacine records the electronic signal into digital data. The use of digital data provided a key development in the transferring of analog film to digital files, one which would be essential to the operations of the film scanners to come.⁴

Though the datacine can be considered a hybrid machine which combines operations of both telecines and film scanners, the most fundamental factor differentiating these devices is the fact that film scanners do not have continuous stream output. Rather than continuously recording and converting a digital or video signal from a reel of film, the film scanner records each individual frame as a unique digital entity.⁵ This would ultimately prove to be an important advancement in the age of digital cinema projection, but in its early stages the film scanner was primarily used as a digital intermediate tool in both production and digital film restoration processes. The digital intermediate process is one by which an analog film is scanned and transferred to digital files, which are digitally manipulated to correct color and, especially in the

³ Albert Abramson. *The History of Television, 1942 to 2000*. Jefferson, NC: McFarland & Company, Inc., 2003: 179.

⁴ Holben. "From Film to Tape." 116.

⁵ Michelle S. Carlos. "A Comparison of Scanning Technologies for Archival Motion Picture Film." Academia.edu. August 02, 2013, 18.

case of restoration, to remove dust and scratches that were present on the film elements during transfer. From there, the digital files would be printed back onto film stock for preservation or theatrical exhibition using a film recorder.⁶ One of the first major film scanners to hit the market for these purposes was Kodak's Cineon—introduced in 1993—which included a scanner, workstation, and recorder; was capable of 2K workflows; and was developed in conjunction with its own file format for digital scans, a precursor to the now commonly used Digital Moving-Picture Exchange (DPX) format. The Cineon was employed in 1993 for the first film restoration carried out entirely through a digital intermediate process: *Snow White and the Seven Dwarfs*.⁷

The primary motivation behind the improvement of these technologies, especially as production and exhibition environments were rapidly progressing towards all-digital workflows, was an increasing desire to achieve the look of celluloid film in digital form. This required that film scanners have the ability to accurately capture grain structure and color at high resolutions. The Cineon was developed with this in mind; its file format (CIN) was designed with a data metric which directly correlates to the color density measurements of negative film and, as such, allows the digitally manipulated images to be recorded back onto film stock with an accurate color space.⁸ No matter how robust the data system, accurate representation of film in digital form would depend largely on how a frame of film was captured in the scanner itself. Accurate digital captures which reduced, to the greatest extent possible, digital artifacts, would require a versatile optical system by which light and color could be adjusted and optimized to any given film stock before the digital files were produced, resulting in minimal adjustments to the subsequent digital images.

⁶ "How to Do a Digital Intermediate." *American Cinematographer*, April 2006, 6-7.

⁷ "History for Colorists." Final Color. <http://www.finalcolor.com/history-for-colorists/>.

⁸ Richard Patterson. "Understanding Cineon." The Digital Intermediate Internet Guide. October 02, 2001. <http://www.digital-intermediate.co.uk/film/pdf/Cineon.pdf>. 2.

Earlier systems of the sort, such as the Spirit DataCine, would use a near-white light source, such as a xenon bulb, which would pass through a selected filter to match either positive, negative, or interpositive film. The filtered light would then pass through the film frame and be split into red, green, and blue beams for digital processing, allowing the separate color channels to be manipulated in isolation during the intermediate stage.⁹ This optical path is outlined in Figure 1.

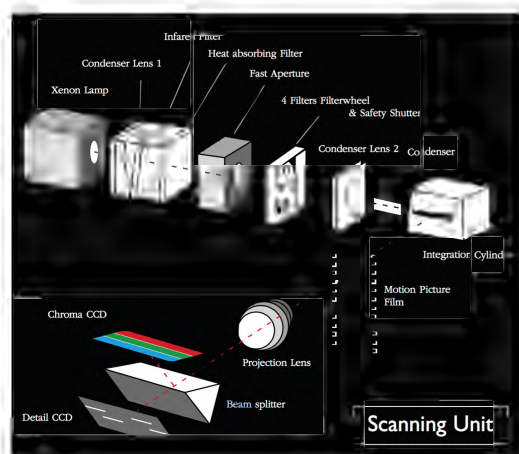


Figure 1: Spirit DataCine optical path.

Though effective for intermediate work of more recent Hollywood productions, archival film presented certain obstacles in the way of this system being optimal for restoration and archival digitization work. Stored in unideal conditions for extended periods of time, color film is prone to dye fading; the different rates at which each dye fades results in film which takes on a distinct, unnatural color, often magenta. To calibrate for these color changes in the scanning process with minimal digital artifacts, it would be necessary to precisely adjust the color of the light illuminating the film, a process which would be virtually impossible with white, xenon- and halogen-based optical systems without a seemingly infinite number of color filters.

The answer to this problem was the introduction of LED optical systems into film scanners. Though LEDs had been known to exist for nearly a century, they had been neither fully understood nor affordable until around the start of the 21st Century. Quick to take advantage of all that LEDs offered in terms of light and color, the first significant output of LED-illumination film scanners to the market began around the early 2000s. The introduction of Arnold & Richter

⁹ Thomson Multimedia Broadcast Solutions. *Spirit DataCine Film Scanner*. http://www.thameside.tv/product_PDFs/spirit.pdf. 6.

Cine Technik's Arriscan in 2003, as well as the Lasergraphics Director and Cintel diTTo in 2005, marked the beginning of a new era in motion picture film scanning.

The Light-Emitting Diode

Essential to a discussion of how light-emitting diodes are employed in film scanning technology is an understanding of the basic science behind the LEDs themselves. Though entire books have been written about the physics and chemistry of LEDs, this section will provide an overview of their basic composition, construction, and function as they pertain to the optical systems of film scanners.

At their most fundamental level, light-emitting diodes are semiconductors: solid elements with an electrical conductivity somewhere between conductors and insulators whose ability to conduct electricity rises as their temperature rises.¹⁰ However, the LED differs from most common light bulbs in that it does not depend on extremely high temperatures to generate light. Rather, the LED emits light through electroluminescence, a process by which semiconductor materials are electronically excited to create photons of light, producing much less heat than an incandescent bulb's glowing wire, for instance.¹¹ For this reason, among others, LEDs have come to be one of the most efficient light sources on the market.

In construction, the typical LED consists of a semiconductor chip, supported on a lead frame and mounted in a reflector cup, and connected to two electrical wires, all of which is embedded inside a solid epoxy dome (Figure 2). Usually, these diodes function by employing two different semiconductor materials in the semiconductor chip, each of which is joined at a

¹⁰ *Merriam-Webster*. November 08, 2017. <https://www.merriam-webster.com/dictionary/semiconductor>.

¹¹ Kenneth R. Spring, Thomas J. Fellers, and Michael W. Davidson. "Introduction to Light Emitting Diodes." Olympus. https://www.olympus-lifescience.com/en/microscope_resource/primer/lightandcolor/ledsintro/.

junction. One side of this junction is a semiconductor material which is dominantly negative in charge (called the n-type region), and the other is a material which is positive in charge (the p-type region). To generate light, voltage is applied through electrical wires at a sufficient enough intensity to move

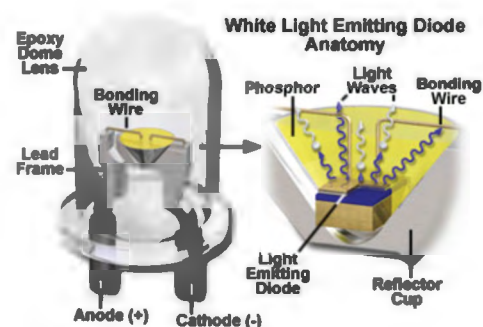


Figure 2: Basic LED construction.

electrons from the n-region to the p-region, where the charges are combined. The resulting energy reduction generates a release of electromagnetic energy in the form of a photon of light.¹² The color of the light is determined by the types of semiconductors employed in the diode; one of the reasons for their efficiency is that, unlike most other light sources, LEDs emit light only in a selected range of wavelengths, resulting in stricter control of their color and, thus, less waste from undesired energy emissions.¹³ The implication of this, however, is that LED lights are inherently monochromatic, which presents both challenges and benefits for their use in film scanning technology (see below).

Though not in the form of the p-n junction diode construction common to contemporary LED lights, the electroluminescent properties of similar diodes were discovered in 1907 during an experiment to see whether silicon carbide (SiC) could be used in the demodulation of radio-frequency signals. It was observed by Henry Joseph Round that applying a small amount of voltage between two points on a SiC crystal produced a dim, yellow light.¹⁴ However, it wasn't until the 1950s and 60s that the discovery of new semiconductor compounds would enable a shift towards commercial viability.

¹² *Ibid.*

¹³ Raymond D. Bengt, Jr. "Light-Emitting Diodes." *Salem Press Encyclopedia of Science*. 2016.

¹⁴ E. Fred Schubert. *Light-Emitting Diodes*. 2nd ed. Cambridge, UK: Cambridge University Press, 2006, 1-2.

This shift was initiated by the development of the first commercially viable visible-spectrum LED in 1962. This diode employed a gallium-arsenide-phosphide (GaAsP) semiconductor which, when voltage was applied, would emit red-light photons. At the time, the light emission of these LEDs was far too dim to be used in more than a couple practical applications, and they remained rather expensive. Nonetheless, this development paved the way for both improving red LEDs and for developing LEDs which could produce any number of other colors.¹⁵ Though green LEDs based on a gallium-phosphide semiconductor became readily available rather quickly, producing a blue LED proved more difficult than any other color. LEDs using silicon-carbide were already known to have blue-light-emitting capabilities, but the luminous efficiency of such diodes were extremely low and, as such, were not of much use in practical applications. It wasn't until the 1990s, with the advent of gallium-indium-nitride semiconductors, that a blue LED with sufficient luminosity was achieved.¹⁶

As it pertains to film scanning technology, the introduction of the blue LED to the market was perhaps the most significant development towards LEDs being incorporated into scanners' optical systems. As mentioned above, LEDs are inherently monochromatic; the production of different colors depends entirely on the distinct semiconductors employed in each diode. The implication here is that a true white semiconductor—one which emits all colors at once—is impossible. However, a primary motivation for developing the blue LED was to exploit the trichromatic theory of human vision: that the combination of red, green, and blue lights produces white light through an additive color process and, when each color is varied, can theoretically produce all visible-spectrum colors.¹⁷ As such, when blue LEDs were finally developed,

¹⁵ *Ibid.*, 8.

¹⁶ Spring et al. "Introduction to Light Emitting Diodes."

¹⁷ Schubert. *Light-Emitting Diodes*, 293.

grouped-arrays of red, green, and blue LEDs combined into one housing unit at appropriate luminosities, employed at the same time, would produce a combination of light emissions which human vision would perceive as true white.

Implications of LED Light Sources for Archival Film Scanning

Seeing a great potential in RGB-array white-light LEDs, both telecines and film scanners began to incorporate them into their optical systems in the early 2000s. The aforementioned ARRI, Lasergraphics, and Cintel were among the first to release film scanners with LED optics, and these products have had a lasting effect in the world of archives and post-production. The application of these new optical systems allowed users to individually modulate each color cluster of LEDs within an array, thus offering the ability to produce any color within its broad gamut.¹⁸ Figure 3 shows the color gamut of a RGB-array LED within the field of human vision.

The ability to modulate a film scanner's

light source to any of the colors within the RGB gamut meant that scanners could be spectrally optimized to represent the color densities of a given film stock and to compensate for dye fading before the digital scans were even created, ultimately minimizing the amount of digital

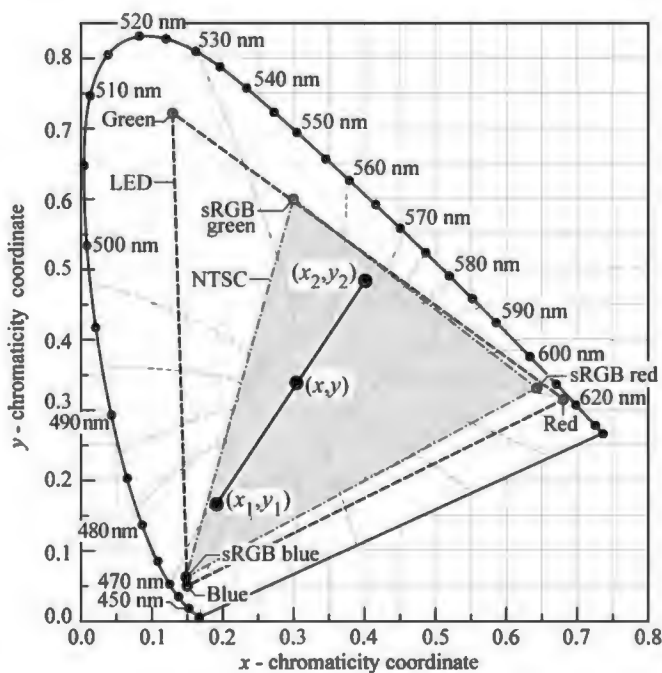


Figure 3: Color gamut of a RGB-array LED (dotted line) within the field of human vision (solid line). The sRGB display standard is also included (shaded area).

¹⁸ *Ibid.*, 314-15.

manipulation necessary and reducing the prevalence of digital artifacts.¹⁹ The modulation of these colors works by adjusting the luminosity of each individual color in the RGB array. For instance, the combination of red and blue LEDs, both at 100% brightness, will display magenta. However, if the blue LEDs are reduced to 50% while the red remain at 100%, the color displayed will be at the midpoint between red and magenta. Continuing to reduce blue to 0% would result in red. As such, by simply adjusting the luminosity of the blue LEDs in this example, any of the colors between red and magenta can be represented (Figure 4).²⁰ Thus, one can see the immense possibilities presented by employing all three colors in the trichromatic array, all at varied degrees of luminosity.



Figure 4: Effect of luminosity on color of combined red and blue light sources.

Added to this, white-light LEDs from RGB arrays have a significantly high color-rendering index (CRI), a measurement used to determine the ability of a light source to accurately represent the true colors of a given object. On a 0-100 scale, the trichromatic LED arrays are capable of a CRI between 60 and 95, which signifies that, at optimal performance, they can very nearly represent a film stock's true colors. Though light sources such as incandescent quartz-halogen lamps have a CRI of 100 (and, as such, are often used in museums and other gallery spaces where accurate color representation is of the utmost importance), LEDs have come to be preferred in film scanners for their RGB modulation and their relatively low heat output, which is far safer for fragile archival film, especially nitrate.²¹ From a film preservation perspective, the ability to accurately represent and tightly control color with low

¹⁹ Michael Senge. "Advancements in Film Scanning Technologies." *SMPTE Motion Imaging Journal* 119, no. 8 (Nov. & dec. 2010): 50.

²⁰ "How Colour Changing LEDs Work." Kitronik Ltd. https://www.kitronik.co.uk/pdf/How_colour_changing_LEDs_work.pdf.

²¹ Schubert. *Light-Emitting Diodes*, 317.

heat output has proved an invaluable replacement to the xenon and halogen bulbs previously employed in film technologies.

Efforts to optimize LEDs for archival film following their introduction into film scanning technology was not limited to color and heat. The construction of the diodes' housing units presented both benefits and drawbacks to this respect. LEDs are housed within a solid, translucent dome made of an epoxy resin, a substance which is widely used in electronics manufacturing for its ability to both insulate electricity and protect electrical units from debris. The shape of the dome is essential to its efficiency; in accordance with Snell's Law of refraction, when light is emitted from a diode, only those photons emitted within the *critical angle* are able to escape, while all those emitted at an angle greater than the critical angle will be reflected internally. Though this angle can differ depending on the specific diode chip and its chemical geometry, this process typically results in only 1-2 percent of generated light escaping the LED

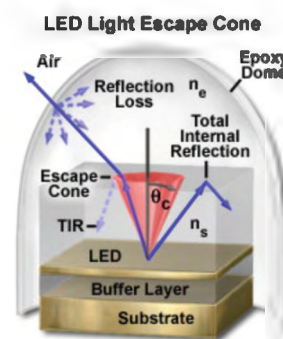


Figure 5: Light emission properties of LED construction. The critical angle is represented by θ_c .

construction.²² The shape of the epoxy dome, however, is designed to maximize the output of generated light. By ensuring that most photons emitted within the critical angle make contact with the dome at a right angle, the refractive index mismatch between the diode and the air is reduced, resulting in minimal loss from reflection.²³ This light emission process is outlined in Figure 5.

²² Spring et al. "Introduction to Light Emitting Diodes."

²³ E.W. Williams, R. Hall, and B.R. Pamplin. *Luminescence and the Light Emitting Diode: The Basics and Technology of LEDs and the Luminescence Properties of the Materials*. Vol. 13. International Series on Science of the Solid State. Oxford, England: Pergamon Press Ltd., 1978, 68.

The implication of this process for its application in film scanners is that LED light is emitted in a relatively narrow and directed path. The average LED, operating at 100% intensity, will emit light at an angle of around 10 to 12 degrees. Though awarding notable benefits in both film scanning and general applications for their ability to precisely direct light to a desired source, the drawback from an archival perspective is that a more directed light tends to emphasize scratches on the film during the scanning process. The underlying principle behind the effect of a scratch on light emissions is that a scratch creates unusual angles in the film material which refracts light away from the image capture device rather than directly into it. As such, these areas appear dark in a scanned image. Though this issue has been addressed through the development of wet-gate scanning—a process by which fluid with a similar refractive index to that of the film base fills the scratches and allows the light to be refracted through to the image capture device—some companies have responded by diffusing the LED light source to achieve somewhat similar results. By diffusing the source, light is emitted at a much wider variety of angles than the more direct, collimated LED. By exposing a scratch on film to light at many different angles, the chances are increased that at least one of these rays will make contact with a scratch at such an angle so as to refract through the scratch and into the image capture device (Figure 6). By 2006, Cintel had patented its own LED diffusion technology for its film scanners; they describe the process as follows:

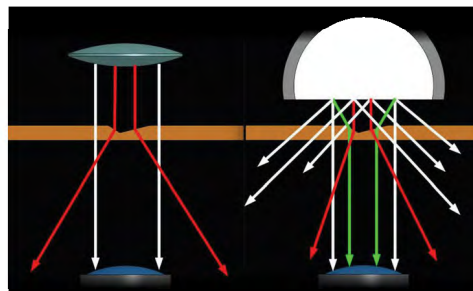


Figure 6: Collimated light source (left) vs. diffuse light source (right).

By using an optical integrator to provide the diffuse light source, the wide range of angles means that light impinging from the film from a wide angle, if then scattered by optical imperfections, may still be captured by the imaging system. The difference in intensity between light transmitted

straight through film and light scattered by imperfections on the film is thus reduced making the scratch or other imperfection less visible.²⁴

LED Optics in Film Scanners

Though the general structure and implications of LED light sources in film scanning is uniform across brands, the ways in which they function within the larger optical system of the scanner often differs depending on both the type of scanner and user preferences. This section will outline some of the basic applications for light-emitting diodes in film scanners and the ways in which different manufacturers and users incorporate them into their larger optical processes.

i. Resolution

Though most contemporary film scanners are designed to accommodate 2K and 4K resolution outputs, recent years have seen an increase in scanners offering anywhere from 5K to 10K options. The implications of digital resolution in film scanning generally become more complex to manage as resolution increases, a principle which has a direct correlation to the scanner's illumination methods. In a typical digital image capture sensor, each pixel has its own sensor which, when illuminated with light, is given an electron charge that can be translated into a voltage signal and converted into a digital signal.²⁵ When resolution increases, pixel size decreases in proportion. Thus, at similar illumination levels, a 4K resolution pixel will receive a smaller electron charge than a 2K resolution pixel since the light is distributed over a greater range of sensors. The ability to make minute adjustments to RGB-array LED illumination

²⁴ Terence William Mead. Optical Scatter Correction for Film Scanners. US Patent US8009190 B2, filed March 23, 2006.

²⁵ Alvin Quach. *Complementary Metal-Oxide Semiconductor Sensors*. Technical paper. College of Engineering, University of California Santa Barbara. 2010, 3.

systems in film scanners has allowed for solutions to this issue. For example, a review of technological innovations in Digital Film Technology's Scanity film scanner indicates that the LED illumination allows each primary color to be spectrally optimized to a given film stock at maximum intensity. Discrete spectral tailoring

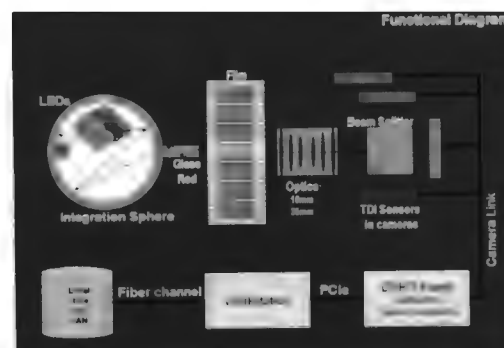


Figure 7: DFT Scanity optical path.

of the sort means that each color can be optimized in isolation from the next, resulting in maximum illumination with minimal excess energy output to the film. Furthermore, rather than flashing the film with each color individually, the Scanity allows for flashing all three colors at the same time to increase the overall illumination on the film; a subsequent pass through a color beam splitter allows the colors to be separated into distinct channels for digital adjustment (Figure 7).²⁶ These features allow accurate scans to be generated at higher resolutions.

ii. *Transport and Strobe*

In general, two options for transporting the film through a scanner's optical path exist across all scanners: continuous and intermittent. Each has its own benefits and drawbacks. While continuous transport offers faster scanning capabilities, it generally only allows for one flash per frame during the scanning process, which may not be ideal for archival films. Intermittent transport stops each frame in the gate and optical path to be scanned, which allows each color of the LEDs to flash in sequence and render discrete color scans for each frame. Intermittent transport, however, can result in a much longer scanning process.

²⁶ Senge. "Advancements in Film Scanning Technologies." 49-50.

Arnold & Richter Cine Technik's Arriscan, for instance, uses intermittent, pin-registered film transport in conjunction with RGB-array LED illumination to provide two essential options for archival film scanning. The first option is to flash each frame of film twice; for one of these flashes, the LEDs are optimized for low-density regions of the film, and the other is optimized for high-density regions. Each of these flashes is subsequently combined into one image, resulting in scans which much more accurately capture the full dynamic range of a frame of film. The second option is to flash each frame three times, one for each of the RGB-array colors. This provides color separation elements for each frame without resorting to a color beam splitter, allowing each color to be precisely adjusted in a digital environment.²⁷

Products such as the previously mentioned Scanity, as well as Lasergraphics' ScanStation, offer continuous film transport for quick and efficient scanning operations. These systems work by continuously pulling the film through the optical path without stopping. Sprocket hole registration features work in conjunction with the illumination system to strobe the LEDs when a frame is positioned within the scanner gate. In contrast to the intermittent system mentioned above, the continuous system does not lend as well to flashing one frame multiple times and, as such, might offer users less control in a digital environment. However, continuous systems have proved a valuable asset as they offer high-quality scans in a relatively short amount of time, which might be essential to labs and archives with less resources (the Scanity has speed capabilities of up to 15fps at 4K resolution and 25fps for 2K; the ScanStation boasts overall speeds up to 60fps).^{28,29}

²⁷ Debra Kaufman. "Scanning the Arriscan's Possibilities." *American Cinematographer*, February 2004, 95-96.

²⁸ Digital Film Technology. *Scanity Data Sheet*. <http://www.dft-film.com/downloads/datasheets/DFT-SCANITY-Datasheet.pdf>.

²⁹ "Lasergraphics ScanStation Film Scanner - Features." Lasergraphics. <http://www.lasergraphics.com/scanstation-features.html#>.

iii. Image Capture

Once the scanner's illumination is flashed, passes through the film and, depending on the scanner, through subsequent beam splitters, the light reaches its final destination in the optical path. At this point, the light reaches what is essentially a digital camera, travelling through a lens and registering on an image-capture sensor. Most top-line scanners utilize one of two types of image sensors: A Complementary Metal-Oxide Semiconductor sensor (CMOS) or a Time Delay Integration sensor (TDI). The most fundamental difference between these two sensors as they are employed in film scanners is that a CMOS sensor is a full image area sensor (i.e. captures a full frame of film as one image), and a TDI images one measured line at a time, compounding the lines to achieve a full-density image (see below).

The CMOS sensor is relatively simple in function. Coming into wide use around the mid-1990s, the CMOS sensor is an array of pixel sensors arranged on a chip which corresponds in size to the gate of the film scanner, and each of these pixel sensors corresponds to one pixel in the subsequent digital image. The pixel sensors are generally composed of a metal substance which, when exposed to photons of light, emits a number of electrons relative to the intensity of the light source. These electrons are converted into a voltage signal in the sensor and sent to an analog-to-digital converter where they are translated into a digital signal. The pixel sensors, in isolation, are only sensitive to the intensity of the light and not the wavelength, which carries color information. As such, each pixel sensor is outfitted with a color filter which only allows light of a specific wavelength to pass through. The most common arrangement of color filters in a CMOS pixel array is the Bayer filter, which consists of a repeated array of two-by-two groupings: one red, one blue, and two green. This arrangement is designed based on the human eye's greater sensitivity to green light and, when arrayed in a pattern of millions of pixels,

generates natural image colors.³⁰ Companies such as ARRI, who has employed a CMOS sensor in their Arriscan, have cited advantages of the sensor's ability to capture the information of a full frame of film with a flash of the LEDs, which results in less exposure time and minimal artifacts.³¹

The TDI, in contrast, scans only one line of image area at a time, employing multiple scan lines in a single sensor for a compounding effect. In this process, a strip of film passes through the optical path of the scanner and multiple line areas of each frame are captured. As the aperture opening of a single line is far less than the CMOS sensor's entire image area, the TDI lets much less light through to the film, thus requiring longer exposure times. The TDI sensor compensates for the lack of illumination intensity by employing multiple scan lines for a single sensor. To illustrate this rather complex process, it is useful to examine how one frame of film is captured by a TDI sensor. As the very start of the frame begins to pass through the optical path, the LEDs illuminate one line of the film and capture that information in the sensor; again, since the amount of light is so low for each scan line, not much image information is captured in the first line. Then, the first scanned line of the film moves to the second scan line where it is captured again and compounded with the previous scan line, generating a scan which is slightly more luminous. The line then passes to the third scan line, where it is captured a third

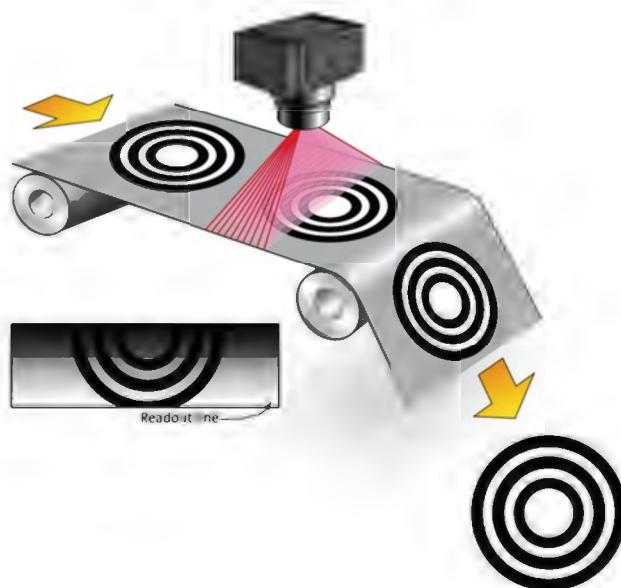


Figure 8: TDI line imaging process.

³⁰ Quach. *Complementary Metal-Oxide Semiconductor Sensors*, 4-5.

³¹ Kaufman. "Scanning the Arriscan's Possibilities." 96.

time and compounded with the previous two. This process continues through until each “line” of film has passed through all of the scan lines, and the compounded image capture of all scan lines is a fully dense and luminous image.³² (This entire process can be visualized in Figure 8). The Scanity utilizes a TDI sensor with up to 96 lines in a scan sequence, generating images which can take advantage of the great benefits offered by LED-array optical systems despite the relatively low light output of LEDs themselves.³³

Conclusion

Having completed the optical path, the digital images generated from these scanners go on to serve a variety of purposes. In archives, these digitized films might be output to DVDs or to online streaming platforms for access purposes, or simply to save the content of a fast-decaying reel of film. In restoration labs, they might be put through a rigorous process of adjustments and manipulations using various restoration software in an effort to bring the film back to some ideal state of being in its new digital form before being output to DCPs for repertory theatrical runs or to Blu-ray for the home video market. In contemporary film studios, those few movies still shot on film will now almost always be scanned and digitized for editing, color grading, and output to digital cinema formats. Regardless of their purpose, film scanners employing LED-based optical systems have come to be the norm in these environments for their versatility, consistency, and efficiency. The technical innovations brought on by the introduction of light-emitting diodes into these processes will undoubtedly continue to make their mark on this new era in cinema history, one fated for a digital world.

³² "TDI Line Scan." Stemmer Imaging. <https://www.stemmer-imaging.co.uk/en/knowledge-base/cameras-tdi-line-scan/>.

³³ Digital Film Technology. *Scanity Data Sheet*.

Bibliography

Abramson, Albert. *The History of Television, 1942 to 2000*. Jefferson, NC: McFarland & Company, Inc., 2003.

A book which outlines the history of television from 1942 to 2000, and the ways its technology has changed over time. For the purposes of this essay, a brief section outlining the use of telecine technology for producing home-video versions of Hollywood motion pictures was especially pertinent. This section provided useful context for the inception of telecine technology and the ways in which it was ultimately adopted into the Hollywood studio system, ultimately leading to contemporary home-video technologies.

Benge, Raymond D., Jr. "Light-Emitting Diodes." *Salem Press Encyclopedia of Science*. 2016.

An encyclopedia article offering a condensed and simplified version of the history and workings of light-emitting diodes. The historical context offered by this article was useful for situating the inception and development of LEDs within a timeline. Additionally, its simplified, tech-focused aspects proved useful for those parts of this paper for which an extremely complex understanding of LEDs would have been either inappropriate or simply beyond the intended scope of the paper.

Carlos, Michelle S. "A Comparison of Scanning Technologies for Archival Motion Picture Film." Academia.edu. August 02, 2013.

An academic paper which provides an overview of film scanning technologies, including the different types of scanners on the market, how they work with films of different gauges, how they manage dust and scratches, how they manage color and resolution, and their various practical applications, among other subjects. This paper proved useful in establishing the differences between telecine, datacine, and film scanning technologies, as well as placing them each within a temporal context.

Digital Film Technology. *Scanity Data Sheet*. <http://www.dft-film.com/downloads/datasheets/DFT-SCANITY-Datasheet.pdf>.

A proprietary data sheet from DFT outlining the technological specifications of their Scanity film scanner. The features of this scanner were useful in providing a practical example of how LED optical functions are applied in contemporary products.

"History for Colorists." Final Color. <http://www.finalcolor.com/history-for-colorists/>.

A timeline which illustrates the introduction of various products and formats to the film industry. Specifically, this timeline focuses on those products and formats which pertain to color in film history. For the purposes of this paper, date entries noting the first film to be scanned entirely to a digital format for restoration provided a useful factoid for incorporation into the larger timeline of film scanning history.

Holben, Jay. "From Film to Tape: 'AC' Takes an In-Depth Look at Some of Today's Top Telecine Hardware: Part 1 in a 2-Part Series." *American Cinematographer*, May 1999, 108-22.

An article which addresses some advancements in telecine technology in 1999. This article was briefly pertinent to an understanding of how telecine technology began to be merged into film scanning technology around the turn of the century, and how the technology changed and improved in the process.

"How Colour Changing LEDs Work." Kitronik Ltd.
https://www.kitronik.co.uk/pdf/How_colour_changing_LEDs_work.pdf.

A very brief article explaining, in greatly simplified form, the workings of multi-color LED arrays function. This article was pertinent to the more elementary discussions of color control and manipulation in LED-array film scanning optics.

"How to Do a Digital Intermediate." *American Cinematographer*, April 2006, 6-7.

An article which notes some of the Arriscan film scanner's capabilities and practical applications in digital intermediate work, which was used as an example of the ways in which contemporary products incorporate LEDs into their overall optical systems.

Kaufman, Debra. "Scanning the Arriscan's Possibilities." *American Cinematographer*, February 2004, 94-99.

An in-depth discussion of the Arriscan film scanner's technological specifications and the ways in which they are employed in practical environments. A number of issues discussed in this article were pertinent to this paper. First, the author discusses the workings of the LED-array optical system of the Arriscan and the reasons behind ARRI's choice to incorporate LEDs into the optical system. Some notable topics here are the low heat output of LEDs and their color control abilities. Second, the author discusses the CMOS sensor employed in the Arriscan's optical system, as well as arguments for its advantages over other types of sensors.

"Lasergraphics ScanStation Film Scanner - Features." Lasergraphics.
<http://www.lasergraphics.com/scanstation-features.html#>.

A page on Lasergraphics' website which outlines the technical specifications of their ScanStation film scanner. These specifications provided a practical example of the ways in which Lasergraphics incorporates continuous-motion, LED-based optics into its product.

Mead, Terence William. Optical Scatter Correction for Film Scanners. US Patent US8009190 B2, filed March 23, 2006.

A patent filed by Cintel in 2006 for a diffusion component to the LED array in its film scanners. Patents being highly detailed in nature, this proved a valuable resource in both understanding the underlying functions behind LED light diffusion in film scanning operations and for a practical example as to how certain companies were responding to the limitations of LEDs.

Merriam-Webster. November 08, 2017. <https://www.merriam-webster.com/dictionary/semiconductor>.

A dictionary entry from Merriam-Webster offering a straightforward, boiled-down definition of what a semiconductor is. This definition was used as a foundation for an in-depth discussion of their use in LED construction.

Patterson, Richard. "Understanding Cineon." *The Digital Intermediate Internet Guide*. October 02, 2001. <http://www.digital-intermediate.co.uk/film/pdf/Cineon.pdf>.

A technical paper outlining the workings of the Cineon file format (CIN). The file format was developed in conjunction with Kodak's Cineon film scanner, the discussion of which provides a useful example as to how digital environments were being tailored to optimal color and density measurements of scanned images of film. This paper offered a basic understanding of how early film scanners were developed and how they continued to strive for an ideal image quality standard.

Quach, Alvin. *Complementary Metal-Oxide Semiconductor Sensors*. Technical paper. College of Engineering, University of California Santa Barbara. 2010.

An in-depth technical paper outlining the workings of CMOS image sensors. As CMOS sensors are employed in many contemporary film scanners, this paper provided valuable knowledge of how the sensors are constructed, how their individual pixels convert light into digital signals, and how they express color. It also offered important distinctions between CMOS sensors and other types of sensors.

Schubert, E. Fred. *Light-Emitting Diodes*. 2nd ed. Cambridge, UK: Cambridge University Press, 2006.

A book which outlines, with great depth, the underlying chemistry and physics of light-emitting diodes, as well as the implications of their use in various lighting environments. This book was useful for a number of purposes. First, it provided some essential details of the history of the LED from its inception onwards. Additionally, it discussed the chemical make-up of an LED's semiconductor material and how they generate light as well as the physical construction and properties of the diodes. Perhaps most essential with regards to this paper were the chapters discussing the color properties of LEDs, including the ways in which they generate colored light, their ability to accurately render the color of various objects, and the ways colored LEDs can be combined to produce white light. The understanding of color LEDs was essential to a discussion of their applications in film scanning technology.

Senge, Michael. "Advancements in Film Scanning Technologies." *SMPTE Motion Imaging Journal* 119, no. 8 (Nov. & dec. 2010): 47-52.

An article discussing the reasons behind the implementation of LEDs into film scanning technologies. The author discusses the issues both raised and resolved by LED optics in film scanners. Additionally, there is discussion of the ways in which LED colors can be tailored to match specific film stocks or to compensate for dye fading in decayed films. Finally, the article discusses the implications of these features for their use with archival film.

Spring, Kenneth R., Thomas J. Fellers, and Michael W. Davidson. "Introduction to Light Emitting Diodes." Olympus. <https://www.olympus-lifescience.com/en/microscope-resource/primer/lightandcolor/ledsintro/>.

A technical paper which provided a backbone of light-emitting diode research. This paper discusses in great detail the chemical and physical workings of LEDs, including how they are constructed, the elements they are composed of, how their elements react to generate photons of light, and the light emitting properties of their materials and their housing. Though much of the detail with which the LED's functions are discussed was beyond the scope of this paper, it nonetheless provided a wealth of essential knowledge for understanding how LEDs work, which was subsequently applied to their use in film scanning technology.

"TDI Line Scan." Stemmer Imaging. <https://www.stemmer-imaging.co.uk/en/knowledge-base/cameras-tdi-line-scan/>.

A website article from Stemmer Imaging describing the process of TDI line scan image capturing. Though the text of the article did provide useful explanations of how the TDI image capture's compounding effect operates, this source was ultimately valuable for an illustration it provided to visually outline how this process works. This illustration was used as Figure 8 in the text of this paper.

Thomson Multimedia Broadcast Solutions. *Spirit DataCine Film Scanner*. http://www.thameside.tv/product_PDFs/spirit.pdf.

A brochure outlining the technical specifications of the Spirit DataCine film scanner. This source provided a useful practical example of early film scanning technology and the ways in which its optical features differed from the LED optical systems that would follow.

Williams, E.W., R. Hall, and B.R. Pamplin. *Luminescence and the Light Emitting Diode: The Basics and Technology of LEDs and the Luminescence Properties of the Materials*. Vol. 13. International Series on Science of the Solid State. Oxford, England: Pergamon Press Ltd., 1978.

A book which details the technical workings of the light-emitting diode. The small portion of this book that proved useful to this paper was a brief discussion of the construction of the LED's epoxy dome housing, including its primary uses and its implications for the refraction and dissemination of light. This discussion was incorporated into a larger discussion of the LED's light emitting properties and the subsequent diffusion technologies that were created because of these properties.

Figures

Figure 1: Thomson Multimedia Broadcast Solutions. *Spirit DataCine Film Scanner*. http://www.thameside.tv/product_PDFs/spirit.pdf. 5.

Figure 2: Spring, Kenneth R., Thomas J. Fellers, and Michael W. Davidson. "Introduction to Light Emitting Diodes." Olympus. <https://www.olympus-lifescience.com/en/microscope-resource/primer/lightandcolor/ledsintro/>.

Figure 3: Schubert, E. Fred. *Light-Emitting Diodes*. 2nd ed. Cambridge, UK: Cambridge University Press, 2006, 315.

Figure 4: "How Colour Changing LEDs Work." Kitronik Ltd. https://www.kitronik.co.uk/pdf/How_colour_changing_LEDs_work.pdf.

Figure 5: Spring, Kenneth R., Thomas J. Fellers, and Michael W. Davidson. "Introduction to Light Emitting Diodes." Olympus. <https://www.olympus-lifescience.com/en/microscope-resource/primer/lightandcolor/ledsintro/>.

Figure 6: <http://www.lasergraphics.com/area-imager-vs-line-scanner-light-integration.html>

Figure 7: Senge, Michael. "Advancements in Film Scanning Technologies." *SMPTE Motion Imaging Journal* 119, no. 8 (Nov. & dec. 2010): 47.

Figure 8: "TDI Line Scan." Stemmer Imaging. <https://www.stemmer-imaging.co.uk/en/knowledge-base/cameras-tdi-line-scan/>.