August 2016

SMPTE Motion Imaging Journal

Covering emerging technologies in film, broadcast, and the connected media ecosystem

Celebrating 100 years in Motion Imaging

This special issue includes:

- Review articles on Color, Image Formats, Audio, Camera & Lens, Recording & Storage, Digitization, and more…
- A timeline spanning the last 100 years of Motion Imaging Film & Video
- And a look back at SMPTE's History Archives

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SMPTE Motion Imaging Journal

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Barbara H. Lange

Happy 100th Birthday, SMPTE!

This issue of the *SMPTE Journal* is a special one, celebrating 100 years of SMPTE and its vital role in this ever-growing industry.

As you read this special retrospective, looking back 100 years and surmising what is ahead, I hope that you will sit and enjoy a piece of cake and raise a toast to SMPTE. Reaching a centennial anniversary is a remarkable milestone that should be celebrated in style.

On 24 July 1916, a group of engineering visionaries, including C. Francis Jenkins, Donald J. Bell, Paul H. Cromelin, C. A. Willatt, Francis B. Cannock, W. Burton Westcott, Paul Brockett, E. Kendall Gillett, Herbert Miles, and J. P. Lyons, gathered before the Notary Public, Ralph S. Sherline, to affirm the formation of the Society of Motion Picture Engineers (SMPE).

“[Motion Picture] is making of the world one great family, and soon we will come to feel that we are a friend of the man over yonder, because we know him so well from seeing him in the picture so often.” –C. Francis Jenkins

Later that day, the Society held its first meeting, in Washington, District of Columbia, where Henry D. Hubbard, the Secretary of the U.S. National Bureau of Standards, spoke before this group about the value and importance of standards, especially for a nascent industry. Hubbard’s paper is extraordinary and, like so much of the past, still rings true today. He spoke of standardization becoming part of our daily lives without us even realizing. Our most basic human necessities—food, shelter, clothing—are all impacted by standards, which we often take for granted. Standards have helped to ensure consumers are able to enjoy a stated expectation. We know that, when we buy a product, it will work because it was built upon a set of industry standards. As Hubbard stated, “Each profession aims to standardize its training, its terminology, its equipment, its data, both numerical and descriptive, its code of ethics, and to fix standards of quality and performance, showing that standardization has a breadth commensurate with human activity.”

One hundred years later, the constant evolution of technology has made standards even more important than ever. Today, SMPTE is active in important developments such as high dynamic range, ultra high definition, video over IP, Interoperable Master Formats, and so much more. In the early days, much of SMPE’s work was on the physical aspects of the business, from film to projection systems. Now, of course, our work is driven mostly by software-related interfaces. With the greater influence of IP-related activities—from production to distribution—SMPTE continues to play a vital role in bringing order to chaos, which we have been doing for 100 years!

It is time to celebrate the Society. During this milestone year, the staff and I have had the pleasure of attending many special Section meetings where the Society is being feted. At each occasion, I am inspired by the generous spirit of the SMPTE members who keep Jenkins’ vision alive, enabling a Society that not only sets standards but brings together like-minded individuals to share knowledge and experiences. Whether in Hong Kong, New York, Los Angeles, or Pittsburgh, our local Section leaders are carrying the torch for today’s and tomorrow’s members. The Society’s membership has ebbed and flowed over the years, but I am delighted to say that we are seeing a tremendous increase in membership—including our younger generations. In 2015, we saw an 8% membership growth, and 2016 is proving to be just as active. As C. Francis Jenkins said during that inaugural meeting in July 1916, our leaders are vital for a strong future, “I know from the spirit shown at that meeting, that this Society was formed with an honest intent to be of service to the industry at large; and that the

SMPTE Sections and partner organizations have been celebrating SMPTE with cake!

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officers and members alike intend to give largely of their time and energy for the promotion of the general good and without thought of financial reward; and as the engineer stands behind it all, we should feel due responsibility, while taking justifiable pride in our vocation."

Happy Birthday to an amazing organization! One built on the good will of so many volunteers and members who believe in the work we do.

Robert P. Seidel

100 Years of Service in Motion Imaging

As President of the Society of Motion Picture and Television Engineers and on behalf of the Board of Governors and staff, I would like to send greetings to all our members around the world on the 100th anniversary of our Society. Your dedication and hard work has transformed the Society into a global organization that is recognized as the leader in motion imaging and sound. In 1916, our Society was founded when C. Francis Jenkins and a small group of engineers signed the incorporation papers establishing the Society of Motion Picture Engineers. The mission of the organization was set forth as "…advancement in the theory and practice of motion picture engineering and the allied arts and sciences; the standardization of the mechanisms and the practices employed therein; and the maintenance of a high professional standing among its members." One hundred years later, these aims remain unchanged. While the technology has changed over the years, in large part due to SMPTE, we have continued to be instrumental in establishing some of the most iconic standards for high quality content. SMPTE Standards and Recommended Practices touch nearly every piece of motion imaging content seen by viewers around the world. Entertainment programming remains one of the leading U.S. exports that entertain and inform the world. Our Society has enabled the production, post-production, and distribution of content on a global scale, which has truly created the "Global Village."

Today, the Society continues to fulfill the original intent of its founders by advancing and standardizing the creative tools used by the storyteller to "suspend disbelief," invoke emotion, inform, and educate the audience.

Our Society is built on three main pillars: Membership, Education, and Standards. Our individual membership roll now exceeds 7000 and is growing. We are also increasing our corporate memberships and expanding into adjacent markets, such as over-the-top (OTT) television and user groups.

To better serve the industry as a whole, SMPTE and the Hollywood Professional Association (HPA) consolidated in 2015. The new relationship between SMPTE and HPA presents many exciting possibilities, including fresh occasions for interaction and dialogue, broader educational opportunities, and even richer contribution to standards development.

In February of this year, SMPTE was honored by the Academy of Motion Picture Arts and Sciences with a special award recognizing the Society for its 100 years of contributions to the motion picture industry. The plaque reads as follows: "For one hundred years, the Society's members have nurtured technology, provided essential standards, and offered the expertise, support, tools and infrastructure for the creation and post-production of motion pictures."

Similarly, The National Academy of Television Arts and Sciences has recognized SMPTE over the years witheight Engineering and Technical Emmy Awards for their contributions to the television industry, including the Philo T. Farnsworth award in 2015.

As the motion picture industry moved to digital image capture and distribution, SMPTE played a critical role in the merging of traditional television technology into the motion picture industry to ensure that the original creative intent of the storytellers was preserved.

Today, the Society continues to fulfill the original intent of its founders by advancing and standardizing the creative tools used by the storyteller to "suspend disbelief," invoke emotion, inform, and educate the audience. As we look to the next 100 years, the Society is already exploring new frontiers such as ultra high definition, 4K, 8K, high dynamic range, IP video, OTT, high frame rates, and wide color space. It has been my honor to serve as President during this major milestone of the Society, and I can assure you we are well positioned for the future.

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SMPTE honored with Scientific and Technical Award from the Academy of Motion Picture Arts and Sciences in 2016, for 100 years of contributions to the advancement of motion picture standards and technology.

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SMPTE receives the Philo T. Farnsworth Award from the National Academy of Television Arts and Sciences in October 2014. (L-R) Pete Ludé, Bob Kisor, Pat Griffis, Barbara Lange, Matthew Goldman, Peter Symes, and Charles Jablonksi.

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Peter Symes
Director of Standards and Engineering

100 Years of SMPTE Standards

While SMPTE is based on three pillars of activity, namely, Membership, Education, and Standards, creating industry standards has been a core activity since 1916 when the Society of Motion Picture Engineers (SMPE) was formed for that very purpose. Obviously, many things have changed during these 100 years—particularly the technologies we standardize and the technologies we use to create and publish standards—but the fundamentals of standards creation, as well as the essential role of standards in the industry, remain largely unchanged.

Film

In 1916, SMPE was asked to bring order to a world where the many variants of film cameras created films that could be projected only on the corresponding projector from the same designer or manufacturer. The most common format, that is, the 35 mm film, already existed when SMPE was formed, but the publication of a full set of standards was a key factor in this format becoming the foundation of the movie industry, as well as its survival to this day. With the advent of "talkies," a frame rate of 24 frames/sec was established, and this, too, survives today—even being adopted by many television productions.

Film technology and applications advanced in many areas: sound, color, widescreen, and several generations of 3D. The quality of the film itself, as well as of the associated equipment, including cameras and projectors, increased dramatically, and the 35 mm image, still beloved by many cinematographers, became the standard against which all competing technologies were judged. Throughout this time, the standards applicable to all aspects of film and related technologies were updated and refined to maximize the benefits to the industry. Even apparently mundane details contributed to the success of the industry; for example, the exact shape, size, and positional tolerances of sprocket holes were refined well into the 20th century, resulting in improved image stability and enhanced longevity of release prints. The 35 mm format was ubiquitous, and prior to the recent emergence of digital cinema, a 35 mm film could be displayed reliably on well over 150,000 screens in all countries around the world.

Today, electronic acquisition and digital cinema distribution are rapidly supplanting film in all major markets, but the 35 mm film remains the most universally acceptable format throughout the world.

Today, electronic acquisition and digital cinema distribution are rapidly supplanting film in all major markets, but the 35 mm film remains the most universally acceptable format throughout the world.

Television

In 1950, the role of the Society was officially expanded to include television, and we became SMPTE. Transmission standards for monochrome television in the U.S. had been developed by the National Television Standards Committee (NTSC), and the second iteration of this committee developed the well-known NTSC color television standard in 1952. SMPTE's role was to develop the standards necessary to generate pictures and sound for transmission, as well as to facilitate interoperability of television equipment from different manufacturers.

Interoperability changed the face of the industry. In the early days of television, a station would generally be constrained to buy everything, from camera to transmitter, from a single manufacturer. Equipment from a different manufacturer could not normally be used in the system. The evolution of a comprehensive set of standards changed this; users could "mix and match" and pick the most suitable or cost-effective item of equipment for each requirement—resulting in greater competition, more versatile equipment, and lowered costs for users. Standards also are key to new companies entering the field. With a standardized infrastructure, small companies can enter the market with "niche" products; they do not have to provide the complete chain in order to become a player in the market.

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Color came to television in the 1950s, and it rose to prominence in the 1960s, but the biggest change to television as an industry was probably the introduction of the videotape recorder (VTR) in the 1960s. Originally conceived as a mechanism for program delay across the various time zones of the U.S., the VTR quickly changed the industry from mostly live programming to pre-production (and, with the advent of editing systems, post-production) of the majority of programs outside of live news and sports.

This era was also very significant in the world of SMPTE standards. VTRs, as well as the tape they used, came from various manufacturers, and standards were absolutely essential to successful recordings and reliable interchange. In this era, engineers from the user community were very active in standards development, and the combined voice of many users was sufficient to coerce manufacturers into agreeing on a common standard for a new class of VTRs—one that dominated the marketplace for many years.

Initially, SMPTE television standards were focused on countries that adopted the NTSC transmission system, and the majority of standards participants were from the U.S. and Canada. The European Broadcasting Union (EBU) published many of the standards for use in the 50 Hz countries using the phase-alternation line and sequential color and memory systems. SMPTE and EBU cooperated in many areas, the most significant being a Joint Task Force in 1981 that established the basic parameters for digital television (CCIR 601/BT.601) and the SMPTE/EBU Task Force on the Exchange of Program Material as Bitstreams that established the basic concepts that led to standards for the handling of video and audio essence, as well as associated metadata. The dialog with EBU led to further cooperation and EBU's decision to entrust SMPTE with the development of standards for European television systems, in addition to those for North American systems. In effect, SMPTE became the source of studio standards for the television world.

> **A major event in 2004 was the first large-scale demonstration for D-Cinema of the 2k DLP projector—and everyone realized that we had created a system that could provide images comparable with the best release prints.**

Digital Cinema

Large screen projection of electronic moving images had been a goal since the introduction of television. Eidophor systems produced color images for venues in the 1960s and very large, high-quality images by the 1990s, but the systems were large and expensive and never threatened the economics of movie distribution by 35 mm release prints.

Texas Instrument's demonstration of the DLP® (Digital Light Processing) projector in 1998 was probably the most significant event leading to serious consideration of electronic distribution and projection of mainstream cinematographic material. If a suitable system could be devised, the economics were compelling. Release prints are expensive to make, heavy and expensive to ship, last only a few weeks, and have to be returned and destroyed to avoid rampant piracy. Hollywood was spending well in excess of $1 billion/year on release prints.

At this time, high-definition television (HDTV) was well established, and some believed that HTDV was a plug-in solution for digital cinema. The movie industry disagreed. It considered that the quality of image represented by 35 mm film could not be approached by HDTV and that an entirely new system was required. This was the view adopted by SMPTE, and D-Cinema (as it became officially known) was developed in a separate Technology Committee. There were many contributions to D-Cinema technology from the television world—most significantly, perhaps, the Material eXchange Format (MXF) file format for distribution—but all aspects of image quality and coding were developed specifically for D-Cinema, with the critically important contribution of the cinematographers. A major event in 2004 was the first large-scale demonstration for D-Cinema of the 2K DLP® projector when many realized that the system could provide images comparable with the best release prints.

However, the greatest complexities of D-Cinema were business related rather than technological. Studios, distributors, and theaters all needed a system that was financially viable, not just a good technology. These discussions are not appropriate for SMPTE committees, and it is not likely that acceptable solutions could have been devised in a public forum. Digital Cinema Initiatives was formed by the studios and created a specification based on the concepts developed within SMPTE, as well as incorporating the security systems essential to a viable movie business. Other parties created financial systems that could support the transition for theaters, and D-Cinema was born.

The success of D-Cinema has been phenomenal. Significant deployment began in 2006, and by the end of 2015, there were over 140,000 D-Cinema screens worldwide, well over 90% penetration. D-Cinema also provided another opportunity for stereoscopic 3D movies, with higher quality and fewer artifacts than any film-based system. Over half of the D-Cinema screens are 3D capable.

The Internet and IT Systems

The original film pull-down device was adapted from a sewing machine mechanism, but most of the development of film equipment has occurred within the industry. Until recently, most television systems have been based on proprietary hardware and/or software systems. As in many industries, that has all changed. Most television functions and many of the elements of the digital cinema chain can be implemented on hardware and software platforms provided by the IT industry, or built using components from this industry. Post-production is already almost entirely based on networks and IT products; new distribution systems rely on the internet; only live production and linear program streams still use many of the traditional approaches—and even these depend more and more on IT technology.

It is inevitable that progress in the IT industry will lead to this technology being the only economically viable approach. This leads to some tensions today. There are those who see this inevitability as a reason to abandon work on all non-IT solutions. Others, although they recognize that IT will be pervasive, believe that traditional pragmatic solutions are a good choice for today, deferring a move to total network connectivity until solutions are tried and tested and, potentially, more affordable.

SMPTE embraces all of these viewpoints. Work continues on high-speed versions of conventional interfaces, and work is under way to standardize network transport of video and audio. However, even the latter can be viewed only as interim solutions; SMPTE is working with other industry groups to visualize the architectures of the future where networked services may not require serial interchange of conventional rasterized video.

Much of the work important to the networked world is not directly related to network hardware or protocols. File formats such as MXF (Material eXchange Format), packaging systems like IMF (Interoperable Master Format), and object storage for archiving by AXF (Archive eXchange Format), service discovery, registration, and device control over IP; all are important elements to allow creative and efficient use by our industry of the tools brought to us by the IT industry.

The need for versatile metadata systems in our industry was identified by the SMPTE/EBU Task Force on the Exchange of Program Material as Bitstreams. SMPTE was a pioneer in metadata standards, but that presents its own problems. The tools used initially are outdated and cumbersome to use, and volunteers and staff are engaged in a complete overhaul to provide better tools, improved access, and timely response to the needs of those working in the field. Phase two of AXF is focusing on the collection and structuring of metadata during production, so that the eventual archive will include all the metadata necessary to make the archive truly useful. This work provides an approach to what has been the most intractable of problems—a simple and practical way to bind metadata to the appropriate essence.

Organization, Participation, Process, and the Future

SMPTE standards are created by a partnership—SMPTE staff provides the infrastructure, publishing services, and general support; volunteers provide the expertise and most of the authoring work. It is important to note the critical roles played by a few select volunteers. The Standards Vice President, the Standards Directors, and the Technology Committee Chairs all play substantial and vital roles in the process. Each of these roles requires experience and expertise, as well as a great deal of personal time. We sincerely thank all of these individuals and, where applicable, the employers who support them in their SMPTE activities.

> Interoperability changed the face of the [television] industry. In the early days of television, a station would generally be constrained to buy everything, from camera to transmitter, from a single manufacturer.

It is important to mention the support provided by organizations who host face-to-face SMPTE standards meetings. Although most of the standard development work is conducted through online meetings, these quarterly in-person meetings are an important part of the process and provide a venue for targeted discussions and resolution of differences, as well as superb networking opportunities. Many companies provide facilities for these meetings, at little or no cost to SMPTE. Some host a single meeting block; others are regulars. All report that hosting is a positive experience for the company and its staff. This support is a very important factor in keeping the cost of participation in SMPTE standards low, and we are always grateful to our hosts.

All the volunteers are important, as is the support of their employers. In any Standards Development Organization (SDO), quality work requires broad participation from every industry sector. In this age of continually challenged headcounts, many organizations, particularly smaller companies, find it difficult to provide experts with the time for standards participation. However, the benefits can be enormous, and few would wish that the standards that will define the future of their industry be left to others.

SMPTE makes participation as easy as possible. All meetings, including the face-to-face meetings, are accessible remotely from anywhere in the world.

The need for efficiency in standards development and the increased interdependency of all functions in a networked world have emphasized the need for inter-SDO cooperation. Today, SMPTE works with a very large number of national and international SDOs, as well as with many trade groups. The Society's contributions are recognized by the accreditations of the American National Standards Institute (ANSI) and by international organizations such as the International Telecommunication Union and the International Organization for Standardization/International Electrotechnical Commission (ISO/IEC).

Finally, after 100 years of standards development, the tools have changed. Early standards relied on documents first handwritten, then typed then typeset for publication—after a draftsman had prepared the precision drawings needed. Word processors helped in document preparation, but for many, many years, the development process was paper intensive. A group of standards meetings was characterized by arriving with one suitcase full of paper and leaving with two. The process has evolved through local networks and servers, to web services and online collaboration, providing the necessary information to all participants, no matter where located. Now, since most SMPTE standards are software related, or include code, schemas, test vectors, etc. the tools available to developers include issue tracking software, repositories, and online databases.

However, there is a need for education. In today's world of fast-moving technology, many young people see standards as archaic and constraining. This is a strange perception in the era of network and internet technology, where incredibly rapid evolution has been made possible by the existence of a comprehensive set of well-written standards from organizations such as the World Wide Web Consortium (W3C) and the Internet Engineering Task Force (IETF). Perhaps the point here is that good standards provide an environment or infrastructure that just appears to be the "natural order of things," and the users who build on them can remain largely unaware of this foundation. We need to show, and persuade academia to teach, that standards exist, not to constrain, but to provide a platform that allows developers to exercise their creativity.

Thus, many things have changed since 1916, but the essentials of the work remain. In 2016, we still gather experts from all parts of the industry to develop standards that will benefit the industry as a whole by providing interoperability, economies of scale, and platforms that are the basis for innovation. The next hundred years will bring technologies we cannot imagine today, but it is likely that a cooperative standards process will be an important element in making the best use of those technologies.

Pat Griffis
Education Vice President
Contributions from Joel Welch and Dianne Purrier

SMPTE Education: Past, Present, and Future

SMPTE has a proud history of education initiatives, and since the Society's inception in 1916, Education has been at the forefront of the Society's activities carried out through Section meetings, conferences, and the society's publications, mainly the *Journal*.

Publications

Dissemination of information began with the publication of the first *Transactions of the Society of Motion Picture Engineers* in July 1916, predating the addition of "television" which did not yet exist! In the 1930s, the Society decided to change the name to the *Journal* to broaden the scope of material from just quarterly meeting reports to include content from other sources. Although the focus and name of the publication have shifted over the years, the *Journal* has always served the function to document significant technical developments in motion picture and later television, starting in 1950.

Conferences

The Society has been educating its membership since the first gathering in Washington, District of Columbia, in July 1916. With growing interest in the Society, by 1921, SMPE meetings took place in New York, Atlantic City, Chicago, Rochester, Cleveland, Philadelphia, Pittsburgh, Montreal, Dayton, and Buffalo (**Fig. 1**). Conferences were two to three times a year, until 1918 when they became biannual events held in May and October and until 1975 when they were reduced to once per year. In 1985, the Society's annual meetings began to alternate between conventions centers in New York and Los Angeles. Since 2008, the Annual Technical Conference & Exhibition has been solely held on the west coast in Holywood, California. Throughout the past 100 years, the format, names, and locations of these annual events have changed, but one constant remains. These meetings continue to serve as a gathering for introduction, discussion, and the exchange of knowledge for emerging technologies in the motion imaging industry.

> Today, SMPTE offers a variety of education services, with the goal of providing the global motion imaging industry a number of ways to learn about important current and emerging technologies.

In the late 1990s, SMPTE joined with five other international societies to partner in the International Broadcasting Convention (IBC), the international exhibition and conference held annually in Amsterdam. Through its many expert members, SMPTE supports the conference by programming various topical sessions.

Over the years, SMPTE has also sponsored topic-specific conferences that address emerging technology trends and issues. A long-standing partnership with the National Association of Broadcasters (NAB) is a two-day program, which is now called the "Future of Cinema Conference," focusing on technology topics in cinema. In 2013, SMPTE launched a two-day conference, in partnership with Stanford University, focused on the growing entertainment activities in the Silicon Valley, which is now entitled "Entertainment Technology in the Connected Age." In recent years, SMPTE has also begun to produce conferences in Europe, in partnership with local organizations, such as the European Broadcasting Union Switzerland) and the Fernseh- und Kinotechnische Gesellschaft (**FKTG**) (Germany).

Education Strategy and Services

In recent years, efforts to strengthen the Education pillar have continued with the formation of the Education Strategy Committee (ESC) in 2014 to provide education-related guidance and recommendations to the Board of Governors on education initiatives. The committee includes members from academia, industry, and SMPTE staff.

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FIGURE 1. President greets SMPTE at the White House in 1930.

Today, SMPTE offers a variety of education services, with the goal of providing the global motion imaging industry a number of ways to learn about important current and emerging technologies (**Fig. 2**). SMPTE produces technical webcasts; a monthly single-topic technology e-Newsletter, SMPTE Newswatch; virtual courses; the Digital Library; and even educational wall chart inserts within the *Journal*.

The Society's Digital Library, which was launched in 2011, not only provides access to SMPTE standards but also holds the entire library of the *SMPTE Journal*, going back to the first days of SMPTE as well as many conference papers. Overall, the library is 100 years of content, including many historically important articles. The *Journal* archive is available free of charge to members.

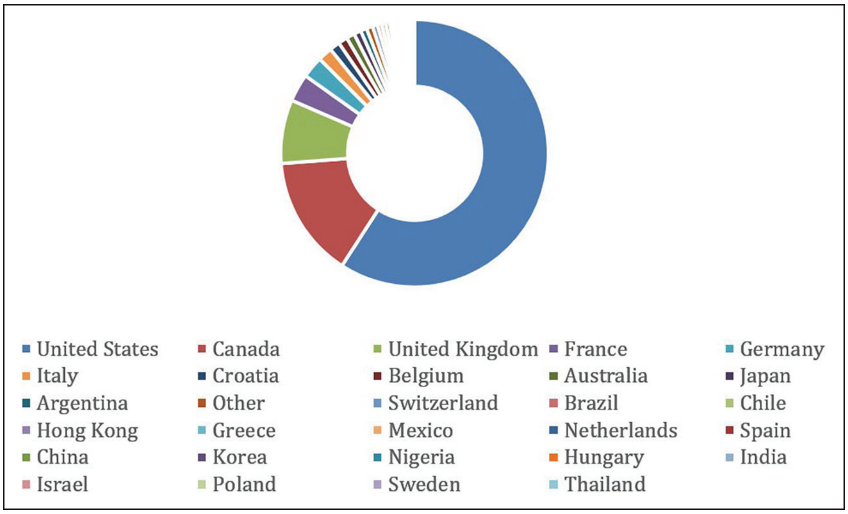

FIGURE 2. SMPTE's Global Education Audience.

The "Monthly Education Webcasts" were the first online education service, which was launched in 2008. These continue to be popular with members and nonmembers alike. They are convenient and provide a broad range of technology topics. Technologies covered include those which are widely deployed, but slightly understood, as well as those which are in the early deployment phase. Each of these webcasts is presented by an expert on the topic and always includes the opportunity for webcast guests to speak directly to the presenter. All webcasts are captured and posted for member on-demand playback. They are also a free SMPTE Member benefit.

More recently, general webcast offerings have been expanded. They now include quarterly series, including one on emerging technologies, and an exclusive, invitation-only series for Executive Members. Finally, a strategically significant series of webcasts is produced to cover SMPTE standards and progress made by the SMPTE Standards Community. No one can help educate the industry on SMPTE standards better than SMPTE itself. With a growing diversity of standards with ever-increasing complexity, this is one of the priorities for the education team.

The SMPTE Virtual Classroom was implemented in 2012 to provide global access to deeper, more intensive learning opportunities on technologies of particular importance to the industry. As of this writing, offerings include intensive, multi-week courses on routing, switching, and internetworking (Cisco's world-renowned Cisco Certified Network Associate program), Essentials of IP Media Transport for Broadcasters, and Navigating the Ultra High Definition (UHD) Ecosystem. Future courses will include SMPTE's Interoperable Master Format standard and others covering various SMPTE standards. The Society's virtual courses include self-study, narrated lessons, assignments, quizzes, and final exams. Interaction is encouraged through the use of course-specific online discussion forums and weekly, live, online instructor coaching sessions. Instructor coaching sessions are captured for on-demand viewing. Participants who complete the minimum course requirements receive a "certificate of achievement" for their efforts.

Education for the Future

Future education plans include adding to education efforts on SMPTE standards. To ensure all levels across the motion imaging industry are covered, several types of media will be implemented. For general, high-level understanding of various SMPTE standards, short summary videos are planned. Webcasts will provide an opportunity to discuss the video topics a little deeper. Select standards will continue to form the basis of future SMPTE virtual courses. This approach will help to raise awareness of SMPTE standards by enhancing understanding, but it will also allow individuals to choose the education service that best matches the depth and scope of coverage needed.

Scholarships

Beyond these education services, the Society is committed to supporting the education of students and future industry leaders. The long-standing Louis Wolf Jr. Memorial Scholarship is awarded annually to help support students with their education in programs related to SMPTE's field of interest. In addition, the ESC is working on a number of other programs, including grants and awards programs, which will help ensure that students, young professionals, and, in some cases, even well-seasoned members of the industry are able to access post-secondary, graduate, and professional development education opportunities. These programs are vital to ensuring that SMPTE remains strong, continues to foster innovation, and develops critical standards while remaining a driving force in elevating the motion imaging industry. SMPTE

William C. Miller
Vice President of Membership

100 Years of Growth

In 1916, as SMPE was being formed, its main purpose was to establish standards in this new industry of motion pictures. In order to do that, the most knowledgeable people needed to come together to discuss and debate the issues at hand. From the earliest stages, the new Society encouraged these people to join the Society to form this network of informed experts.

In the early days, membership was determined by invitation and recommendation only. This was a common method for professional associations. The practice persisted through at least the 1970s; I recall that when I applied for Active membership, my application had to be countersigned by two other members. Today, we have departed from this practice; we encourage anyone who wishes to join to do so. The objective of the Society was, and still is, the advancement in theory and practice of the motion picture engineering and allied arts and sciences, the standardization of the mechanisms and practices employed therein, and the maintenance of the high professional standing of its members. Active members were engaged in designing, developing, or manufacturing materials, mechanisms, or processes used in this or allied arts. The Society was open to anyone who embodied these qualities.

Today, while the notions of invitation and recommendations have long been dismissed, the general characteristics of membership have not changed.

To give context, when the Society was formed in 1916, there were two types of membership: Active and Associate. Active members paid $10, and Associate members paid $5. In today's dollars, that $10 dues payment would equate to more than $229. The leadership realized that it needed these rates as the Society was forming as an investment in its growth. This level of dues was determined to be too high and was moderated once the Society reached a level of financial stability. In 2016, SMPTE membership is $145 for Active members and only $45 for Associate members, a bargain compared to the early days.

From engineers to creatives and from television to digital media and still to film, SMPTE's membership is broad and vast.

It was also clear to the early leaders that, in order to grow the Society, it needed to expand its boundaries and become an international organization. As early as 1927, the Society was already accepting members from the following countries: Argentina, Austria, Australia, Canada, England, France, Germany, Holland, India, Italy, Japan, New Zealand, Norway, Poland, Russia, and South Africa. Today, the Society is pleased to have members represented in all these countries, plus about 50 more.

In 1916, the Society had 26 members. In 1927, after 11 years, it had a membership of only over 220 (**Fig. 1**). Today's membership of nearly 7000 individuals reaches across the globe. From engineers to creatives and from television to digital media and still to film, SMPTE's membership is broad and vast. The broad range of expertise and diversity of perspective our members possess is truly the greatest source of our strength, as will be apparent to anyone who has attended an SMPTE Section meeting, conference, or standards committee.

As the membership grows, groups of members are encouraged to form Sections where they can conduct monthly meetings to educate the local audience on the latest in standards and industry technology. The first to be formed was the Pacific Coast Section in 1924 (now the Hollywood, San Francisco, Sacramento, and Pacific Northwest Sections). Today, SMPTE has 29 Sections from New York to Hollywood to Australia and the U.K. Across the globe, an SMPTE member could attend a Section meeting on nearly every continent.

Our Student Members represent the future of our Society. In recent years, it became apparent that the annual dues we charged students, while modest compared to what we ask of working professionals, was becoming a barrier to entry. We now ask only $10 a year of students, with

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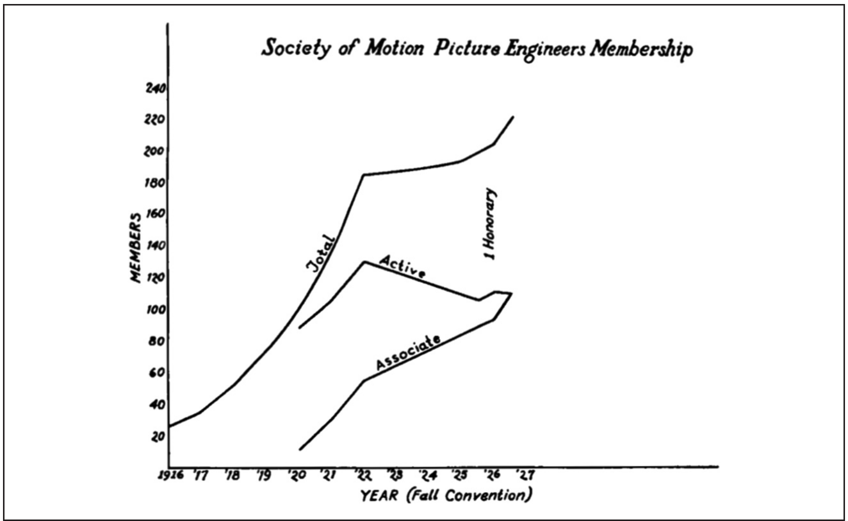

FIGURE 1. SMPE membership trends.

the first year of membership being free to them. The result has been an explosive growth in the number of Student Members and, thanks to the hard work of our Section Officers and Managers and the commitment of our Faculty Advisors, an equally explosive growth in the number of student chapters to 24.

The Society has been supported over the years by many corporations through sustaining membership. This category of membership was established in 1930 with ten companies, four of which (Kodak, Paramount, Technicolor, and Sarnoff Laboratories [successor to RCA]) continue as Sustaining Members today. The Society currently includes no film-only companies, but our more than 250 Sustaining Members span the full field of motion imaging, from studios to television networks to internet-streaming companies, as well as the vast array of manufacturers who support the industry.

A crucial aspect of membership is as a source of leadership for the Society. From within the membership, the Sections and the Society have produced inspiring leaders who have given their own time and talents to manage this marvelous organization. From the local Section Managers to the Regional Governors to the Society President, each of these leaders started out with that first membership application, many of them, like myself, as Student Members.

While SMPTE was founded principally to set industry standards, it is its people—in the form of a global membership—who keep the Society alive and thriving into its second century. SMPTE

SMPTE Celebrates Founder's Day!

In honor of Founders' Day, Executive Director Barbara Lange rang the Closing Bell for Nasdaq at MarketSite on Friday, 22 June, surrounded by many members, volunteers, and staff.

MarketSite is located in Times Square, which is often referred to as the "crossroads of the world" and is filled with moving images. In fact, one of our members, John Footen, was part of the team that developed the original Nasdaq MarketSite video wall!

www.smpte100.org

U.S. Presidential Milestone Congratulatory Letters to SMPTE

THE WHITE HOUSE

WASHINGTON

October 20, 1986

It gives me great pleasure to extend warm greetings to the members of the Society of Motion Picture and Television Engineers on the occasion of your National Conference.

Thirty years ago in Redwood City, California, a six-man team of Ampex engineers developed the world's first practical videotape recorder. Their brilliant technological breakthrough is yet another example of how American inventiveness and the "can do" spirit has helped revolutionize the communications industry. Today, half the homes in America have at least one videocassette recorder and television broadcasters and producers throughout the world depend on this modern miracle of technology.

Your organization is to be commended for its dedication to the advancement of communications technologies and the creation of worldwide standards of technical excellence. It is our fervent hope that you will do all that you can to encourage the continued development and wholesome use of this marvelous invention.

Nancy joins me in saluting our six technological pioneers and in wishing you a successful and memorable conference.

God bless you.

Ronald Reagan

Sent to Harold J. Eady, SMPTE President,
at 128th Conference in New York City
to commemorate the 30th anniversary of the
videotape recorder machine invented by Ampex
and presented to Charles Steinberg, President of Ampex.

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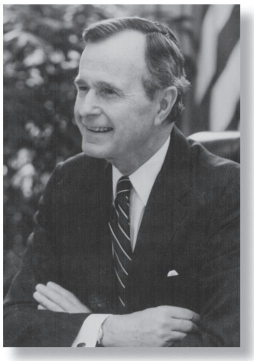
U.S. Presidential Milestone Congratulatory Letters to SMPTE



THE WHITE HOUSE

WASHINGTON

August 20, 1991

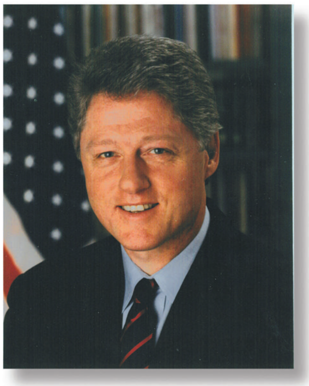
I am delighted to send warm greetings to all those who are gathered in Los Angeles to celebrate the 75th Anniversary of the Society of Motion Picture and Television Engineers. A special welcome to our friends from abroad.

Film and television are among the most popular and influential media in the world today. From television coverage of the Persian Gulf War to the latest movies, the work of your profession touches nearly everyone's lives. Your commitment to continuing education and to the exchange of information not only benefits viewers but also contributes to the success of this vital industry.

The Society's efforts to develop and to maintain industry standards are both forward-looking and commendable, as are your activities in higher education. As you may know, my Administration's National Educational Strategy is designed to ensure that all American students acquire the knowledge and skills -- including the technical skills -- that are needed to succeed in an increasingly competitive and interdependent world. You can play an important role in helping us to fulfill that strategy. I have every confidence that your commitment to excellence will help to guide our Nation to a new golden age of technological achievement.

Barbara joins me in sending best wishes for a productive and enjoyable conference.

U.S. Presidential Milestone Congratulatory Letters to SMPTE



THE WHITE HOUSE

WASHINGTON

December 28, 1995

Congratulations to the members of the Society of Motion Picture and Television Engineers as you celebrate your organization's eightieth anniversary.

Since their invention, motion pictures and television have become the preeminent entertainment and communications media of the twentieth century, forever changing the way we view and understand our world and ourselves. Today, the magic of film and television transcends international boundaries, informing and entertaining, stimulating thought and reflection, and stirring the imagination.

All of you can be proud of your long-standing contributions to the success of these remarkable industries. Ensuring the highest standards of excellence in film and media integration, SMPTE members have served to advance our cultural heritage for the better part of the twentieth century. I salute all of you for your precision, your dedication to your work, and your commitment to progress.

Best wishes for a wonderful anniversary year.

Bill Clinton

U.S. Presidential Milestone Congratulatory Letters to SMPTE

THE WHITE HOUSE

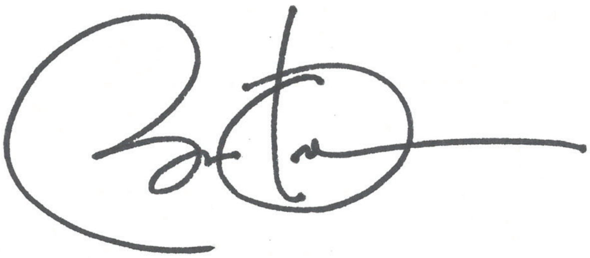
WASHINGTON

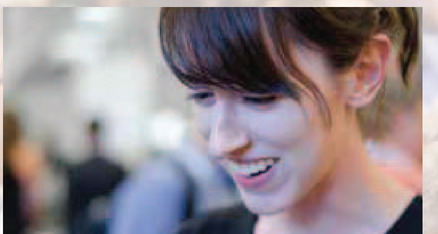
June 1, 2016

I send my regards as you celebrate your organization's 100th anniversary.

Throughout the American story, each generation has continued the unending work of building a better future and making our Nation more just and more equal. By joining in a spirit of common purpose and contributing to shared progress, you are helping drive America forward. As you reflect on your achievements, I hope you take pride in the difference you have made in the lives of others.

Congratulations on all you have accomplished. I wish you the very best in the years ahead as you continue working to forge an ever brighter tomorrow.





More, Faster, Higher, Wider: A Brief History of Increases in Perceptible Characteristics of Motion Imaging

By Mark Schubin

Abstract

Since at least the 19th century, if not earlier, people have tried to improve such characteristics of motion imaging as spatial resolution, aspect ratio, frame rate, dynamic range, and color gamut. Many of those improvements have affected other characteristics. There is no indication that improvements will soon stop.

Keywords

Aspect ratio, high dynamic range (HDR), high frame rate (HFR), motion picture history, television history, UHD, wide color gamut (WCG)

Introduction

Recent SMPTE standards have been related to topics such as higher spatial resolution (HSR), higher frame rate (HFR), higher dynamic range (HDR), wider color gamut (WCG), and higher luminance, all for motion imaging systems,[i] and so have recent papers in the *SMPTE Motion Imaging Journal*.[ii]

The term "ultra-high-definition" (UHD) suggests that the current push for such increases might be the last, resulting in the final form of motion imaging. Historical research, however, suggests that increases in all of those characteristics—and more—have been going on throughout SMPTE's history and even before the first motion picture or video signal. SMPTE's founder and first President, Charles Francis Jenkins, for example, was involved in both HSR and HDR in some of his television work.

Spatial Resolution

As a television pioneer, Jenkins might be known best for his work in the 1920s, which included what was probably the earliest wireless transmission of live motion images in 1923.[1] However, Jenkins's connection to what we today call television was much older. A decade earlier, before he founded the Society of Motion Picture Engineers (SMPE), he published "Motion Pictures by Wireless."[2] In addition, his first publication on electrically delivered motion pictures appeared in 1894.[3] It involved wired rather than wireless transmission, but a bigger problem was that the images were not to be scanned; there was a need for individual connection between each photosensitive element in the camera (called a "transmitter") and each glowing filament of the display (called a "receiver").

As a television pioneer, Jenkins might be known best for his work in the 1920s, which included what was probably the earliest wireless transmission of live motion images in 1923.

The diagram in that 1894 publication was remarkably similar to those in Plate 1 of "Seeing by Electricity," published in *Scientific American* in 1880, as shown in **Fig. 1**.[4]

[i]See, for example, SMPTE ST 12-3:2016, "Time Code for High Frame Rate Signals and Formatting in the Ancillary Data Space"; ST 2036-1:2014, "Ultra High Definition Television—Image Parameter Values for Program Production"; ST 2048-0:2012, "2048 × 1080 and 4096 × 2160 Digital Cinematography Production Image Formats FS/709—Roadmap for the 2048 Document Suite"; ST 2084:2014, "High Dynamic Range Electro-Optical Transfer Function of Mastering Reference Displays"; ST 2085:2015 "Y'D'ZD'X Color-Difference Computations for High Dynamic Range X'Y'Z' Signals"; and ST 2086:2014, "Mastering Display Color Volume Metadata Supporting High Luminance and Wide Color Gamut Images."

[ii]See, for example, P. Putman, "Display Technology: The Next Chapter," *SMPTE J.*, 125(3):30–34, Apr. 2016; K. C. Noland, "High Frame Rate Television: Sampling Theory, The Human Visual System, and Why the Nyquist-Shannon Theorem Does not Apply," *SMPTE J.*, 125(3):46–52, Apr. 2016; and S. McCarthy, "How Independent Are HDR, WCG, and HFR in Human Visual Perception and the Creative Process?" *SMPTE J.*, 125(4):24–33, May/June 2016.

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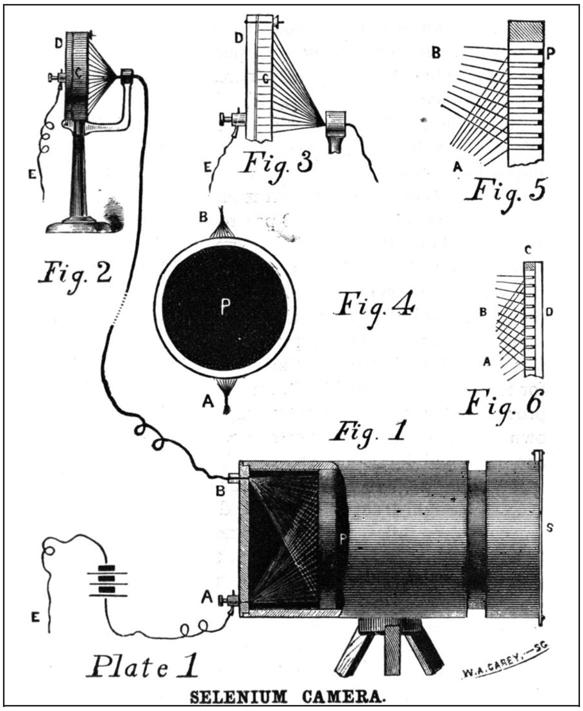

FIGURE 1. "Seeing by Electricity," *Scientific American*, June 5, 1880.

It related to the work of George R. Carey, possibly the first person to apply the word *camera* to an optoelectronic device. The figures are based on drawings in Carey's notebook (acquired by the Karpeles Manuscript Library Museum in 2001). The diagram of the camera in the notebook shows a matrix of eight photosensitive elements across by eight down.[5] According to his notebook, Carey was inspired to begin his work on image transmission by an article in *Scientific American* on 9 December 1876 about a "sensitive artificial eye" shown in London earlier that year by Charles William Siemens, which was, in effect, a single-pixel camera.[6]

Pretelevision Image Transmission

Higher spatial resolutions for electrical image transmission existed long before either Carey's camera or the Siemens eye. In 1843, Alexander Bain patented what came to be known as a "copying telegraph."[7] His invention included horizontal scanning lines, pixels, line synchronization, and frame synchronization. According to a 1984 history of electronics, "The concept embodied all the geometrical and timing methods of the modern television system."[8] It primarily lacked optical input; images had to be created in a way that would control the making and breaking of a circuit (e.g., being written or drawn in insulating ink on a metallic sheet).

Figure 2 shows what might be the oldest existing transmitted image, dated 12 November 1850, from the archives of the Institution of Engineering and Technology.

FIGURE 2. Portion of an 1850 image transmission, from the Institution of Engineering and Technology Archives.

Frederick Bakewell received it by using his copying telegraph, and it shows 30 scanning lines in what was originally a height of about 2 cm. By the time commercial image-transmission service was inaugurated between Paris and Lyon in 1865, resolution could be increased simply by increasing the image area.[9]

Shortly after the Siemens eye, Denis D. Redmond attempted to combine the scanning of the copying telegraph with an optoelectronic image sensor but found the latter's light-to-dark recovery time too slow. His first live video image, therefore, which was achieved by 1879 and one which he described as "crude," involved a direct connection for each pixel.[10]

Video Scanning

In what appears to have been the first television patent, one of Paul Gottlieb Nipkow's drawings showed a disk with a spiral of apertures that, when spinning, would create images with a fixed 24 scanning lines, as shown in **Fig. 3**.[11] Although for his 1923 wireless transmission of moving images Jenkins used a scanning disk with a fixed 48 lines, he also developed "prismatic disks" for scanning that did not have a fixed resolution.[12] Instead, spatial resolution in scanning lines was based on the ratio of the rotational speeds of the horizontal and vertical scanning disks.[13] Using a form of the Nipkow disk, probably with 30 scanning lines, SMPTE Honor Roll member John Logie Baird achieved the first video image of a recognizable face in 1925.[14]

At the fifth German Radio Exhibition in 1928, August Karolus introduced 96-line television images, which were high definition (HD) when compared to the 30-line

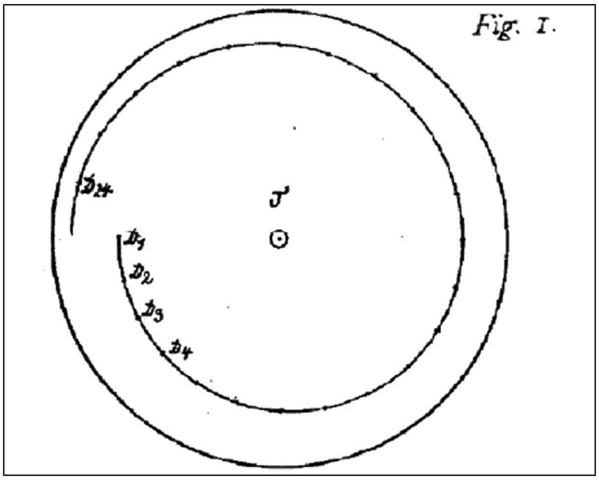

FIGURE 3. Scanning disk from Nipkow's 1885 patent.

standard-definition images of the time.[15] The British government offered an official definition of HD television in a parliamentary report published in January 1935: "it should be not less than 240 lines per picture…."[16] Two years later, the same government was the first to adopt a single standard for television broadcasting.[17] Utilizing electronic scanning, it was described as 405 lines, but some of those lines were in a blank interval, allowing time for the electron beam to move from the end of one image to the start of the next; thus, there were only 377 lines carrying picture information ("active" lines).[18] The images were also interlaced, possibly reducing perceptible resolution.[19]

Remarkably today, in an era of digital cinema projectors using digital micromirror devices (DMDs), mechanical scanning is again being used in cameras. Researchers at Carnegie Mellon University and Columbia University have built and reported on one version called LiSens, using a DMD for scanning to a line array sensor.[20]

UHD pixel counts pale in comparison to some others. UHD-1, which is commonly called "4K," has around 8 megapixels; UHD-2, which is commonly called "8K," has about 33 megapixels. Canon has already demonstrated a 120-megapixel image sensor, and at the NAB Show in April 2016, the new Lytro Cinema lightfield camera was said to have an extraordinary 755 RAW megapixels.[21]

SMPTE's publications and meetings have long covered high spatial resolution. The Nippon Hoso Kyokai (NHK) motion-imaging system with what today is considered HD resolution, for example, was demonstrated at the SMPTE Winter Television Conference in San Francisco in 1981. The Society's first standard dealing with resolution was SMPTE 240M, "Signal Parameters—1125-Line High-Definition Production Systems," which was approved in 1987 but initially opposed as an American National Standard.[22] Although the 1125 number of total lines has not changed, the number of active lines changed from 1045 to 1035 in SMPTE 240M and then to today's common 1080 lines in SMPTE 274M.[23]

Aspect Ratio

Another characteristic in which SMPTE 240M differed from NHK's HD proposal was in aspect ratio (width: height). NHK proposed 5:3; SMPTE 240M specified 16:9.[24] The earliest published appearance of that aspect ratio (as "5.33:3") was in a 1984 paper in the *SMPTE Journal* by Joseph Nadan and Richard Jackson.[25] It closely matched an aspect ratio, as shown in **Fig. 4**, which was developed in SMPTE's working group on HD electronic production, based on minimal area loss for different presentation aspect ratios.[26]

Imagery does not have an inherent aspect ratio. In fact, the image produced by a round hole (or round lens) is round, not rectangular. However, planar artworks are usually rectangular and are often framed, perhaps suggesting windows or doorways (which might be rectangular due to the orthogonality of a person standing on the ground).

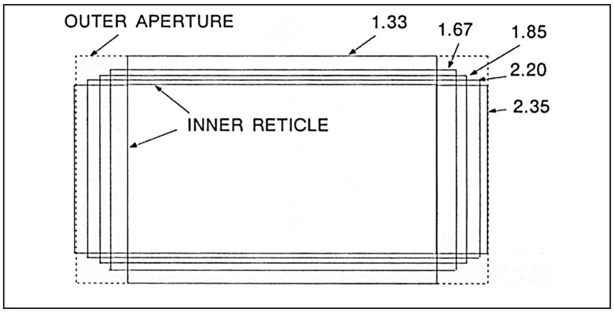

FIGURE 4. Derivation of a camera aspect ratio (*SMPTE Journal*, June 1990, p. 439).

Picture tubes were initially round to best contain the vacuum within. In area, the largest rectangular image that can fit in a circle has an aspect ratio of 1:1. The initial aspect ratio of British 405-line television was a very close 5:4, which was changed in 1950 to 4:3 to match television practices elsewhere in the world.[27] The U.S. had indeed been broadcasting television in a 4:3 aspect ratio. It was selected by the National Television System Committee (NTSC) in 1940, after the evaluation of systems ranging from 3:4 to 11:8, because, according to committee documents, 4:3 "has all advantages found in motion picture practice" and "permits scanning of motion picture film without waste of screen area or distortion of the aspect ratio."[28]

Introduction of the Sound Track

What is strange about mentioning those criteria for selection is that motion picture film had gone through its own aspect ratio changes and was no longer 4:3 at the time. When the same television aspect ratio selection process had been performed in 1929, a match to motion picture film practice was also chosen, but at that time, the selected aspect ratio was 6:5 because the allocation of space for a sound track within the film width made the initial 4:3 images of silent film narrower.[29] Even before the sound track, as early as 1913, it was suggested to exhibitors in Britain to try masking 4:3 frames to create a wider aspect ratio. According to the article, "the result is a better shaped picture—more artistic. The portion masked off will never be missed."[30]

To solve the sound-track space problem (and, perhaps, create a "better shaped picture"), SMPE participated with the Academy of Motion Picture Arts and Sciences on the development of both wide-film motion pictures and improvement of the shape of images projected from common 35 mm film.[31] The result of the latter effort, the so-called "Academy aperture," was reported in 1932: "The Standards Committee unanimously agreed to recommend for adoption by the Society the dimensions 0.600 by 0.825 inch as standard dimensions for 35 mm. projector apertures."[32] Thus, at the time the NTSC selected 4:3 as matching film practice, film practice had long since

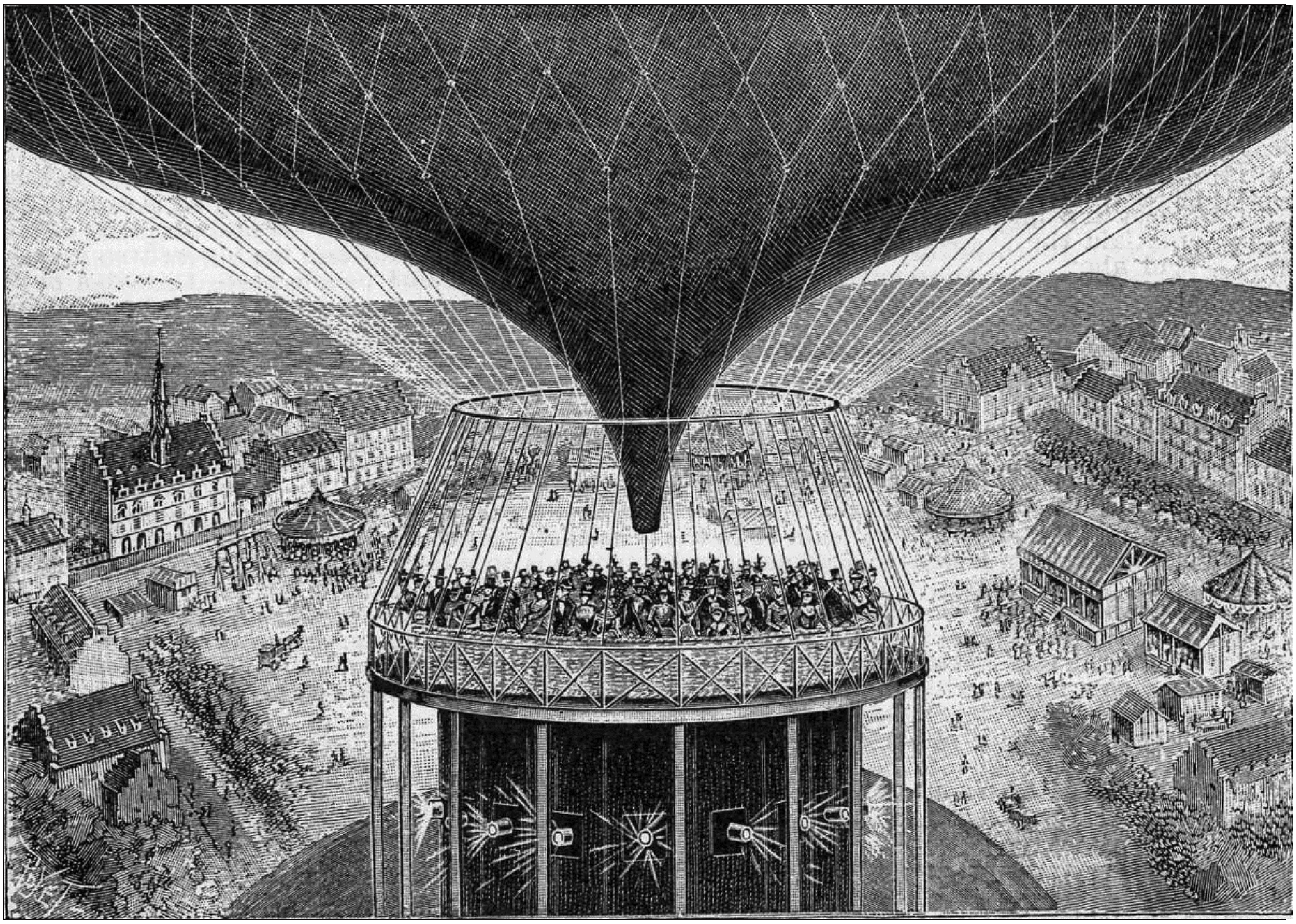

FIGURE 5. An artist's conception of the Cinéorama.

changed to 11:8 (an aspect ratio the NTSC considered) or 1.375:1.

Wider Than 16:9

The 16:9 aspect ratio has endured into the era of UHD, with a slight increase to ~1.9:1 in cameras and projectors intended for digital cinematography and digital cinema applications, as in SMPTE ST 2048 (see footnote [i]). Many movies have been released in wider aspect ratios, however; thus, a number of television set manufacturers have introduced models with 21:9 displays.[33]

The displays used in augmented and virtual reality systems usually have a fixed aspect ratio, but such systems also usually allow viewers to look beyond the display's edges by moving their heads.[34] Viewers could also move their heads to look at motion images all around as early as 1900 in Raoul Grimoin-Sanson's Cinéorama, at the Paris Exposition, with ten synchronized projectors, as shown in **Fig. 5**.[35]

Frame Rate

Motion image displays have aspect ratios; caves do not. Paleolithic cave art might exhibit all other characteristics of motion imagery: spatial resolution (affected by the width of the painting tool), color (affected by pigments), and, perhaps surprisingly, animated motion. According to Marc Azéma, a member of the scientific team studying the Chauvet Cave in France, "If we take into account the dynamic properties of Paleolithic lighting, consisting of flickering torch light or oil lamps, of the interaction of parietal images with the rocky relief they are painted on, and the existence of optical effects such as anamorphism, we can reasonably assume that the majority of the images appeared to be animated by Paleolithic humans."[36] Azéma has attempted to recreate the look of that animation using modern moving-image tools.

His recreations have frame rates; the originals did not. The first projected motion pictures also had no frame rates. In 1685/1686, Johann Zahn described magic lantern-type projectors with revolving slides. He also described projection clocks and projectors that could depict the motion of small living animals.[37] Movies and television rely, however, on the apparent motion of the presentation of a sequence of image, rather than on actual motion.

Apparent Motion

Following research into visual fusion frequencies by Joseph Plateau in the late 1820s and into stroboscopic visual effects by Michael Faraday shortly thereafter, in 1832,

FIGURE 6. Phenakistoscope-like disk made by cinematography pioneer Eadweard Muybridge.

Plateau and, independently, Simon Stampfer introduced the first sequential-image apparent-motion devices; that is, slotted disks with drawings depicting different stages of motion, as shown in **Fig. 6**. When the disks were spun in front of a mirror and viewed through the slots, apparent motion was seen. The name "phenakistoscope" (view deceiver) was soon applied to the devices.[36] In an 1852 addendum to a patent for a stereoscope, Louis Jules Duboscq described a motion picture disk with photographic images, probably the earliest patent for a form of photographic movies (and in stereoscopic 3-D).[38] As recently as the end of 2015, Finland broadcaster Yle distributed photographic phenakistoscope disks to celebrate the 150th anniversary of the birth of composer Jean Sibelius.[39]

Phenakistoscopes and, later motion picture disks, cylinders, and flip books had no fixed or even suggested frame rates, but they were somewhat self-regulating; if a viewer saw apparent motion, the rate was good. SMPTE Honor Roll member Louis Aimé Augustin Le Prince was probably the first to introduce motion picture devices not relying on disks or cylinders but on an image band (film) of indeterminate length, with cameras and projectors that were cranked.[36] His October 1888 motion pictures of *Roundhay Garden* and *Leeds Bridge* are among the oldest existing filmed motion pictures. Their frame rates, however, were very different. His son, Adolphe, wrote on a print of *Roundhay*, "Taken from 10 to 12 a second," and of *Leeds Bridge*, "taken at 20 pictures a second in poor light."[40] SMPTE Honor Roll member Thomas Edison reported that his kinetograph shot 46 pictures per second.[41] His assistant, SMPTE Honor Roll member William K. L. Dickson, reported, however, that they were at an "average 23 pictures a second."[42] A report on the Kinesigraph of Wordsworth Donisthorpe and William Carr Crofts in 1891 said it operated at "a rate from eight to twelve per second," while citing its patent specification as indicating images would be projected at "about seven flashes per second" and shot at "from eight to six times in a second."[43]

Fixed Frame Rates

Redmond, an ophthalmic surgeon, published the earliest television frame rate in 1879, actually preceding all film frame rates: "every portion of the image of the lens should act on the circuit ten times in a second…."[10] However, by the time electronic television broadcasting began, the motion picture industry had adopted a fixed rate of 24 frames/sec.

The rate needed to be fixed so that sound could be played at a constant rate, without changes in pitch. As for the selection of the rate, Western Electric engineer Stanley Watkins said, "According to strict laboratory procedures, we should have made exhaustive tests and calculations and six months later come up with the correct answer." Instead, "What happened was that we got together with Warners' chief projectionist and asked him how fast they ran the film in theaters. He told us it went at 80 to 90 feet per minute in the best first-run houses and in the smaller ones anything from 100 feet up, according to how many shows they wanted to get in during the day. After a little thought, we settled on 90 feet a minute [24 fps] as a reasonable compromise."[44]

Separate Frame Rate from Image Flash Rate

While 24 was an adequate number for the portrayal of apparent motion, it was too slow for flicker fusion; thus, film projectors used multibladed shutters, allowing each frame to be presented twice (for a two-bladed shutter), with 48 flashes of image per second, sufficient for flicker fusion on relatively dim cinema screens. A rough equivalent to the multiblade shutter in television was "interlace." In 2:1 interlace, every other scanning line is transmitted in one "field," followed by the skipped lines in a second field, the two fields combining to form a single frame. A patent was issued for the concept as early as 1915.[45] A form of 3:1 interlace for television was demonstrated in 1928 and broadcast in Chicago.[46] A patent for an electronic version was applied for in 1932 (and issued in 1939).[47]

There remained two problems for the television frame rate. One was a power frequency-induced ripple affecting the images. The other was an insufficient flicker fusion frequency under home viewing conditions. Both were resolved in the U.S. with a move to 30 frames and 60 fields per second, tied to the power frequency. This introduced a new problem of compatibility with 24 frame/sec film, which was resolved by designing a special projector that

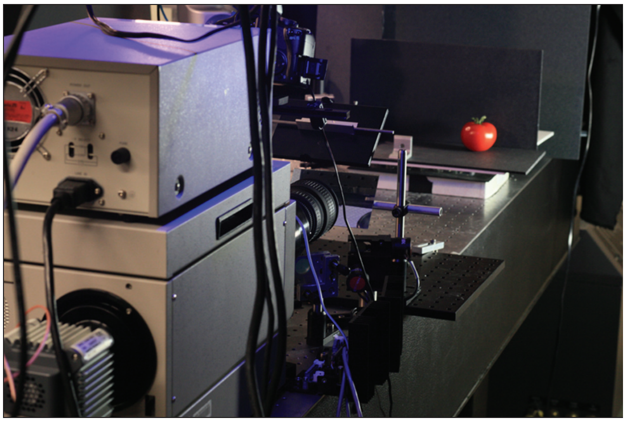

FIGURE 7. MIT trillion-frame-per-second camera.

FIGURE 8. Scene with a 10,000,000:1 contrast ratio.

would keep even film frames stationary for two video fields and odd frames for three.[48]

Progressive Scanning and Beyond

In the days of low-resolution mechanical scanning and even with early electronic picture tubes, reductions in perceived static spatial resolution and increased perceptibility of scanning lines, both potentially caused by interlace, were not noticed. Some of the very factors (reduced scanning-line visibility, reduced flicker, and finer detail) cited by proponents of noninterlaced or "progressive" scanning today were attributed to interlaced scanning in 1932.[49] However, as lenses, cameras, and displays have improved and spatial resolutions have increased, the artifacts of interlace have become more noticeable.

Eliminating 2:1 interlace means a doubling of frame rate for the same flicker fusion at the same luminance and viewing angle, but that is not the only reason for increasing frame rate. Spatial resolution may be measured in different ways. For stationary images, static and dynamic spatial resolutions are the same; for motion images, they are not. The clearer images of increased static spatial resolution can become blurry, again, in moving images.[50]

New camera and display technologies allow extraordinarily high frame rates. **Figure 7** shows a trillion-frame-per-second camera developed at the Camera Culture Group at the MIT Media Lab in conjunction with the Bawendi Lab at the MIT Department of Chemistry. At this rate, the camera can depict the motion of a pulse of light passing through a soda bottle.[51] It can also see around corners.[52] Moreover, it has already been surpassed in speed by a 4.4 trillion frame/sec camera.[53]

Dynamic Range

The Jenkins 1923 wireless motion picture transmission was unusual aside from its precedence. It had no dynamic range. The picture elements were not black and white but black *or* white. Jenkins explained at a meeting of the SMPE that the reason for the silhouettes was that he was using continuous-wave transmission rather than a modulated carrier.[54] Baird's early television work was also limited to silhouettes ("shadowgraphs") but for a different reason: Silhouettes were acquired by both Jenkins and Baird by shooting people or objects against a very bright background ("possibly several thousand candle power," according to Baird). "In the transmission, however, of actual objects," said Baird, "even where only black and white are concerned, the [photosensitive] cell has to distinguish between darkness and the very small light, usually indeed only a small fraction of a candle power, reflective from the white part of the object."[55] In other words, it was a sensitivity issue. The achievement of "daylight television," able to be shot in broad daylight rather than under extreme studio lighting conditions, was celebrated on both sides of the Atlantic Ocean in 1928.[56] Today, sensitivity is no longer a major concern, with the recent introduction of an HD camera with a minimum subject illumination of 0.0005 lx or less (at 75 dB, F1.2, 29.97P, 50IRE). It is described as being as sensitive as film with an ISO speed in excess of 4,000,000.[57]

The "range" of the term "dynamic range" suggests that mere sensitivity is not enough. **Figure 8** shows a scene, shot with Xensium CMOS image sensors, presented by Peter Centen of what was then Thomson Grass Valley at the SMPTE Digital Cinema Summit in April 2008. The only light in the room was coming from the lamp aimed into the camera, yet both the filament of the bulb and the darkest chips on the reflectance chart were clearly visible in the projected image. The scene was said to have a contrast ratio of 10,000,000:1, in excess of 23 stops.[58]

Displays are now capable of greater dynamic ranges, too. In January, the UHD Alliance specified that television sets displaying the UHD Premium logo had to, aside from other characteristics, comply with the SMPTE ST 2084 electro-optic transfer characteristic and offer either a peak luminance of at least 1000 cd/sq. m and a minimum of less than 0.05 or a peak of at least 540 and a minimum of less than 0.0005.[59]

The 1900 surround-pictures Cinéorama was shut down after three days due to what the authorities considered excessive heat in the projection booth.[34] It might seem that increasing the illuminance of a cinema auditorium's screen, all else remaining the same, requires increasing the output of a single projection lamp. Today, autoalignment and stitching software allow multiple projectors to be used to increase illuminance. Scalable Display Technologies demonstrated their version at the HPA Tech Retreat in 2005.[60]

Gray Scale

The UHD Alliance calls for a 10-bit depth.[58] In theory, any dynamic range can fit in any bit depth, each additional bit simply increasing the signal-to-noise ratio by approximately 6 dB.

One technique for dealing with the processing of digital video signals without the need to increase bit depth was described in the *SMPTE Journal* in June 1989.[61]

The issue of necessary bit depth was raised early in the era of digital video, however, when signal processing seemed to introduce visual contouring.

Color

A strange report of something that supposedly occurred in France appeared in many publications around the world in 1863. It involved Giovanni Caselli's pantelegraph, the image-transmission system that would be used commercially two years later.

At the receiver, chemically treated paper was subjected to an intermittent electric current, depending on the information being transmitted. **Figure 2** is from an earlier system. Other colors would be possible, as would an inversion of background and foreground, but changing color on a pixel-by-pixel basis does not seem possible. Nevertheless, the report stated, "…recently the inventor telegraphed a painting of a full-blown rose from the Observatory to the Bureau of the Telegraphic Administration. The petals were of a beautiful pink color, and the leaves of an equally good green—in short, were exactly like the tints of the original."[62] Perhaps someone hand colored a transmitted image; perhaps the idea of image transmission so astonished the reporter that the image seemed, afterward, to have been in color.

Only 17 years later, Maurice Leblanc actually *did* consider how to transmit color imagery. Most color television systems utilize three display color primaries, and the colors that can be reproduced fall within a shape defined by those three primaries. For any three visible color primaries, some colors, such as saturated blue greens, will fall outside the shape. One way to increase the color gamut is to increase the number of display primaries. Leblanc appears to have considered a fairly wide color gamut; he planned to use seven different color sensors and display elements in his image-acquisition system.[63] **Figure 9** shows Leblanc's color-transmission arrangement.

A British patent was issued in 1924 for a more conventional three-primary color-television system.[64] In the U.S., another patent, this one applied for in 1924, seems very similar to the tube-based color television in use for much of the second half of the 20th century.[65]

In ST 2048-1, SMPTE standardized a system of "nonphysical" primaries in 2011, exceeding the color gamut of even camera-negative film (see footnote [i]). A good discussion of color primaries may be found in a book by SMPTE Sarnoff Gold Medal Award winner and Fellow Charles Poynton.[66]

Interactions

The earliest color-television system compatible with existing black-and-white television sets was the U.S. NTSC, named for the second National Television System Committee, which standardized it in 1953. Its display primaries encompassed what appeared in two dimensions to be a large color space, but the phosphors that generated those colors were dim; hence, they were generally not used. Moreover, a beat between the color subcarrier frequency and the sound carrier of broadcast television stations led to a change in U.S. television's frame rate by a factor of 1000/1001, leading, in turn, to a "drop frame" version of SMPTE time code to maintain clock time.[67] Thus, color affected display luminance and frame rate.

There has long been a conflict (or compromise) between different image characteristics. SMPTE ST 125 suggests a one-third increase in data rate simply for changing from a 4:3 to a 16:9 aspect ratio (with equivalent screen height and area-based spatial resolution).[68] Doubling frame rate means either doubling information rate or reducing spatial resolution. Even in the era of mechanical scanning and analog signals, Baird's early television systems might have operated at rates as low as 3 frames/sec.[14]

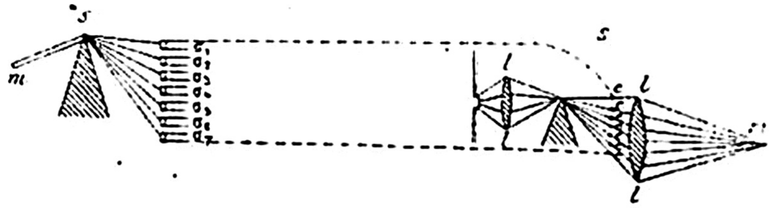

Fig. 11.

FIGURE 9. From Leblanc's color-image transmission proposal of 1880.

Larger screens occupy more of the field of peripheral vision, seemingly requiring a higher frame rate. A constant panning speed covers more pixels per second in higher spatial resolutions, also seemingly requiring a higher frame rate. Does a higher frame rate, however, affect suspension of disbelief for dramatic storytelling? Sean McCarthy's paper published in the May/June issue of this journal this year offers a large number of interactions just between high dynamic range (HDR), wide color gamut (WCG), and high frame rate (see footnote [ii]).

Sometimes, unusual technological solutions appear. Human vision, for example, can detect very fast events without having any frame rate at all. Might the same be done in a motion-imaging camera? Some recent research and demonstrations suggest that it might, indeed.[69]

Conclusion

With the motion picture and television industries just starting to consider frame rates higher than 60 frames/sec (for display) and cameras in laboratories already beyond trillion-per-second rates, with UHD production just moving to 8-megapixel sensors, and the Lytro Cinema lightfield camera dealing with 755 megapixels, there is no indication that we have reached the end of the line for improvements. Throughout much of the history of motion imaging, however, certain characteristics were tied to others because of available technology. Thus, interlace increased the image flash rate, and physical color primaries were chosen to maximize color space because there seemed no better way. Now, despite interactions, some decisions can be made independently of others.

Director Sergei Eisenstein once argued for a "dynamic square," an ability to change aspect ratio to meet the needs of shots.[70] At the SMPTE-NAB Future of Cinema Conference in April in Las Vegas, director Ang Lee astonished the crowd with a segment from his upcoming *Billy Lynn's Long Halftime Walk*, captured in stereoscopic 3D 4K 120 frame/sec HDR and WCG.

Given that image scanning was patented in 1843 and seven-primary color was proposed in 1880, it is likely that people today are already working on our technological future. Let us move onward into SMPTE's second century.

About the Author

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The SMPTE Century: Evolution in Cameras and Lenses From 1916 to 2016

By Laurence J. Thorpe

Abstract

The SMPTE Centennial opened in 1916 when motion picture film production was a flourishing new industry. International manufacturers have continued to develop related lenses and film cameras up to recent times. Color film systems emerged in the late 1930's. That same decade saw the birth of electronic motion imaging systems in the form of television. Ensuing decades were spent on the pursuit of refinements in related image sensors. Color television arrived in the 1950's. Embryonic HDTV systems appeared in the early 1980's followed by a surge in competitive developments in related lenses, cameras and recording systems. The past decade is witness to an escalation in developments in large format single-sensor digital motion imaging systems with ever increasing resolution, dynamic range, color gamuts, and frame rates. The SMPTE Centennial of 2016 is witness to a stunning renaissance in motion imaging.

Keywords

HDTV, image Orthicon, large-format Single-Sensor, plumbicon, prime lens, UHDTV, vidicon, zoom lens, 35mm film

> **The SMPTE century began in 1916—with the initial founding of SMPE and was focused exclusively on motion imaging as originated on motion picture film.**

Introduction

George Eastman's development of film rolls in 1889 was followed two years later by Thomas Edison's invention of the motion picture film camera. In 1909, the 35 mm film format was recognized as an international gauge. The SMPTE century began in 1916—with the initial founding of SMPE and was focused exclusively on motion imaging as originated on motion picture film. Lenses, cameras, and the film medium itself were soon to be surrounded by multiple standards that helped define a long and sturdy history. The year 1916 saw more than 20,000 movie theaters in the U.S. and the rise of the powerful independent companies that would ultimately become "Hollywood." In 1923, optical sound on film was developed, and in 1932, the first three-color Technicolor film was developed.

SMPTE is witness to a hundred years of motion imaging. The following is a fast and light overview of the same.

Early Lens Developments

On the lens front, Cooke Optics was founded in the U.K. in the 1890s and introduced their famous Speed Panchro Prime Lenses in the late 1920s (**Fig. 1**) and followed this with the first cinematography zoom lens a decade later.

In 2013, the Academy of Motion Picture Arts and Sciences gave the company an award of merit, saying it "helped define the look of motion pictures."

In 1935 in France, Pierre Angénieux formed the company that bore his name, with the intention to specialize in optics for cinema. He introduced a 35 mm cine lens in 1951. Angénieux designed a constant-aperture 17–68 mm zoom lens in 1956 and a 12–120 mm zoom lens in 1958 (**Fig. 2**).

In Germany, the Zeiss Company was born in the 1840s and made optics for telescopes and instrumentation. When the film camera was invented, they turned their attention to lenses. Carl Zeiss is one of the oldest existing optics manufacturers in the world and was resurrected in the late 1940s. Also in Germany, Schneider Optical Company was founded in 1913. In 1964, they launched the first zoom lens with fixed back focus for 35 mm cameras. In 1990, they ceased making lenses for broadcast television (TV) cameras.

Motion Picture Film Camera Developments

During the early 1900s, when Chicago was the center of the motion picture industry, the Bell & Howell company designed the first all-metal camera. Introduced in

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FIGURE 1. Cooke Speed Panchro primes and their first cine zoom lens (manufactured by Bell & Howell).

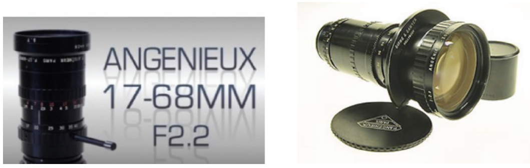

FIGURE 2. (Left) 1956 Angénieux 17–68 mm zoom; (Right) 1958 12–120 mm zoom.

1912, their model 2709 soon earned a high reputation and was produced for 46 continuous years. Mitchel and Kodak soon followed (**Fig. 3**). Panavision entered the film camera arena in the mid 1950's (**Fig. 4**).

In Europe, ARRI produced their first reflex mirror shutter camera, the Arriflex 35, in 1937 and followed this with the 1946 Arriflex II. They continued film camera innovations (**Fig. 5**) over many decades and have continued into today's digital era.

TV Camera Developments

While motion picture film was flourishing worldwide, there began a protracted quest in pursuit of electronic motion imaging. Scientists around the world were to devote their lives to seeking the transducer that would transform optical images into electronic signals that might ultimately support realtime imaging and realtime transmission of those images.

As far back as 1918, Philo T. Farnsworth developed the electronic image dissector. In 1926, a Hungarian engineer Kalman Tihan filed a patent for an all-electronic TV system. Two years later, he patented a pickup tube technology based on a storage principle that produced a significant increase in sensitivity. In 1934, he sold his patents to Radio Corporation of America (RCA), and that same year, Vladimir Zworykin of RCA developed the more sensitive Image Iconoscope tube (**Fig. 6**).

Meanwhile in 1932, in the U.K., Electric and Musical Industries Ltd. (EMI) began work on the Emitron, basing it on experimental work by James McGee and William Tedham. By 1936, cameras developed for the BBC by the Marconi-EMI Television Co. Ltd. were used for the start of the world's first regular "high-definition" TV service in 1936. The image orthicon subsequently emerged and it proved far more sensitive than the Iconoscope-based tubes (it was initially deployed as an image transducer for unmanned radio-controlled flying bombs) (**Fig. 7**). RCA dominated the early years of black and white television with their TK-30 image orthicon camera (**Fig. 8**).

In parallel with the development of TV cameras, almost from the beginning, motion picture film lenses and cameras were used to originate TV program material. In 1947, the first telecine machine to transfer film to video was developed.

Meanwhile, RCA had grown in stature and in resources and were developing the NTSC-compatible color TV system. NTSC was formalized as the U.S. standard in December 1953—superseding the field-sequential system that had earlier been developed by Dr. Peter Goldmark of

FIGURE 3. (Left) Bell & Howell 2709 film camera, which was launched shortly before the founding of SMPTE; (Center) 1933 Kodak Special; (Right) 1940s Mitchel Blimp.

FIGURE 4. Panavision started developing film cameras in the 1960s. (Left to Right) Milestone models: the R-200, the 1986 Platinum, and the 1997 Millennium.

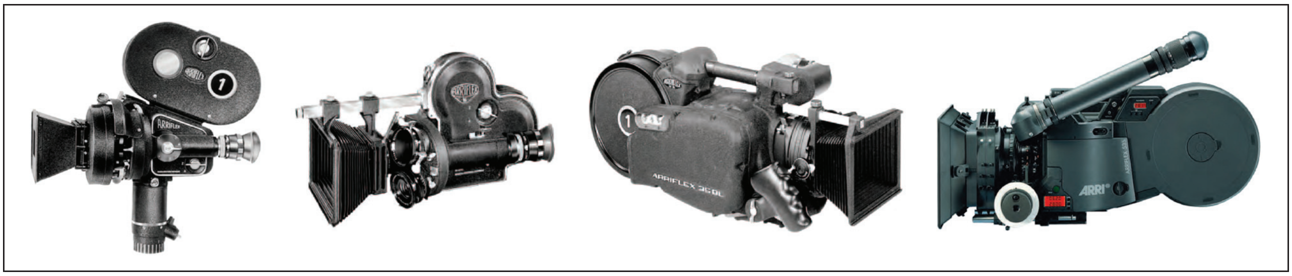

FIGURE 5. (Left to Right) 1946 Arriflex II, 1952 16 mm Arriflex 16ST, 1972 Arriflex 35BL, and 1990 Arriflex 535.

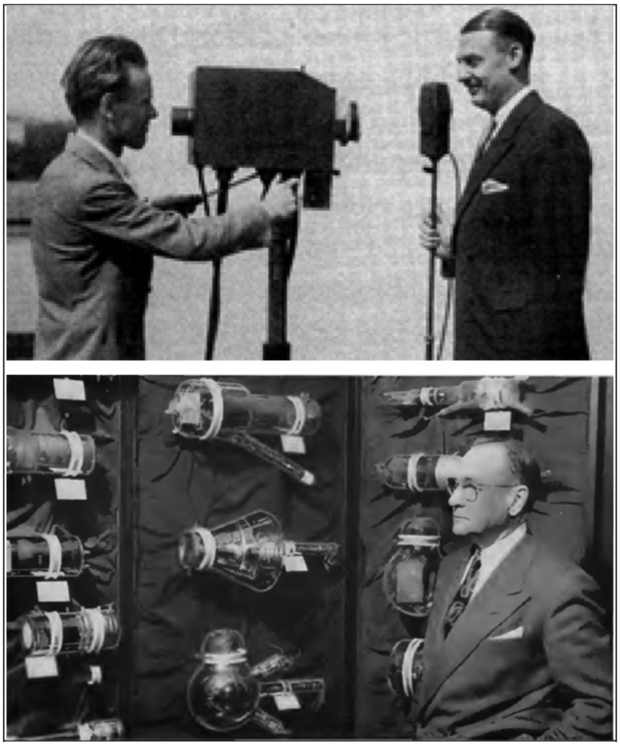

FIGURE 6. (Top) Farnsworth and his image dissector camera; (Bottom) Vladimir Zworykin of RCA with some of the early image sensors he developed.

CBS. NBC started broadcasting color images in 1953 using the first commercially available color TV camera—the RCA TK-40. Mass production of color cameras began in 1954 using the updated TK-40A. These cameras used three image orthicons and, with their large viewfinders, weighed almost 400 lb.

In the early decades, TV cameras used lenses of different focal lengths mounted on a *turret* on the front of the camera, as shown on the left in **Fig. 8** (these were typically Kodak Ektar lenses). The camera operator rotated each lens into position and focused it when the camera was not on the air. Zoom lenses came into common use in the early 1960s, with the major suppliers being British Rank Taylor Hobson and French Angénieux.

The most impressive early TV zoom lens was the 1953 Varotal III from Rank Taylor Hobson from U.K. In 1956, Pierre Angénieux introduced the mechanical compensation system, enabling precise focus while zooming, in his 10× lens released in 1958. Angénieux received a 1964 technical award from the Academy of Motion Pictures for the design of that 12–120 mm zoom lens.

In 1953, Vladimir Zworykin at RCA developed the small Vidicon pickup tube, and in 1965, RCA introduced the four-tube color camera—one 4.5 in. image orthicon and three 1 in. Vidicons **Fig. 9**. 1954 saw the first SMPTE TV standards dealing with dimensions of slides and opaques and image areas for 16 mm and 35 mm films used for TV.

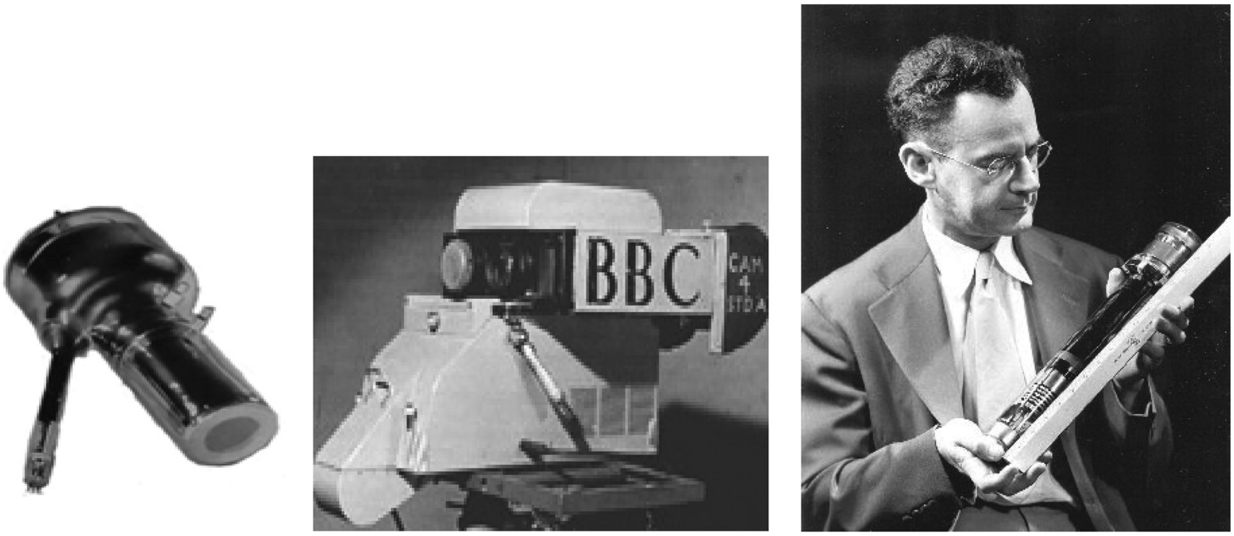

FIGURE 7. (Left) 1937 Super Emitron camera at the BBC; (Right) image orthicon camera pickup tube that was developed during World War II by Albert Rose of RCA.

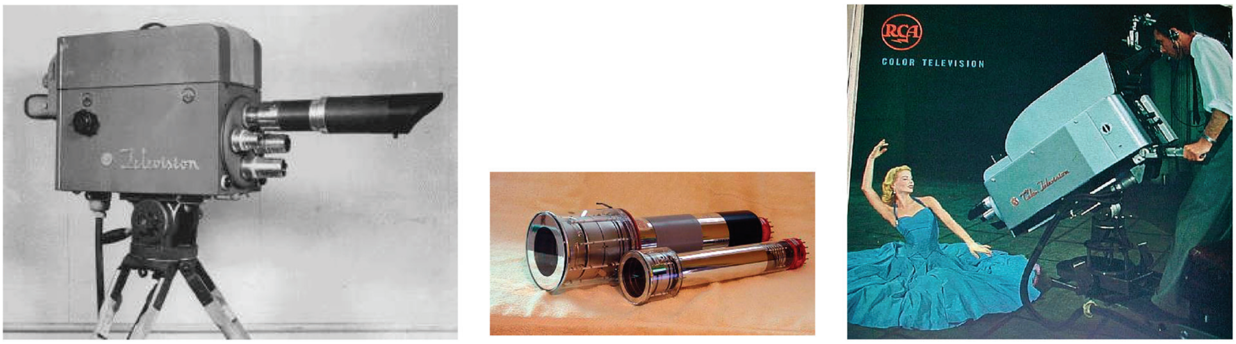

FIGURE 8. (Left) TK-30 image orthicon camera that was to dominate black-and-white TV cameras throughout the late 1940s; (Right) early color TV camera of the mid-1950s.

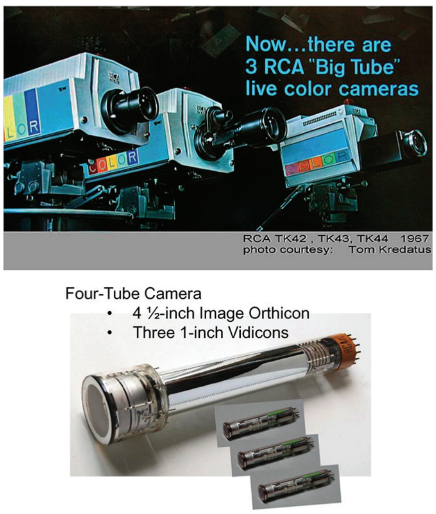

FIGURE 9. Four-tube cameras developed by RCA in the 1960s, with the camera on the right featuring a novel new image isocon (1967), which unfortunately fell victim to the meteoric rise of the Plumbicon.

In 1960, Phillips invented an imaging tube called the Plumbicon that promised true color fidelity. They were made in Slaterville, Rhode Island, at the Phillips subsidiary, Amperex Electronics. In the early 1960s, a new broadcast camera featuring the new Plumbicon tube was being developed by the Phillips Company in Holland. It was called the Norelco PC 60 and was introduced in U.S. in late 1964. Following the 1964 introduction of the Norelco PC 60 came models PC 70, PC 72, PCP 90, and the LDH series. At the same time, German Bosch Fernseh marketed a line of high-end broadcast studio cameras (KCU, KCN, KCP, and KCK) in the U.S., ending with the tube camera KCK-40 in 1978 (**Fig. 10**).

Meanwhile, Japan was now stirring. In May 1946, Sony was founded as a consumer business but, in 1976, formally entered the broadcast TV business. In September 1946, Ikegami was founded and introduced their first broadcast camera in 1975. Precision Optical Industries Co. Ltd. was founded in 1947 and soon thereafter became Canon Camera Co. and introduced their first broadcast studio lens in 1955. By the early 1980s, the combination of

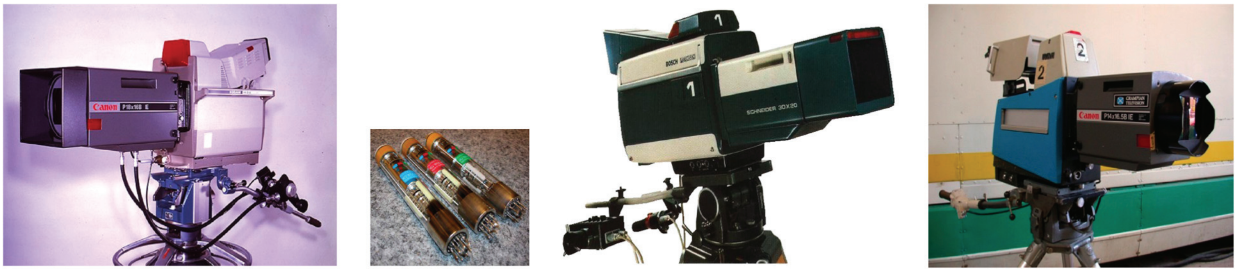

FIGURE 10. Some of the last of the famous three 30 mm Plumbicon-based studio cameras. (Left to Right) Ikegami HK-312, Bosch KCK-40, and RCA TK-47.

FIGURE 11. 1970s early portable cameras: (Left) RCA in 1978; (Center) RCA TKP-46; (Right) 1977 EMI portable.

Canon and Fujinon had virtually displaced Angénieux and Rank Taylor Hobson in TV optics.

In 1978, RCA introduced the TK-47 (**Fig. 10**), a camera that what would become the company's last hurrah in full-size studio cameras. This ubiquitous camera became a TV industry workhorse until the era of charge-coupled devices (CCDs) made it obsolete. Meanwhile, in 1980, the first step into digital cinematography was made by Image Transform in Universal City, California, using a specially modified 625-line 24-frame KCK-40 for their "Image Vision" system.

Portable Video Camera Developments

While companies like ARRI and Aaton had wrought mechanical miracles in their developments of portable 16 mm, S16mm, and even S35mm film cameras, the birth of the portable video camera proved far more arduous. One of the earliest attempts was by the redoubtable RCA in the mid-1980s and featured a daunting shoulder mount camera that was tethered to the processing electronics in a backpack on an assistant. It proved to be one of those unavoidable first baby steps from which much would be learned (**Fig. 11**).

The real breakthrough was in 1976, when RCA introduced the world's first fully self-contained portable camera—the TK-76—based on the new 2/3 in. image format size pickup tube (**Fig. 12**).

However, the notoriety of the TK-76 was short-lived as now Japan had vigorously thrust into the western world in the form of Ikegami, Hitachi, Panasonic, and Sony, and they were to soon dominate both the broadcast studio camera and the camcorder landscape. The 1980s was a crucial decade in accelerating the development of portable camcorders and introducing the

FIGURE 12. Evolution in 2/3 in. image format cameras—the pioneering RCA TK-76 on the left, which was soon challenged by the Ikegami HL-79A on the center—and Ikegami's later foray into electronic cinematography with their EC-35 (Right).

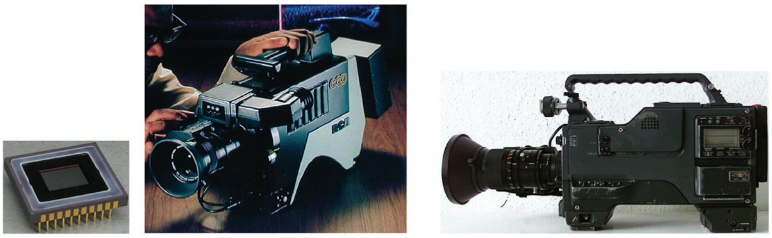

FIGURE 13. Showing a 2/3 in. CCD image sensor and RCA's first broadcast camera to use this technology. Within five years, the integrated camcorder had become ubiquitous (Sony BVW-200 shown on the right).

integrated camcorder. This decade saw the "format wars"—a fierce competitive struggle between competing videotape recorder (VTR) recording formats—and SMPTE Working Groups grappling with multiple related standards. Dramatic reductions in size and weight and incorporation of a host of operational features saw portable video production totally eclipse 16 mm motion picture film capture for TV news (electronic news gathering) and for electronic field production. Separately, as early as 1983, Ikegami introduced the world's first electronic cinematography camera—the EC-35—based on three 2/3 in. Plumbicons (**Fig. 12**).

Arrival of the CCD Image Sensor

At NAB 1984, RCA showed the first broadcast camera based on the new CCD technology they had developed (**Fig. 13**). NEC and Sony followed, and by the end of the decade, the integrated CCD camcorder had arrived, and the broadcast format wars had become a global struggle for dominance in VTR recording formats.

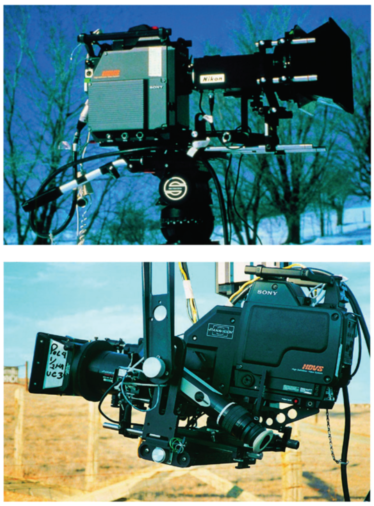

FIGURE 14. In 1984, Sony introduced the HDC-100—the world's first commercially available HDTV camera (shown on the left with Nikon lens), and by 1987, a second-generation camera saw collaboration between Sony and Panavision on an HD electronic cinematography camera.

Arrival of HDTV

This same 1980s decade also saw the arrival of high-definition TV (HDTV) in the form of highly expensive photoconductive cameras and gigantic analog tape recording systems (**Fig. 14**). The ensuing technical developments were flanked by an extensive global effort to forge a unified standard for HDTV production and international program exchange. SMPTE was to play a central role here—forming a Working Group on Electronic Production that ultimately produced the standard ST 274M in 1996. That effort carried over to the international body, the International Telecommunications Union (ITU), and ultimately produced a worldwide standard based on the 1920 (H) × 1080 (V) digital sampling format with standardized frame rates for both the 50 and 60 Hz regions—a historic first in the annals of TV.

1992 saw the world's first CCD-based HDTV camera which was to propel motion imaging to an entirely new level (**Fig. 15**). In 1994, protracted industry collaboration produced the BTA S-1005-A standard for the 2/3 in. HDTV lens-camera interface—entailing optical, mechanical, and electronic interfaces—a first such standard in video history that holds firm to this day. This was to add significant impetus to global developments in HDTV optics and cameras and helped rapidly establish the small 2/3 in. image format size as central to ensuing developments. The first integrated HDTV camcorder emerged in 1997. A pent-up industry discussion on the possibilities of 24-frame HDTV encouraged Sony to develop a total production "24P" system and the SMPTE and ITU to develop related standards.

FIGURE 15. (Top) First CCD HDTV camera HDC-500 based on a 1 in. image format size from Sony; (Bottom) only five years later, the world's first integrated 2/3 in. HDTV camcorder HDW-700.

FIGURE 16. (Upper) Sony-Panavision Super 35 mm HD camera debuted in 2003 and initiated a vigorous global development in large-format single-sensor digital motion imaging; (Lower) RED One 4K camera that first entered the marketplace in 2007.

1996 saw the establishment of the ATSC 1.0 standard for over-the-air transmission of digital HDTV—but the broadcast industry held back for some years. The new century saw accelerating developments in HDTV studio and field cameras, and when ESPN launched their initiative to cover major sporting events in HDTV in 2003, the race was on to deliver HDTV services to the home. Global competitive manufacturing forces were unleashed, and quite astonishing developments in HDTV lenses, cameras, recording, and displays were to follow.

Large-Format Single-Sensor Camera Developments

The mid-2000s witnessed the arrival of the final challenge to motion picture film imaging in the form of large-format single-sensor digital cameras—largely based on variants of the established Super 35 mm image format size. Sony and Panavision collaborated on the development of the Genesis S35mm digital motion imaging camera that set the stage for a rapid proliferation of competitive products (**Fig. 16**). The use of the established huge global inventory of Super 35 mm prime and zoom lenses developed over decades of motion picture film production propelled the initial half-decade of these digital camera developments. Most of the early such systems were based on the established standards for 2K and HD.

The past five years has seen digital motion imaging camera development on an unprecedented scale. AJA, ARRI, BlackMagic Design, Canon, JVC, Panasonic, RED, Sony, Vison Research, and Kinefinity are today offering a wide range of 2K/HD/4K/UHD digital single-sensor cameras to service the theatrical motion imaging and the TV industries (**Fig. 17**). Around 2010 to 2011—within a year—major camera manufacturers ARRI, Panavision, and Aaton quietly shut down production of their motion picture film cameras and turned their attention to digital cine camera systems. In 2013, Fujifilm ceased manufacturing motion picture film. However, the huge installed base of film rental cameras continues to sustain motion picture film production.

By 2010, new Super 35 mm lens developments were vigorously underway among the world's major optical manufacturers as the large-format cameras extended themselves to 4K resolution and beyond (**Fig. 18**).

Centennial of SMPTE

The SMPTE 2016 Centennial is witness to a renaissance in motion imaging. The rapidity and diversity in developments of lenses, cameras, and recording systems appear to hold no bounds. Boundaries are being pushed on all of the multiple dimensions that contribute to overall video image quality. While 4K UHD is presently taking center stage in terms of advances in resolution, there are already

FIGURE 17. Indication of the prolific developments underway in large-format cameras from AJA BlackMagic, Canon, JVC, Kinefinity, Panasonic, RED, and Sony (most offer families of these cameras).

FIGURE 18. Contemporary 4K prime and zoom lenses presently being offered by some of the world's major optical manufacturers—Angénieux, Canon, Cooke, Fujinon, Leica, Schneider, and Zeiss.

lenses available for the future promise of 8K UHD. Prototype 8K cameras were shown at NAB 2016.

Startling developments in digital camera dynamic range—now hovering in the 15-stop range—have made high dynamic range (HDR) motion imaging a reality. HDR display technologies—both professional and consumer—are adding impetus to rising industry preoccupation with HDR. And again, SMPTE proved extremely timely in their October 2015 publication of their *Study Group Report: High-Dynamic-Range (HDR) Imaging Ecosystem*.

Hardly has the ITU Radiocommunication Sector (ITU-R) BT.2020-2 standard been established with its extraordinary wide color gamut (WCG) than manufacturers are offering even wider gamuts in the quest to allow digital emulation of all of the beloved motion picture film stocks. Digital motion imaging camera capture rates now extend up to hundreds of frames per second. Meanwhile, in July 2016 the ITU published the latest standard: ITU-R BT.2100-0 — Image parameter values for high dynamic range television for use in production and international programme exchange.

It might be argued that this year of the SMPTE Centennial is witness to "too much too fast" in the progression of motion imaging. Some argue that 4K UHD must be accompanied by HDR and WCG to realize a significant enough step beyond current HDTV. Others argue that 1080p with HDR and WCG will eclipse any need for 4K UHD. Data pragmatists point to the soaring digital data rates required for digital post-production and distribution that accompany many of these advances.

What is for sure is that this SMPTE Centennial epitomizes "Exciting Times."

About the Author

Laurence J. Thorpe is a senior fellow with the Imaging Technologies & Communications Group, Professional Engineering & Solutions Division, Canon U.S.A., Inc. He joined Canon U.S.A. in February 2004. In January 2015, he was awarded the 2014 Engineering Emmy Charles F. Jenkins Award for lifetime achievement by the Academy of Television Arts and Sciences. In October 2015, Thorpe was a recipient of Honorary Membership in SMPTE. In 1982, Thorpe joined the Sony Broadcast Company. From 1984 to 2003, he was responsible for HDTV market development. From 2001 to 2004, he was senior vice president of content creation systems. He received the NAB 2000 Television Engineering Achievement Award and the Montreux 2000 Gold Medal Award for Digital Cinematography. From 1966 to 1982, Thorpe worked for RCA's Broadcast Division, where he developed a range of color television cameras and telecine products. In 1981, Thorpe received the David Sarnoff Award for his innovations in automatic studio color cameras. He holds ten patents based on his work at RCA.

A Contribution received from the author July 2016.

Recording and Storage: A Brief History

By Tom Coughlin

Introduction

The modern media and entertainment industry would not exist without ways to record and play back content. Without recording, the only performances would be live performances. Since the time of Thomas Edison's invention of the phonograph, inventors and engineers have been developing ways to record first voice and then images.

The combination of recording audio and video, first as analog recording and later, as ever more sophisticated digital records, has enabled the growth and complexity of the modern media and entertainment industry. The ability to store more expressive and immersive content has created greater financial value for these stored assets, leading to standards that enable modern media workflows.

The Early Days of Recording

Recording Images

The recording of images depended primarily on manual drawing until the development of photography in the early 19th century. On 7 January 1839, members of the French Académie des Sciences were shown pictures created by Louis-Jacques-Mandé Daguerre. Daguerre had been working with Nicéphore Niépce since the 1820s to make a permanent recording of an image from a camera obscura or a pinhole camera, using light and chemistry (**Fig. 1**).[1]

Photography with light-sensitive silver salts was developed in the late 18th and 19th century to become a commercial method to capture still images. In the second half of the 19th century, inventors developed processes to create color images, which became commercially available as Autochrome images about 1907. Kodachrome film became available in 1935 for 16 mm home movies and 35 mm slides in 1936 and was the longstanding standard for still image color photography.

The combination of recording audio and video, first as analog recording and later, as ever more sophisticated digital records, has enabled the growth and complexity of the modern media and entertainment industry.

In the 1830s, moving images were produced independently by Simon von Stampfer in Austria, Joseph Plateau in Belgium, and William Horner in Britain using still images on revolving drums and disks. Eadweard Muybridge was sponsored by Leland Stanford on the Stanford Ranch in Palo Alto, California, in 1878 to capture the motion of a galloping horse by using a sequence of images captured by independent still cameras and then to use a sequence of these photographed horse silhouettes on a glass plate to project the images on a screen, effectively the first movie projector.

Etienne-Jules Marey invented the chronophotographic gun in 1882, which recorded 12 consecutive frames/sec on the same picture. An early projector was built by Ottomar Anschutz in 1887 using 24 images on a rotating glass disk.[3]

The first motion picture camera was invented by Louis Le Prince in the 1880s while working in Leeds, England. His first invention was a 16-lensed camera in 1887. He patented the first single-lensed motion picture camera in 1888. He used it to shoot the world's earliest known motion picture on film: *Roundhay Garden Scene* in 14 October 1888. He initially shot his motion pictures on gelatin or glass plates but later switched to celluloid, using film 1.75 in. wide. In 1889, Le Prince presented the first photographic picture projection using an electric arc lamp to project images onto a white screen (**Fig. 2**).[4]

William Friese-Greene was a contemporary of Le Prince and experimented with the use of celluloid film in 1887. He developed his own camera in 1889. Wordsworth Donisthorpe in England filed for a patent on a film camera in 1876 but could not build one at the time. In 1889, he took out a patent with William Carr Crofts for a camera using celluloid roll film and a projector system. Thomas Edison's employee, K. L. Dickson, developed a camera, which was patented in 1891, that took a series of instantaneous photographs on standard Eastman Kodak photographic

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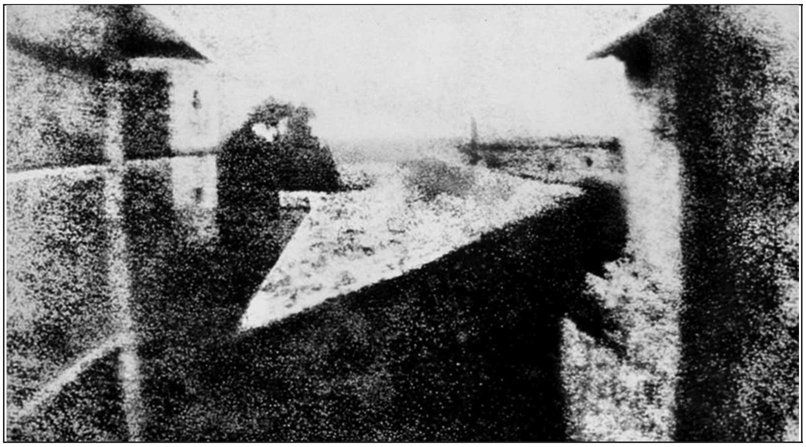


FIGURE 1. Earliest known camera photographic image, Joseph Nicéphore Niépce: *Point de vue du Gras*, 1826 or 1827.[2]

Recording Sound

Thomas Edison invented the phonograph in 1877 (**Fig. 3**).[5] The phonograph recorded sound mechanically when sound vibrations were recorded as physical deviations of a spiral groove on the surface of a rotating cylinder or disk.

When a playback stylus traces the groove and is vibrated by the deviations, it creates a faint reproduction of the recorded sound. Vibrating diaphragms and speaker horns were originally used to amplify the sound, but later, with the vibrations turned into electrical signals, electronic amplification allowed increased sound volume from the reproduced content.

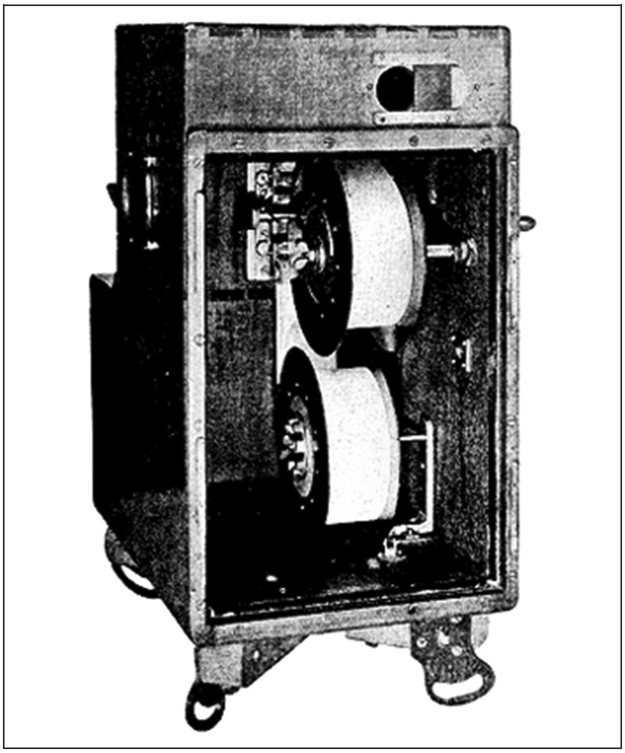


FIGURE 2. Louis Le Prince's single-lens Cine Camera-Projector MK II, the first motion picture camera, built in 1887 to 1888.[i]

emulsion coated on a transparent celluloid strip 35 mm wide. The Edison Kinetoscope was demonstrated at the Chicago World's Fair in 1893 in coin-fed peephole projector machines. The first Kinetoscope parlor with coin-fed peephole projectors opened in April 1894 and spread rapidly after that. Louis and Auguste Lumiere and Max and Emil Skladanowsky were the first to do public film projections in 1895, followed by Edison with his Vitascope.

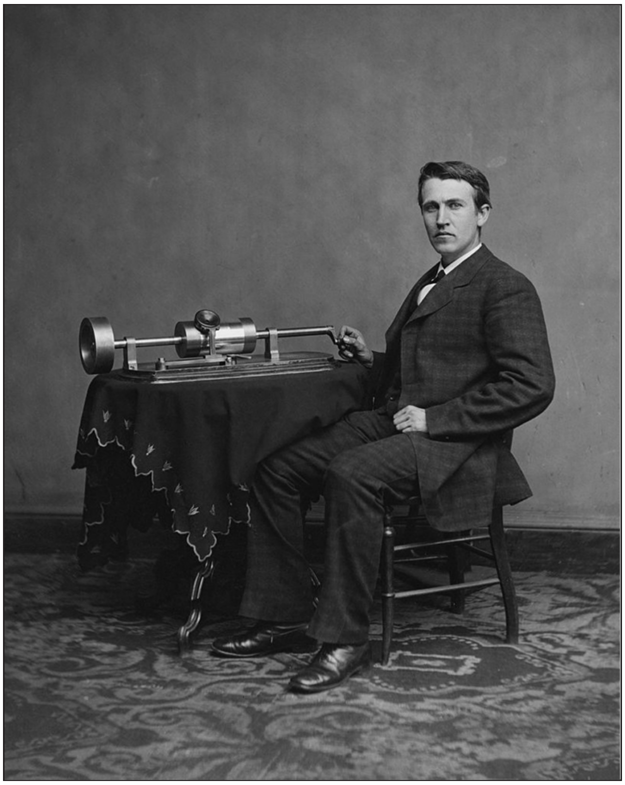


FIGURE 3. Thomas Edison with his second phonograph, photographed by Matthew Brady in April 1878.[ii]

Oberlin Smith, of Bridgeton, New Jersey, visited Edison and saw the early phonographs in 1877 or 1878. He thought that he could come up with a better way to record and reproduce sound and began to work on improved recording methods. He first looked at turning the phonograph cylinder into a tape or a wire with mechanical

[i]Reproduced courtesy of the Science Museum London, England.

[ii]This image is available from the U.S. Library of Congress' Prints and Photographs division under the digital ID cwpbh.04044. Brady-Handy Photograph Collection, Public Domain, https://commons.wikimedia.org/w/index.php?curid=2118716.

recording on the tape surface. In 1878, he began to work on recording sound on a magnetic material (again a tape or a wire) (**Fig. 4**). Recording was done by using magnetic fields to change the magnetic state of a recording media, and induction was used to read back the recorded sound. He continued to work on this technology while running his metal working shop and published a description of his electrical phonograph in *The Electrical World* on 8 September 1888.[6,7]

In 1898, Danish engineer Valdemar Poulsen introduced and patented a magnetic wire recorder for recording telephone conversations (**Fig. 5**). He was the first to introduce commercial magnetic recording equipment. Poulsen developed magnetic recording on tapes and disks as well. Despite the earlier work of Oberlin Smith, Poulsen was able to get a patent on his invention in the U.S. as well as Europe.

Magnetic recording on wires was largely replaced by magnetic tapes by the early 1930s. Engineers in Germany at AEG and BASF developed practical tape recorders using carbonyl iron magnetic particles (later magnetite particles and finally gamma ferric oxide particles) in a cellulose acetate matrix bonded to the surface of cellulose acetate substrates. In 1935, AEG introduced the model Magnetophon K1 recorder and Magnetophon Type-C tape at a Berlin commercial exhibit as a commercial recording device. Later, development of AC bias recording by the Germans (accomplished two years earlier in Japan) allowed the recording of music. The AEG Magnetophon tape recorder was used in German radio stations in World War II (WWII) (**Fig. 6**).[9]

After WWII, servicemen took several of the German Magnetophons back to the U.S., in which, in addition to development work at Brush and 3M, they helped to spur the development of American magnetic recording. Jack Mullin brought back two of the German Magnetophons to the U.S., in which he demonstrated them at engineering meetings and used the recorders in film production work at W. A. Palmer Studios. Harold Lindsey attended one of Mullin's Magnetophon demonstrations at a meeting of the Institute of Radio Engineers (IRE) in San Francisco in May 1946 and was shortly thereafter hired as a consultant by Alexander Poniatoff, the founder of Ampex, to find new products.[9]

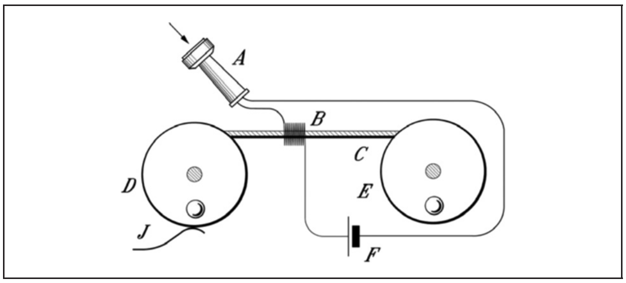


FIGURE 4. One of Oberlin Smith's magnetic sound recording apparatus.

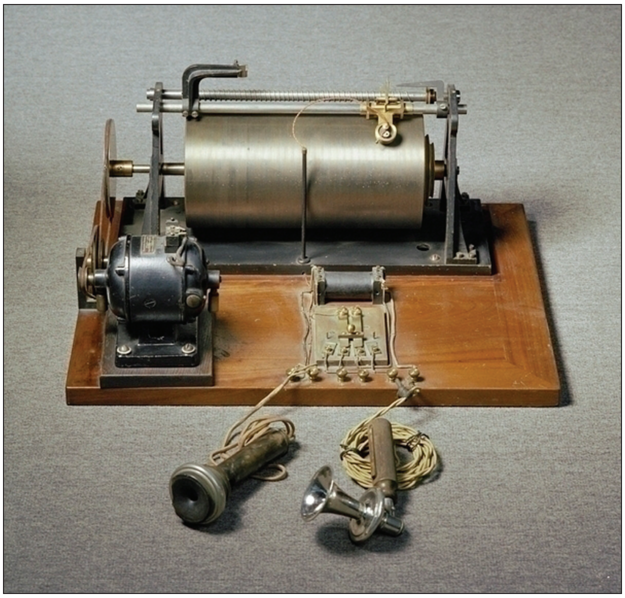


FIGURE 5. Valdemar Poulsen's magnetic wire recorder.[8]

Poniatoff also attended a Society of Motion Picture Engineers' demonstration of the Magnetophon in Los Angeles. Mullin worked as a consultant with Lindsey at Ampex, and Lindsey and Myron Stoloroff, another Ampex employee, began development work on a professional tape recorder in December 1946. Ampex developed its own ring head manufacturing and introduced its Model 200 tape recorder in 1947 (**Fig. 7**).

Mullin helped Bing Crosby create magnetic recording of radio shows using the Magnetophon and then introduced him to Ampex. Crosby ordered 20 recorders; Bing Crosby Enterprises became the distributor of the product in the Western United States and provided an advance payment that financed the early Model 200 manufacturing. Crosby kept two of the recorders and sold the rest to ABC's Chicago studios. Decca Records purchased Ampex Model 200 recorders to record master tapes from which phonograph records were made.

FIGURE 6. German AEG Magnetophon tape recorder.

FIGURE 7. The Ampex Model 200 magnetic tape recorder.

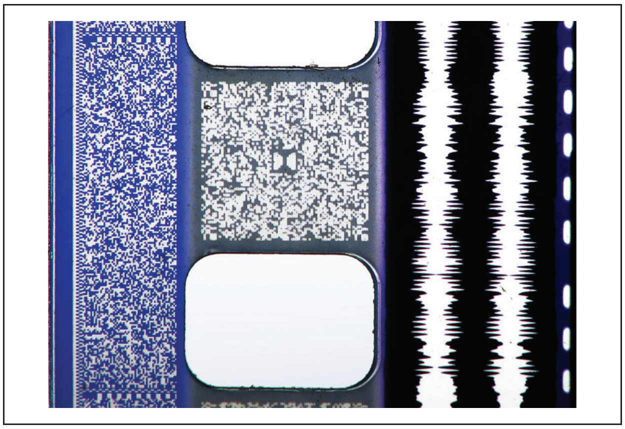


FIGURE 8. Macro image of 35 mm film audio tracks, from left to right: Sony SDDS, Dolby Digital, analog optical, and, finally, DTS time code.[10]

Recording Sound in Movies

During his early work developing the Kinetoscope, Thomas Edison tried unsuccessfully to use the phonograph to bring sound to moving pictures. An American company, Vitaphone, produced the first commercially viable sound system for film with a very large phonograph platter hooked up to a film projector with large leather belts to synchronize the sound with the images.

The first commercial screening of short motion pictures using sound-on-film, in which the sound accompanying the picture is physically recorded onto the photographic film, started in 1923 (**Fig. 8**). Later in the 1920s, feature-length movies used recorded sound for music and effects. The first feature film originally presented as a talkie was *The Jazz Singer* in October 1927 using an improved sound-on-film technology from Vitaphone. Sound-on-film became the standard method for talking pictures until the development of digital cinema technology.

Video Recording

Magnetic Tape Recording

Although early work on video recording was done by Bing Crosby Enterprises, Radio Corporation of America, and the British Broadcasting Corporation, the first successful magnetic video recording system commercially available was the Ampex VRX-1000 (**Fig. 9**). It was demonstrated at the 1956 National Association of Broadcasters (NAB) Conference and delivered to customers the following year. This machine used the quadruplex format with 2 in. wide tape moving linearly at 15 in./sec past and in contact with a thin wheel that rotated at right angles to the tape motion and contained four recording heads spaced evenly around its circumference. This wheel rotated at 240 rps, and the effective writing speed was about 1500 in./sec, which permitted recording of the short wavelengths required to capture and reproduce a specially modulated carrier containing a monochrome video signal. Over time, this technology was extended to color video recording as well and has long served the media and entertainment industry.

With the advent of video recording, early television programming moved from being mostly live performances to a predominance of playback of recorded content. Recording and editing with videotape became common practices and eventually was done electronically and then using computers, rather than by cutting and splicing. Videotape also could be viewed immediately after shooting, avoiding the delay to "develop" photographic film, leading to faster video production projects. Video recording on magnetic tape became the way that all content was collected and then played out at television stations.

As television production and program distribution came to depend on magnetic tape and as the number of companies making tape recorders and tape media increased, there was a need to create tape formats that allowed easy exchange of media between different equipment and tape manufacturers. These formats are standards

FIGURE 9. The Ampex Mk IV Quadruplex Videotape Recorder with its developers (left to right) Fred Pfost, Shelby Henderson, Ray Dolby, Alex Maxey, Charles Ginsburg, and Charles Anderson.

that define the physical, electrical, and magnetic characteristics of the recording media that are to be exchanged. In the U.S., SMPTE developed the video magnetic tape standards. These standards were then approved and published by U.S. and international standards organizations.

Because these standards are meant to provide long-term interoperability, they tended to cause a slower evolution of recording formats than might occur without such standards. Thus, the capability of standard formats may lag well behind the development of the underlying technology. The quadruplex recording system, which was initially invented by Ampex in the mid-1950s, was internationally standardized in the early 1960s. This quadruplex form was, in general, used in television production studios and broadcast stations for nearly 20 years, with only minor changes in the format.

Ampex introduced an open-reel 1 in. wide helical scan videotape format in 1965. SMPTE standardized this format as Type A, and it became the first open-format videotape standard.

In the middle of the 1970s, Ampex and Sony each proposed a 1 in. open-reel helical scan tape format for standardization. The user community of broadcasters in SMPTE insisted that the two companies agree on a single format before a standard would be approved. The result of this collaboration was the SMPTE Type-C format in 1976 (**Fig. 10**).

Bosch introduced a 1 in. tape standard through SMPTE that was labeled Type B. These formats provided superior performance over the original quadruplex video format, and the machines cost less to purchase and operate. These technologies eventually replaced the quadruplex tape format and remained in common use by broadcasters until the mid-1990s.

Digital Video Recording

Magnetic Tape

Sony introduced its D1 digital tape format in 1986. This format recorded an uncompressed standard-definition component video signal in a digital form rather than analog as in earlier videotape formats. The D1 digital videotape format was used primarily by facilities with component-video infrastructure, such as large television networks.

FIGURE 10. SMPTE Type-C tape and tape recorder.

FIGURE 11. D2 digital tape cassette (left) next to a digital audio tape (foreground, right) for scale.[iii]

In 1988, Sony and Ampex developed and released the D2 digital videocassette format at the 1988 NAB show (**Fig. 11**). D2 was also uncompressed but differed from D1 in that it encoded composite video data in the National Television System Committee (NTSC) standard and used a single-cable video connection to the recorder. The use of a single cable, rather than the three cables required by component video, allowed D2 to be a successful video format in the late 1980s and through the 1990s. D2 was also used as the master tape format for laserdiscs.

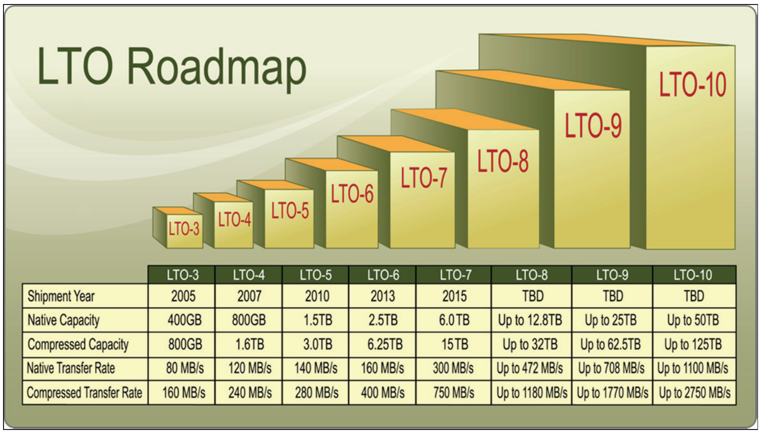
D1 and D2 tapes were replaced by cheaper videotape systems using video compression, enabling more recorded content per cassette. These included the Sony Digital Betacam, which is still in use by some professional television producers. Other digital video formats using compression were Ampex's Digital Component Technology (DCT, introduced in 1992), DV and MiniDV, and professional variants Sony's DVCAM and Panasonic's DVCPRO. Sony also introduced the Betacam SX, which used MPEG-2 compression at a lower cost than Betacam.

Ampex introduced DCT and Data Storage Technology video digital tape recorders in 1992. This tape was 19 mm wide (3/4 in.) and used discrete cosine transform video compression.

Digital tape is the most popular true archival media because there are historical data supporting storage lifetimes of at least 20 years for digital tape under proper storage conditions. Digital tape and optical discs are the most likely storage media for long-term content retention.

Based on a recent survey,[12] the most popular digital magnetic tape format for archiving in the media and entertainment industry is the Linear Tape-Open (LTO) tape. The LTO-7 tape, which was introduced in 2015, has native storage capacities as high as 6.0 Tbytes. The LTO consortium has a roadmap for LTO tapes with native storage capacities as high as 50 Tbytes (**Fig. 12**). In general, these tape generations appear every two to three years (**Fig. 13**).

[iii]Image by Flickr user DRs Kulturarvsprojekt, available under a Creative Commons Attribution ShareAlike license (CC BY-SA 2.0). Courtesy of the Danish Broadcasting Corporation.



	LTO-3	LTO-4	LTO-5	LTO-6	LTO-7	LTO-8	LTO-9	LTO-10
Shipment Year	2005	2007	2010	2013	2015	TBD	TBD	TBD
Native Capacity	400GB	800GB	1.5TB	2.5TB	6.0TB	Up to 12.8TB	Up to 25TB	Up to 50TB
Compressed Capacity	800GB	1.6TB	3.0TB	6.25TB	15TB	Up to 32TB	Up to 62.5TB	Up to 125TB
Native Transfer Rate	80 MB/s	120 MB/s	140 MB/s	160 MB/s	300 MB/s	Up to 472 MB/s	Up to 708 MB/s	Up to 1100 MB/s
Compressed Transfer Rate	160 MB/s	240 MB/s	280 MB/s	400 MB/s	750 MB/s	Up to 1180 MB/s	Up to 1770 MB/s	Up to 2750 MB/s

FIGURE 12. LTO projected tape generations.

IBM and Oracle also support enterprise tape formats with storage capacities up to 10 Tbytes per half-inch tape cartridge.

Magnetic Hard Drives

Hard disk drives (HDDs) have long been an important element in professional media and entertainment. In March 1967, Ampex introduced its HS-100 analog videodisk recorder. This was developed for ABC to provide stop-motion video for sports broadcasts. It was first demonstrated on air on 18 March 1967 on the ABC Wide World of Sports coverage of the World Series of Skiing from Vail, Colorado. The system used Co-alloy plated thin-film media rotating at 3600 rpm for NTSC. The disk could record 30 sec of NTSC video. The video could then be played back in slow motion, stop action, or freeze frame.

In 1971, Ampex introduced HS-200, which provided more control, including variable-speed playback. This product was often used for instant replay of sports events and precise frame and timing control in post-production applications, such as special effects and titles.

With the advent of nonlinear recording in the early 1990s and the push to file-based workflows that began in the mid-1990s, digital hard drives, which were used for years in personal computers (PCs), began to be used for nonlinear editing (NLE) applications. HDDs, being directly connected with the host computer and offering a significant amount of storage, were usually faster to access than magnetic tape, in which a tape had first to be mounted in the tape drive.

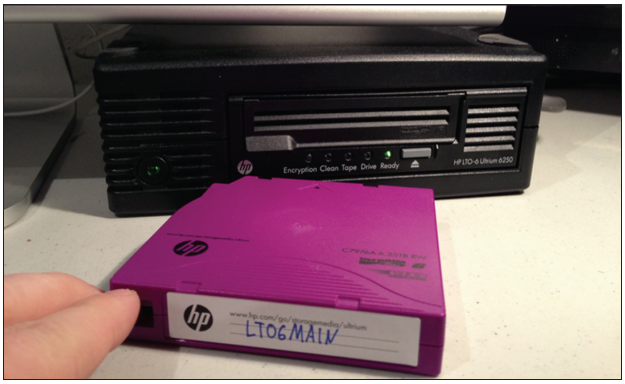


FIGURE 13. LTO-6 tape cartridge.

Even today, HDDs are very common in post-production environments for NLE and other applications. However, the increasing performance needed to support today's high resolution, high frame rate, and high dynamic range content is starting to favor flash memory as at least a first tier of storage in post-production environments.

External storage products using HDDs have long been used to provide project storage for creative professionals. These external storage devices using Firewire, USB, or Thunderbolt interfaces allow almost unlimited expansion of the storage available for video projects.

Apple computers were probably the first computers that used commercial external HDDs. In 1983, Apple introduced 5-Mbyte and, later, 10-Mbyte ProFile external HDDs that could connect to a special port on the back of the Apple II computer (**Fig. 14**).

As the areal density of HDDs (the storage capacity per area on a hard disk) increased, the total storage capacity of these devices increased (**Fig. 15**). These higher storage capacities made external and internal storage products popular for high-resolution video content. In the future, areal densities of 10 Tbits/sq. in. or higher are possible for HDDs (a 10 times improvement; **Fig. 16**).

As electronic integration resulted in smaller electronic circuits and HDDs developed power-saving modes, the size of the enclosure that housed the HDD decreased in size. It was also easier to achieve higher recording areal densities in smaller form factors. The higher areal density also enabled useful storage capacities in ever-smaller form factor HDDs, resulting in HDDs with external storage in 2.5, 1.8, 1, and even 0.85 in. HDD packages.

Through the 1980s and into the 1990s, parallel small computer system interface (SCSI) interfaces were common for external HDDs. These devices were used to support NLE and other media applications running on workstations or PCs. Micropolis was one of the early companies providing commercial SCSI peripheral HDDs. In 1991, they introduced up to 1.75 Gbytes in an external SCSI storage device. By the mid-1990s, there were many suppliers of external SCSI interface HDDs.

Apple introduced IEEE 1394 serial interfaces (also called FireWire) on its computers starting in 1999 and continuing until 2011. Other companies built FireWire interfaces into digital cameras. FireWire interfaces were faster than most available USB interfaces and more convenient than external SCSI interfaces. FireWire was a popular interface for external HDDs as well as media capture devices. In 2011, Apple began to replace FireWire external interfaces with the Thunderbolt interface.

FIGURE 14. Apple ProFile external HDD.

In 1998, the first computers were introduced with USB interfaces. USB became the popular interface for connecting computers to peripheral devices, and it could provide both DC power and high-speed connectivity. USB interfaces allowed the introduction of flash memory–based USB drives (also known as thumb drives), which quickly displaced the floppy disks that had been used by computer users for decades as the preferred media for physical data transfer. USB 1.0 allowed up to 12 Mbit/sec data rates. USB 2.0 was introduced in 2001 and had a data rate up to 480 Mbits/sec. The USB 3.0 specification was published in 2008 with data rates up to 5 Gbits/sec. USB 3.1 increased this data rate to 10 Gbits/sec.

With the introduction of various generations of USB interfaces, external storage devices proliferated. All the HDD manufacturers have their own line of external storage products, and there are many independent external storage suppliers as well. Today, both 2.5 and 5.25 in. external HDDs are available, which use a USB cable connection for power as well as data.

USB Type-C interfaces were developed in parallel with USB 3.1 and were finalized in 2014. This interface had a reversible connector to achieve better success in connecting than the earlier Type-A and Type-B physical interfaces. USB Type-C physical interfaces are used in new USB connections as well as the Thunderbolt 3 interface.

The Thunderbolt interface was developed by Intel as a high-speed interface for external peripherals for computers. Thunderbolt 1 and 2 used the same connector as the Mini DisplayPort, whereas Thunderbolt 3 used a USB Type-C interface. Intel first marketed this interface under the name Light Peak starting in 2011 (initially as an optical cable interface but later moving to copper). Thunderbolt sits on top of the PCIExpress (PCIe) interface and can supply DC power as well as high-speed connections to peripheral devices. Up to six peripherals can be supported by one connector.

Thunderbolt 1 supported up to 10 Gbits/sec and was introduced on Apple, Sony, and some other computers starting in 2011. Thunderbolt 2 provided up to 20 Gbit/sec data rates starting in 2013. Thunderbolt 3 products started to ship in 2015 and provide up to 40 Gbit/sec data rates (5 Gbytes/sec). Thunderbolt is a popular interface for external devices used in video capture and production because of these high data rates.

The most popular and portable external HDD products have a single HDD, but there are also array products that include multiple HDDs and may include one or more Ethernet ports for network connectivity as well as a direct-connect USB or FireWire interface.

In addition to direct-connect external storage devices, such as Firewire, USB, or Thunderbolt, larger video production facilities often have network storage as well as direct-attached storage systems. Network storage facilitates collaborative workflows within a facility. These systems may provide block-level access at the storage (a storage area network [SAN]) or file-level access at the storage (a network-attached storage [NAS]), or both block and file access. They contain several HDDs in an array that provides both data protection, through redundancy, as well as high capacity.

The storage network uses interface protocols, such as Fibre Channel (for SAN storage) or Ethernet (perhaps

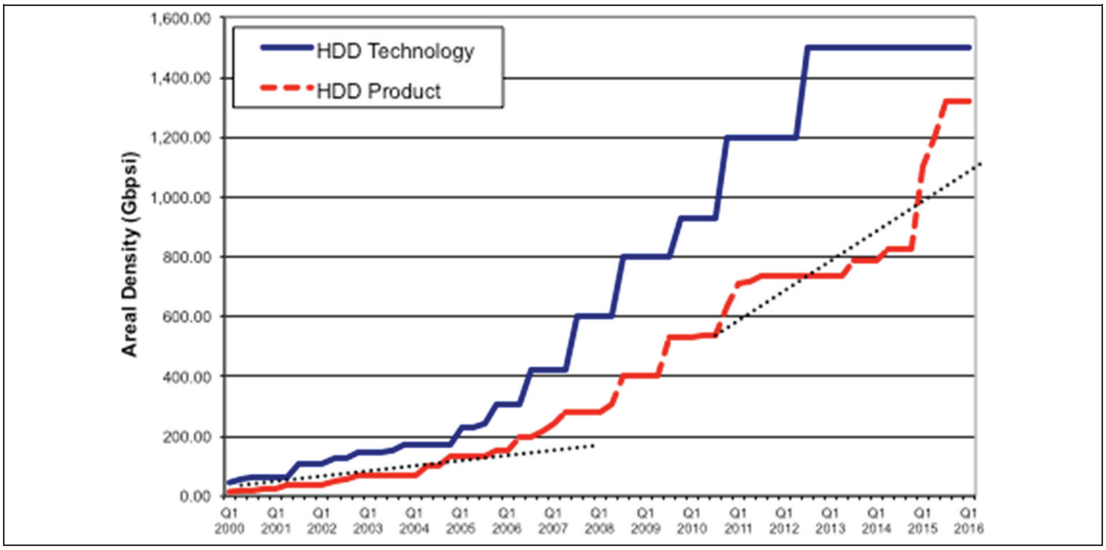


FIGURE 15. History of HDD areal density industry (public laboratory and announced products) quarterly from Q1 2000 through Q2 2016.

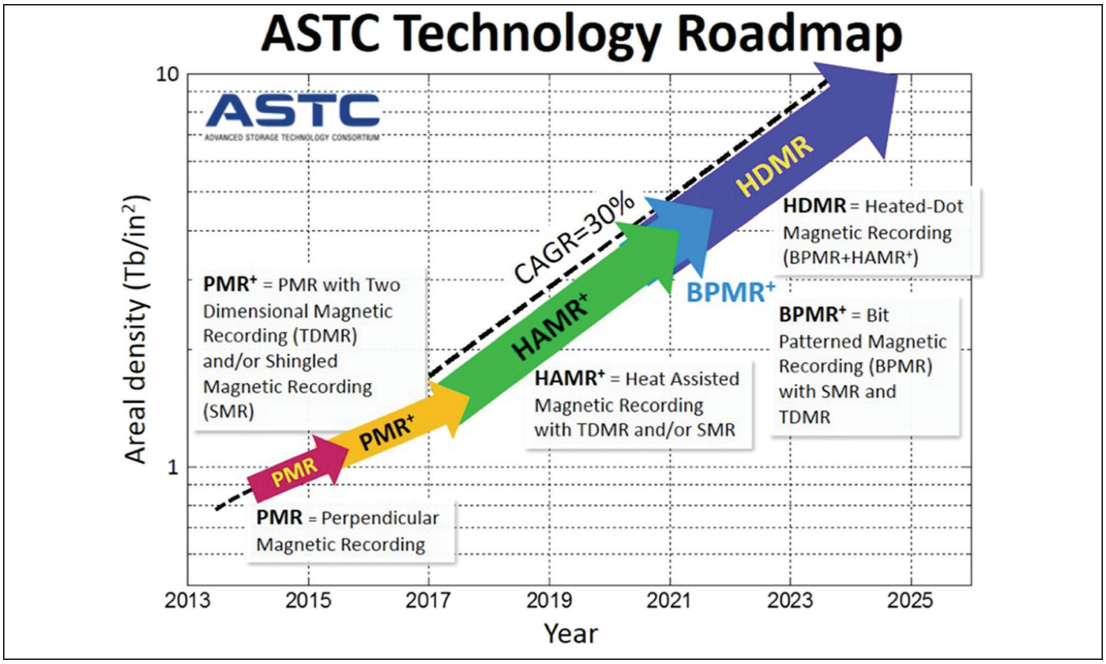


FIGURE 16. Advanced Storage Technology Consortium (ASTC) roadmap of HDD areal density development.

running the internet SCSI protocol). If the facility is large enough, these may be rack-mounted storage systems with hundreds of drives in a data center environment that controls the ambient environment. Many companies make multidrive storage systems for media and entertainment applications (which might include solid-state drives as well as HDDs). These include G-Tech (part of HGST), EditShare, EMC, EVS, Facilis, NetApp, NexSan, OWC, Seagate, Tiger Technology, and many other companies.

The HDDs used in these storage systems may use serial-attached SCSI (SAS) or Fibre Channel interfaces or the Serial Advanced Technology Attachment (SATA) interface. SAS and Fibre Channel are high-speed interfaces generally used with higher revolutions per minute HDDs, and SATA is a slower interface used with HDDs that focus on storage capacity rather than performance. The SAS and Fibre Channel HDDs are being replaced with flash memory because of the latter's higher performance. Because of the large storage capacity and low cost of HDDs, SATA drives will likely continue to be useful for large capacity storage for many years to come.

Optical Discs

Optical discs have served a variety of uses in consumer and computer applications. They are the most widespread medium for physical content distribution (compact discs [CDs] for music and digital video discs [DVDs] for video). They are used in computers for backup and archiving of content, as well as file sharing.

Optical storage over the past 30 years has provided a multiplicity of storage solutions. The range spans the first analog videodisk and 12 in. Write Once (WO) systems in the 1970s to today's Blu-ray disc drives and media (**Fig. 17**). Optical storage was conceived for specific consumer applications (primarily, digital audio and video in the forms of read-only and recordable/rewritable CD and DVD media). Strict media standards (specifications) permit specific applications to be implemented by means of signal processing, logical and applications level software, and packaging. These standards lead to longer useful life for an optical disc format, but they also slow the pace of technological development. As a consequence, optical discs for content distribution have increased very slowly, and their use for professional media distribution has declined.

However, modern optical discs can survive for many decades and still retain their data, making them interesting as a long-term archive. This has led to robotic optical disc archives for long-term content storage. Facebook has been using this technology for storing customer photographs.

Panasonic and Sony announced a roadmap of write-once archive optical discs that promise high-capacity, long-storage-life archive media in multiple-disc cartridges (**Fig. 18**). This may include holographic storage sometime after 2020, with storage capacities of 1 Tbyte per disc. There are other developments that can make conventional

FIGURE 17. Sony Blu-ray optical disc cartridge and drive.

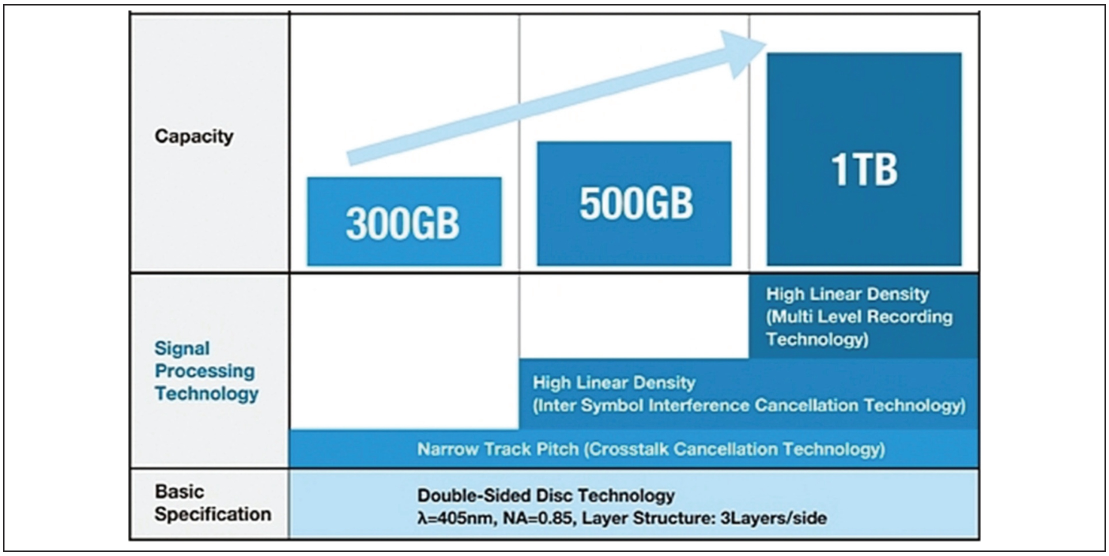


FIGURE 18. Sony/Panasonic optical archive roadmap.

optical discs with nonplastic (ceramic) materials that will degrade more slowly with time than conventional plastic optical discs. Such products are in development by a few companies, such as Millenniata, and accelerated testing indicates media lifetimes exceeding 100 years.

Flash Memory

Flash memory enabled consumer entertainment products as well as consumer still and video cameras. Flash memory is the clear leader in professional video camera media, increasing from 19% in 2009 to 66% in 2015, whereas magnetic tape shows a consistent decline over the same period; in particular, magnetic tape declines from 34% to 4% (**Fig. 19**). Optical discs use between 2009 and 2015 bounced around between 7% and 17%. Film shows a general decline, with 15% usage in 2009 to 1% in 2015. The trend with declining film use follows the trend toward completely digital workflows.

Proprietary flash storage modules are available from Panasonic, Sony, and other companies. Many DSLR cameras used for video capture use standardized compact flash cards. The CFast CompactFlash standard was created to provide lower cost, high-performance flash camera storage (**Fig. 20**).

In addition to their use in cameras, flash-based storage is popular in content delivery, both at the edge and in the central delivery system. This is due to its ruggedness, environmental insensitivity, and high performance. From the media survey,[14] about 20% used flash memory on their edge servers for content delivery in 2015 (this was 21% in 2014, 12% in 2013, 14% in 2012, 16% in 2010, and 20% in 2009).

Flash memory is also starting to attract attention for high-resolution video editing and other post-production operations, as the cost of this storage declines and its performance improves (particularly for streaming access). Several companies are offering all flash arrays and blade systems for fast content delivery (**Fig. 21**). Flash memory also has applications in content creation, such as image rendering. Although people have advocated using flash memory for archive installations, this is not likely since flash memory data retention (without refreshing) is generally only a few years and probably less if the flash is rewritten often.

Recording for the Future

As can be seen from the history of image and audio storage, there are two issues in preserving content for the long term. The first is the finite useful life of various digital storage media. HDDs may provide active archives, but the useful life of HDDs is generally five years or less. Flash memory data retention without refreshing is only a few years. Magnetic tape, stored properly, can probably last for several decades (30 years is a common quoted number). Optical storage may last over 100 years with special disc technologies. In comparison, there are analog films that have survived more than 100 years.

The second, and probably the biggest issue for preserving content for the long term, is technology obsolescence. As this history of recording shows, the technology for capturing and preserving content has changed rapidly over the years. As a consequence, it can become difficult to

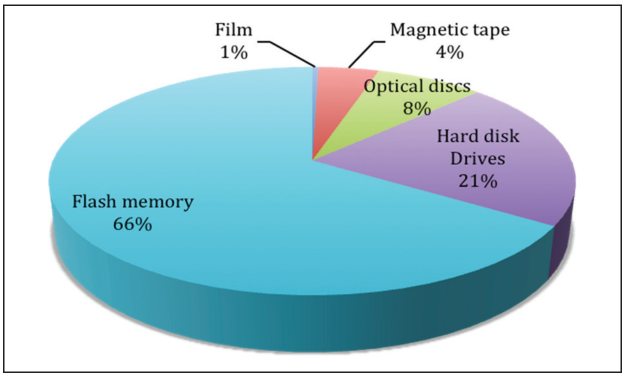


FIGURE 19. Percentage of various recording media in professional video cameras.[12]

FIGURE 20. SanDisk CFast CompactFlash card.

read back data on an ancient recording media because it is difficult to find the technology to read it back.

This issue becomes even more profound when the master version of content, kept for an indefinite period of time, is stored on digital media. With digital content, not only the physical hardware obsolescence is an issue, but also the obsolescence of the software that generated and replays the content. In this sense, digital content, if not regularly migrated from one storage media and format to another as these technologies develop, is in continuous danger of being effectively lost.

In order to increase the longevity of digital media, SMPTE has created a standard for long-term data retention. The Archive Xchange Format (AXF) is a new SMPTE specification, that is, ST 2034. AXF has capabilities that make it particularly attractive for archiving.

AXF is an open-standard transport, storage, and preservation object storage format that supports interoperability between content storage systems and thus provides long-term access to content independent of the evolution of storage and file systems. AXF is a file collection “wrapper” that can encapsulate any number of files of any type and size (**Fig. 22**).

AXF provides universal transport and interoperability for archives like the Master eXchange Format provides for media. AXF isolates digital content from the underlying complexities of storage technology, operating systems, and file systems. AXF works with all current digital storage technologies and can be modified with new technologies as they are introduced.

AXF abstracts the underlying file and operating system technology and includes several Open Archive Information System (OASIS) preservation characteristics to provide long-term protection of file-based assets. AXF adds self-describing features to the AXF objects as well as the media on which they are stored. This provides independence from the systems that originally created them. As long as applications understand the AXF format, they can decode and provide the original stored content.

AXF addresses the obsolescence of content formats, but to make sure the information survives long term, regular migration of the digital content from an older storage technology to a new one is still needed. Thus, we can avoid some of the issues that content owners faced in the past when they changed from one magnetic tape standard to another.

In addition to helping to preserve content and making sure that it is available in the future, regular migration of content may pay for itself long term, since new storage technology will likely allow using less media for storing a given amount of content of a given resolution with each generation of storage technology. This saves on the physical footprint of the storage system and on the energy required to support that storage system.

Conclusion

Media and entertainment storage technologies, whether flash memory, HDD, magnetic tape, or optical disc, continue to develop, providing continual advances in both the price of digital storage and the overall storage system

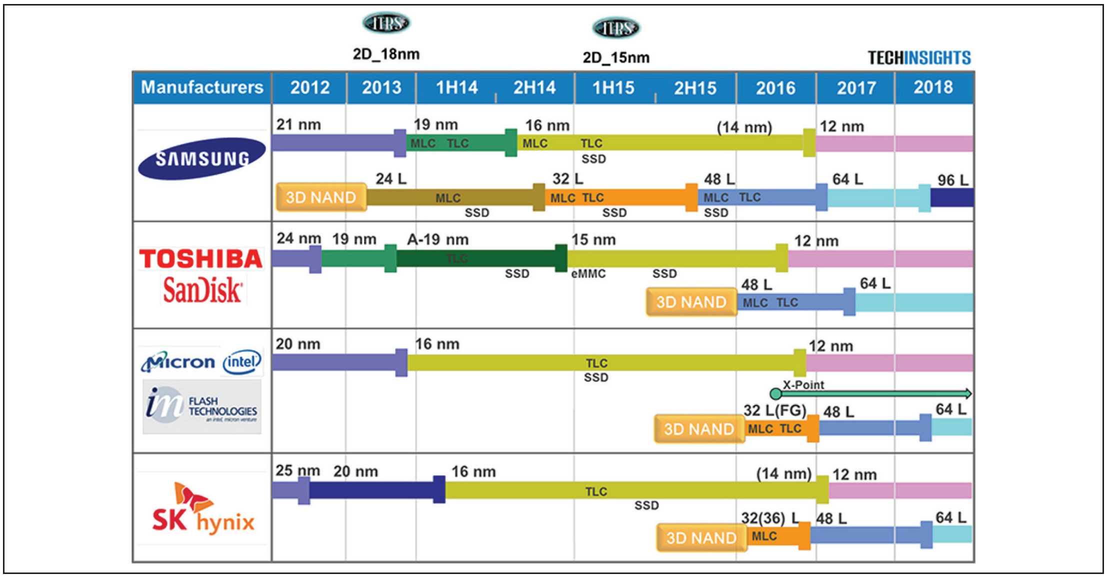


FIGURE 21. Flash memory technology roadmap.[13]

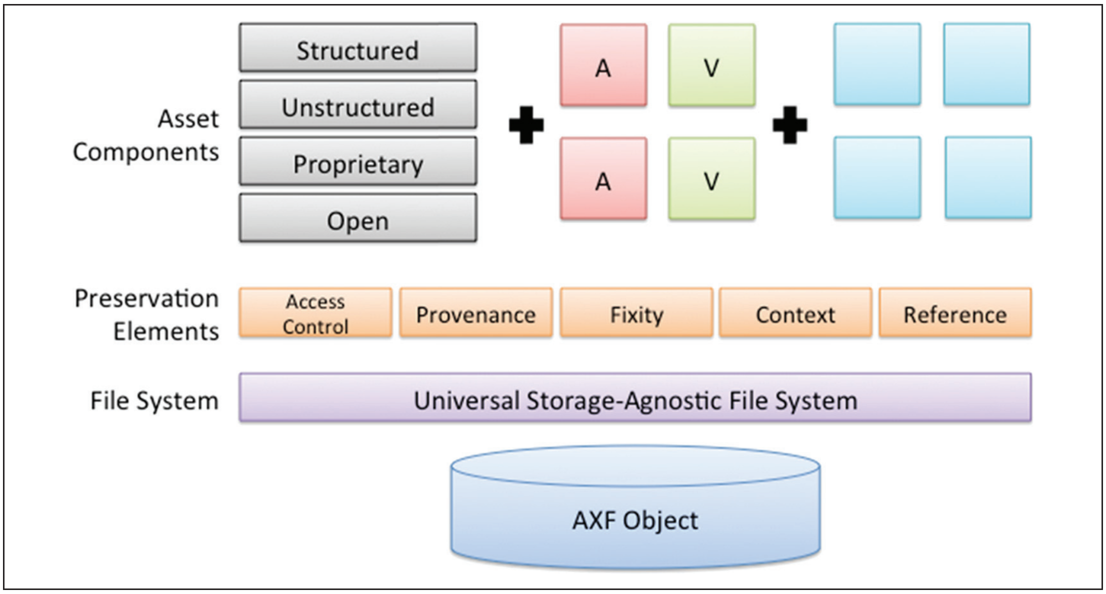


FIGURE 22. Elements in an AXF object wrapper.

performance. The development in recording technology will support the creation of richer content with higher resolution, higher frame rates, higher dynamic range, and with more cameras used at one time.

SMPTE standards have played an important role in the development of media recording over the years, from the days of film to today's digital media workflows. The SMPTE AXF standard should also allow better tools for long-term preservation of media content, allowing these recordings to survive so that they can entertain and educate future generations of viewers.

About the Author

Tom Coughlin is the president of Coughlin Asociates. Coughlin Associates provides market and technology analysis as well as data storage technical and business consulting services. He is a widely respected digital storage analyst as well as a business and technology consultant. He has more than 35 years in the data storage industry, with engineering and management positions at high-profile companies. Coughlin has many publications and holds six patents. He is also the author of *Digital Storage in Consumer Electronics: The Essential Guide*, which was published by Newnes Press. He publishes the *Digital Storage Technology Newsletter*, the *Media and Entertainment Storage Report*, the *Emerging Non-Volatile Memory Report*, and other industry reports. He is also a regular contributor on digital storage for Forbes.com and other blogs. Coughlin is active with SMPTE, the Storage Networking Industry Association, the IEEE (he is the director for IEEE Region 6 and is active in the Consumer Electronics Society), and other professional organizations. He is the founder and organizer of the Annual Storage Visions Conference (www.storagevisions.com), a partner to the International Consumer Electronics Show, as well as the Creative Storage Conference (www.creativestorage.org). He is the general chairman of the annual Flash Memory Summit, a senior member of the IEEE, a leader in the Gerson Lehrman Group Council of Advisors, and a member of the Consultants' Network of Silicon Valley.

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Video Compression and Its Role in the History of Television

By Glenn Reitmeier and Gary J. Sullivan

Abstract

This paper outlines the history of video compression, emphasizing how the concepts we now apply in today's digital world also applied in earlier work on analog television. The paper describes how analog techniques such as gamma correction, interlaced scanning, vestigial sideband transmission, and the transmission of reduced-bandwidth color components using a color subcarrier can be interpreted in terms of video compresion concepts. The basic principles of digital video compression are also outlined and are traced through the generations of standards including H.261, MPEG-2, H.264/AVC, and HEVC.

Keywords

Analog TV, digital TV, video broadcasting, video compression

Introduction

In a modern context, the term "video compression" refers to a complex process of removing spatial and temporal redundancy from the pixel arrays of a series of frames that represent a moving image.

The engineering discipline of *information theory* rigorously defines the concepts of *symbols* to be communicated for a given information source, as well as their *entropy* in terms of the minimum number of bits that are required to perfectly represent them. In a video context, each pixel is a source symbol, and the entropy of a video source represents the lower bound to which "[mathematically] lossless compression" can be achieved. Entropy coding techniques, such as conditional probability estimation, Huffman variable-length coding, and arithmetic coding, can be used to approach that lower bound.

However, most digital video compression that is commonly used today is "lossy compression" because it does not perfectly reproduce every bit of every pixel in a rigorous mathematical sense. It thus crosses into the domain of *rate-distortion theory* rather just statistical analysis and entropy coding. Very high quality digital video compression is often referred to as "visually lossless compression," because while it may not be a mathematically perfect representation, it is visually indistinguishable from the original source for most viewers. "Visually lossless compression" is commonly used today in digital cinema and in the high-quality video contribution links that carry live remote feeds around the world for important sports and news events.

The lower bit rates required for the ultimate delivery of video content to consumers using digital discs, digital television (TV) broadcasts over terrestrial, cable and satellite, and video streaming over the internet can all be categorized as both mathematically and *visually* lossy because they can produce visible *compression artifacts* that may be apparent even to casual viewers. The art and science of modern system engineering for compressed digital video delivery systems involves finding the right trade-offs among various aspects of picture quality at a technically and economically feasible bit rate for a given delivery system.

> **The tremendous advances of modern digital video compression are built upon the previous advances in video engineering from before the digital age.**

The tremendous advances of modern digital video compression are built upon the previous advances in video engineering from before the digital age. The very name "visually lossless compression" refers to the fact that not all details of the video content have the same subjective importance. Some amount of distortion can be introduced without a *perceptible* loss, whereas changing the values in other ways can result in immediately obvious compression artifacts. Video data also have a high degree of statistical *redundancy* that can be exploited to reduce the amount of data that needs to be transmitted. Much of the video picture content tends to be repeated in each frame with a very slight change, and when there is a change, the changes might just be a minor shift in spatial position due to object motion, and pixels that are spatially near each other tend to have very similar values. Modern digital video compression systems are carefully designed to exploit both the

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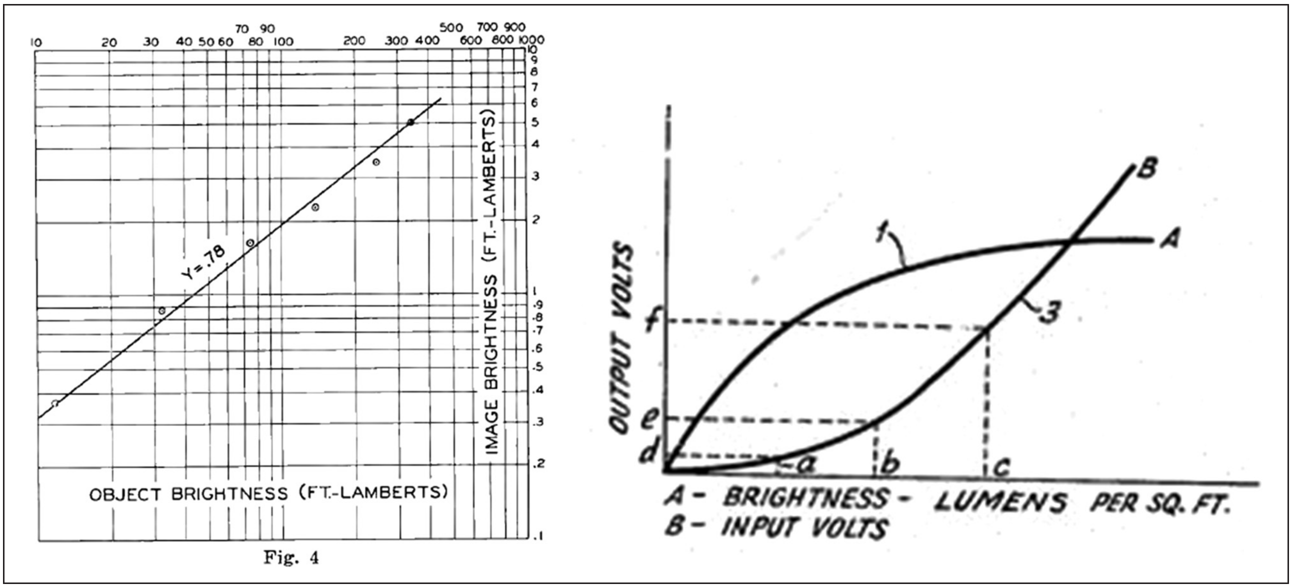

FIGURE 1. (a) End-to-end transfer function of early monochrome TV (Malof 1939, figure 4); (b) electrical-to-optical transfer function (EOTF) of a CRT display (Somers 1944, figure 1).

statistical redundancy in the data and the characteristics of human visual perception.

However, the clever exploitation of human visual system (HVS) characteristics by video engineers is nothing new. While not referred to as "video compression" by the innovators of the time, the clever exploitation of the characteristics of the signal and the HVS was crucial to the successful design of TV systems from their very inception. Such principles have continued to be a key factor in each successive advance, and many remain in use by today's most modern digital video compression systems.

In our attempt to provide a high-level overview and perspective on the development and application of "video compression" techniques over the course of TV history, this paper is necessarily superficial on many technical details and nuances of both analog and digital systems. The interested reader is referred to the literature that we cite in our references and bibliography.

Video Compression in Analog Monochrome TV

At its most fundamental level, TV engineering is the challenge of designing a practical system that captures a scene from a camera, delivers it over a transmission system, and reproduces the scene on a display. In an era of analog circuitry and vacuum tube technology, the "video compression" techniques of using a nonlinear luminance signal, interlaced scanning, and vestigial sideband transmission were essential to the development of practical monochrome TV technology during the 1920s and its subsequent embodiment in standards. The U.K. analog 405-line standard was set in 1936, the U.S. 525-line National Television Systems Committee (NTSC) standard in 1941, and the European 625-line standard in 1946, each using these early video compression approaches, which continue in use today.

Nonlinear Signal Space—Gamma Correction

The development of cathode ray tube (CRT) display technology was a critical enabler to the creation of TV. As shown in **Fig. 1**, the light intensity output of a CRT display is a nonlinear power-law function of its input voltage, $I \propto V_S^{\gamma}$, where gamma γ is generally in the range of 2.2 (for NTSC) to 2.8 (for phase-alternation line [PAL] and sequential color and memory [SECAM]).

Serendipitously, this nonlinear EOTF relationship also mimics HVS perception so that equal steps in CRT input voltage result in approximately equal steps in human-perceived brightness.[1] Recognition of this fortunate coincidence allowed a gamma-correction circuit to be placed in cameras.[2] Thus, a TV camera senses linear light over a large dynamic range and transforms it into a companded "gamma-corrected" luminance signal Y' with a lower dynamic range for analog signal transmission.[i] The reduced dynamic range Y' signal was key to practical analog circuit design, and it subsequently enabled the use of 8-bit samples (256 levels) in digital TV systems. As a notation convention, the prime symbol ($'$) is used to indicate a quantity in the gamma-corrected domain as contrasted with the linear light domain.

However, the use of gamma-corrected signals in a noisy system with a limited dynamic range is "lossy compression" and, indeed, it has a "compression artifact" of "crushed whites" that has always been associated with the "TV look." Since its invention in the 1930s, the gamma

[i]More properly, a distinction can be drawn between true perceptual "luminance" and "chrominance" versus TV "luma" and "chroma" signals; however, we dispense with this here in the interest of informal discussion.

EOTF has been used for over 70 years; it is only now, with the prospect of high dynamic range (HDR) and wide color gamut (WCG) video systems, that different EOTF nonlinearities are coming into use for modern TV systems.

Interlaced Scan

In analog TV systems, the picture is sensed and displayed by a *scanning raster* that progresses from top left to bottom right, tracing a series of *scan lines* that comprise the transmitted analog Y' luminance signal. The bandwidth required to transmit an analog TV signal is directly proportional to its horizontal resolution times the number of scan lines (its vertical resolution) times the frame rate. The careful selection of these parameters is also a "video compression" issue, as analog TV transmission bandwidth was limited by practical analog circuitry considerations, CRT display characteristics, and spectrum regulatory constraints.

The designers of analog TV systems faced a conundrum, because the obvious approach of continuously repeating the scanning pattern for each frame (i.e., progressive scan) of video resulted in unacceptable tradeoffs. In order to avoid display flicker on CRTs, the refresh rate had to be greater than the 24 Hz frame rate used by film and the 48 Hz used by a double-shuttered projector. Furthermore, it was advantageous in the design of the high-voltage power supplies needed to drive CRTs to lock the display frame rate to the power line frequency and hence the development of monochrome TV systems that had 50 and 60 Hz variations. At 50 or 60 Hz, only 200 to 300 scan lines could be transmitted within a practical amount of radio-frequency (RF) bandwidth (6 to 8 MHz), and the result was a low-resolution picture with a coarse, highly visible scan line structure. However, if the number of lines was increased, the display frame rate was correspondingly reduced, resulting in an unacceptable display flicker.

The solution was the invention of interlaced scanning, which separated the odd and even scan lines of a frame into two separate *fields* that are sent sequentially (**Fig. 2**). With a delicate balance of CRT electron beam spot size and display phosphor decay times, interlaced scan lines could overlap just enough to reduce the visibility of the display raster while maintaining high vertical resolution, and the phosphor light emission would persist just long enough to avoid display flicker and motion blurring.[3] (The "Kell factor" related the perceived vertical resolution to the number of actual scanning lines used in an interlaced CRT display.)

Although not discussed as such by its inventors, the scanning process of TV is a vertical and temporal sampling process. Interlaced scanning is a quincunx sampling pattern across the vertical and temporal domains that achieves a 2:1 video compression with its staggered sampling pattern, and it has "post-filtering" effects from the CRT's electron beam spot profile and its phosphor persistence. It was well understood that interlaced scanning introduced both imaging system artifacts (e.g., vertical-temporal aliasing, as manifested in "crawling jagged edges" on nearly horizontal slanted scene edges) and display artifacts (e.g., interline flicker), but with the technology available at the time, it was an ingenious compromise between vertical resolution and display frame rate (flicker). Interlaced scanning was fundamental to the development of analog TV, and it remained an effective "lossy compression" approach for decades, continuing in use even in current digital TV and high-definition (HD) TV systems (sometimes more than we would wish, now that video receivers have become computers and CRTs have been replaced by flat panel displays).

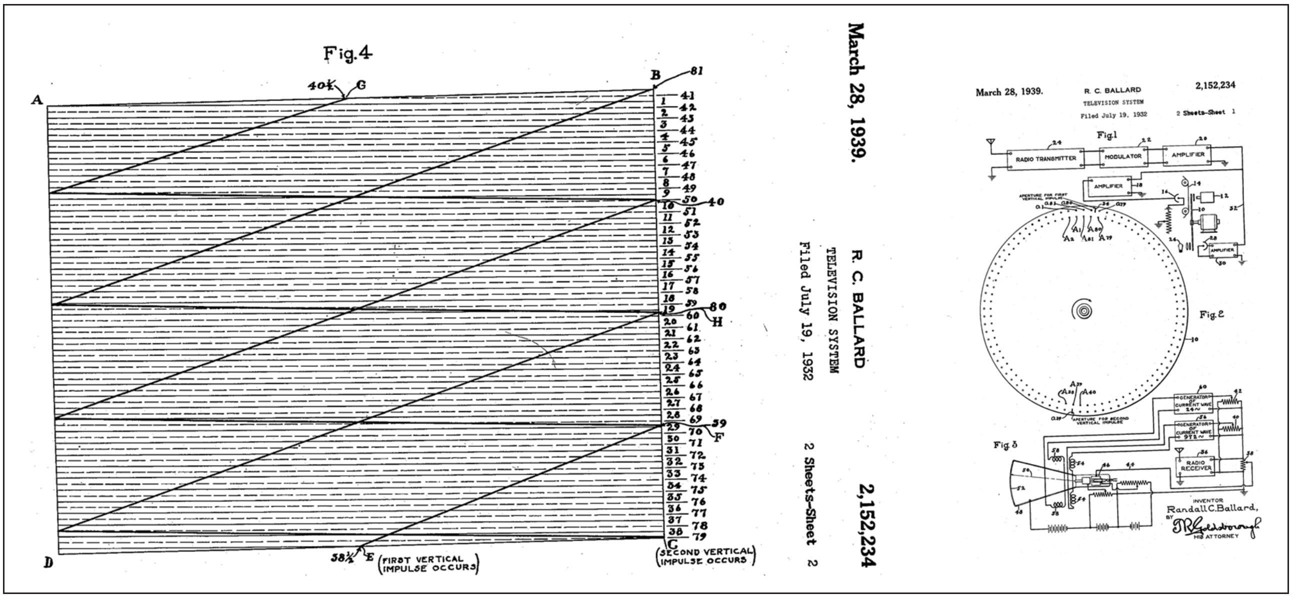

FIGURE 2. Interlaced scanning raster and Nipkow disc implementation.[3]

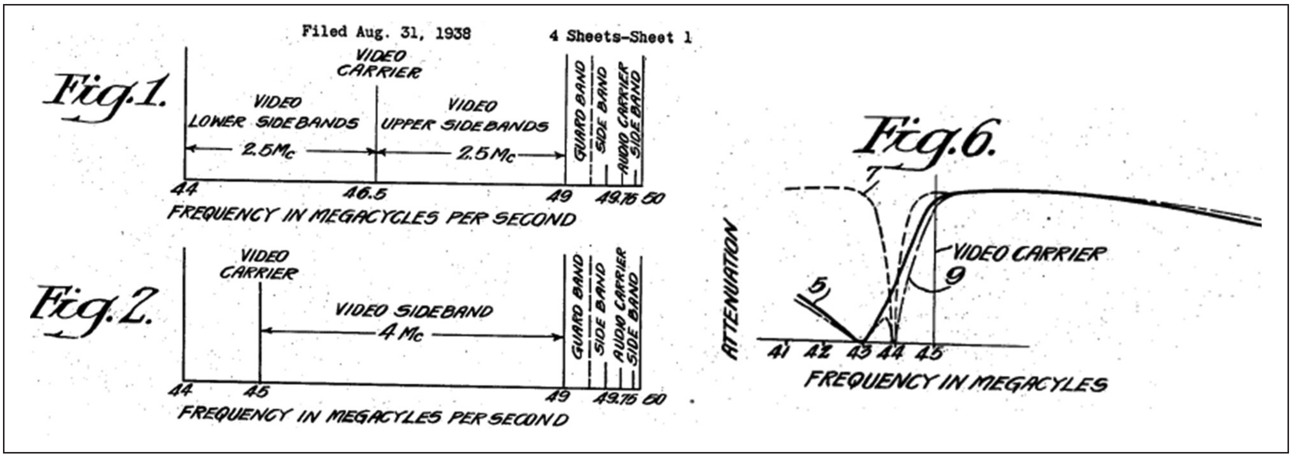

FIGURE 3. Vestigial sideband transmission and filter.[4]

Vestigial Sideband Transmission

One additional "video compression" technique was essential to the creation of monochrome TV. Early RF communication used amplitude modulation of an RF carrier, which conventionally requires a double-sideband RF signal that occupies twice the amount of spectrum as the baseband information signal. Although the concept of single-sideband modulation was understood, as a practical matter, the analog filters required were completely impractical to implement. The invention of vestigial sideband modulation[4] was a practical compromise that transmitted all of the upper sideband and a portion of the lower sideband, which enabled signal demodulation using practical filters while reducing the necessary transmission bandwidth (**Fig. 3**). For example, in the NTSC system, this approach enabled a baseband video signal with 525 scan lines and a 4.2 MHz bandwidth to be modulated into a 6 MHz RF transmission channel. Vestigial sideband transmission was used in all analog TV transmission systems.

Video Compression in Analog Color TV

The desire to leap from monochrome to color TV brought a host of new "video compression" challenges. Red (R), green (G), and blue (B) signals had to be sensed, transmitted, and displayed, but the use of three RF transmission channels was a nonstarter. Color TV had to be sent in a single transmission channel and, furthermore, it had to be backward compatible with existing monochrome TV systems. The challenge of achieving a 3:1 video compression in a backward-compatible representation was a seemingly impossible task, but once again, the clever exploitation of HVS and CRT characteristics achieved an acceptable balance of engineering trade-offs that could be made with analog technology. Still in the era of analog circuitry and vacuum tube technology, the "video compression" techniques of using reduced-bandwidth color components and a color subcarrier were essential to the development of practical color TV technology during the 1940s and its subsequent embodiment in standards. The U.S. NTSC color standard was set in 1953, the European PAL standard in 1963, and the SECAM standard in 1967, each using these color-related video compression approaches. The use of reduced-bandwidth color components continues even in today's most modern digital video compression systems.

Reduced-Bandwidth Color Components

Early attempts to develop color TV took different approaches to transmit the required red, green, and blue signals. The failed "color-sequential" system successively transmitted R, G, and B frames to a CRT display and required a rotating "color wheel" to merge the colors on a display screen.[5] A competing approach was to send the colors on a "dot-sequential" basis (i.e., predating the use of horizontal sampling and three component arrays of pixels[ii] by many decades), but the reduction in resolution and the level of backward compatibility were not acceptable. Notably, the luminance signal of monochrome TV was mostly composed of green information. In order to create a backward-compatible color TV system, R', G', and B' signals could be linearly combined (*matrixed*) to form Y', a very close approximation to gamma-corrected monochrome luminance.

However, sending R' and B' in addition to Y' could still require three times the signal bandwidth of a monochrome signal. Another advance was taken to derive *color-difference* signals, $R' - Y'$ and $B' - Y'$ (**Fig. 4**). Fortunately, experimentation showed that human visual acuity is more sensitive to brightness than color and that acuity is higher in some colors than in others. It was found that the signal bandwidths of $R' - Y'$ and $B' - Y'$ could be significantly reduced without resulting in too much

[ii]In some usage, the term "pixel" would refer to a complete tristimulus color value (e.g., an *RGB* triplet) associated with a position in the picture; here, we informally refer to the sample value for a *single* color component at a position in the picture as a "pixel."

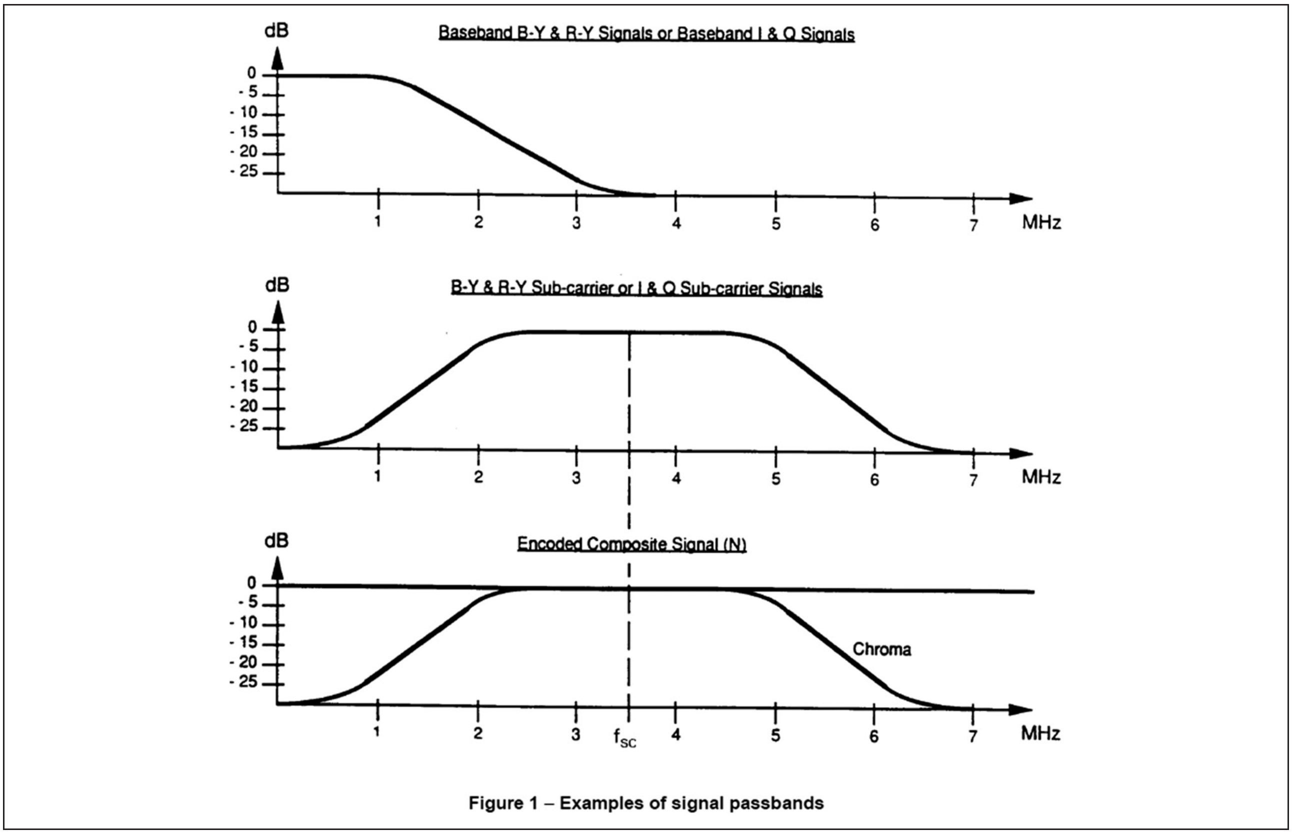

FIGURE 4. Examples of NTSC component signal passbands [from SMPTE 170M-2004, “Composite Analog Video Signal—NTSC for Studio Applications,” figure 1].

visible degradation of color edges. This effect is cited in the SMPTE color bars test pattern,[6] and in fact the order and colors of the bars were developed to exercise the maximum signal transitions in the color-difference signals. In the development of the NTSC color system, an additional step was taken to rotate the phase of the color-difference signals to form *I* and *Q* color components. The *Q* color axis is purplish blue—a region of color where the HVS has its lowest acuity, and this allowed the bandwidth of the *Q* signal to be reduced even further.

This principle of *reduced-bandwidth color-difference signals* has been applied in every color TV system design, from the analog NTSC, PAL, and SECAM transmission systems to all current digital TV systems.

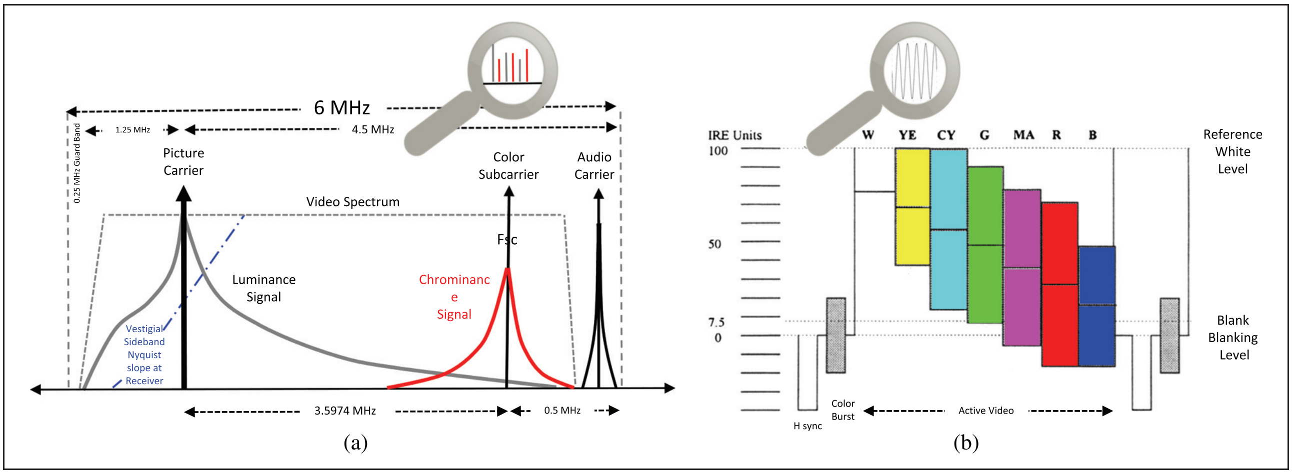

FIGURE 5. In NTSC analog color television, a color subcarrier is quadrature (amplitude and phase) modulated by the chrominance signals and superimposed on the luminance signal, as shown in (a) the composite signal spectrum and (b) a scan line waveform of the color bar pattern. The instantaneous subcarrier amplitude and phase represent color saturation and hue.

Color Modulation

Another key invention in developing a backward-compatible analog color TV signal was to recognize that the dot-sequential transmission of reduced-bandwidth color-difference signals was essentially a quadrature (i.e., amplitude and phase) modulation of a *color subcarrier* frequency (**Fig. 5**). By carefully selecting the frequency to be an odd multiple of one-half the horizontal line frequency, the phase of the color subcarrier would invert itself on each scan line and on each frame, tending to be "averaged out" by the HVS.[7,8] The resulting "crawling dot pattern" of the color information was thus deemed to be acceptably "backward compatible" because, although it was visible on monochrome TV receivers, it was not an obnoxious picture quality impairment.

In modern signal processing terms, the NTSC color system is understood to be a mapping from the $R'G'B'$ signal cube to the $Y'U'V'$ hue/saturation dual-cone space, where the color subcarrier is a diagonal spatial frequency with a 30 Hz (frame rate) temporal frequency[9] and its instantaneous amplitude and phase represent the color saturation and hue, respectively. In addition to being less perceptually visible, the subcarrier was filtered by both the electron beam shape and the phosphor persistence of early CRT displays.[10] After the introduction of color signal transmission, monochrome TV receivers often contained additional electronic filters to further reduce the visibility of the color information. Color TV receivers improved for decades by using increasingly sophisticated approaches to separate luminance and chrominance signals.

As the need for color TV production emerged, it quickly became apparent that maintaining separate component signals on separate coaxial cables was impractical, and thus the use of the *composite video* signal (i.e., with a color subcarrier) on a single cable became the ubiquitous practice. The NTSC composite signal was documented for studio use as RS-170A, which later became SMPTE ST 170M.

Video Compression in Digital Component Signals

Coincident with early analog TV development in the 1920s to 1930s, the theoretical foundation for modern digital signal processing was being established by the work of Nyquist and Shannon, as they discovered the basic principles of sampling signals and what constituted information. It took more than five decades for high-speed analog-to-digital (A/D) and digital-to-analog (D/A) conversion to be practically applied to video signals. By the 1970s, it was possible to digitize composite video signals, usually sampled at an integer multiple of the color subcarrier frequency.[11] SMPTE 244M standardized a bit-parallel signal interface and established the basis for the earliest uses of digitized video.

Component Sampling Using 4:2:2

By the early 1980s, the limitations of using composite signals in TV production became apparent, as video switchers progressed from simple switching and fading to picture squeezes, zooms, and increasingly complex digital video effects. While some simple operations could be performed directly on composite signals, complex operations required disassembling the composite signal back into separate color component signals for processing. In Europe, the use of PAL and SECAM transmission standards complicated program exchange and live signal feeds.

Thus, the goal of establishing a common digital component signal interface for production and broadcast equipment emerged.[12] As with previous analog signals, the use of R', G', and B' signals was impractical, and it was clear that Y', C_R, and C_B (with C_R and C_B being scaled versions

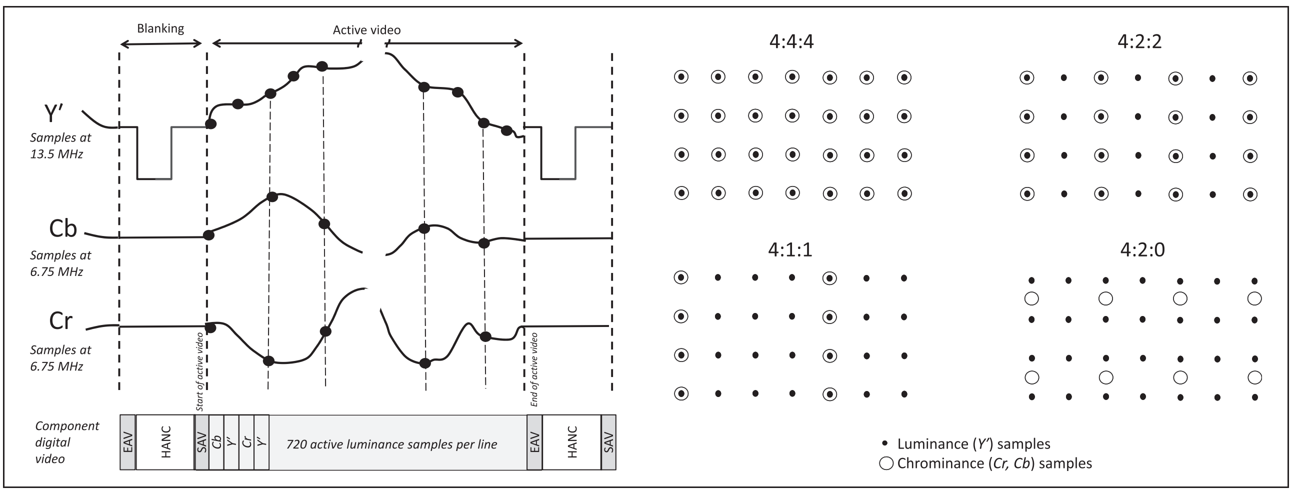

FIGURE 6. (a) Component digital video signals are samples of analog video waveforms that represent pixels in the scanned image; (b) various luminance and chrominance sampling structures.

of the $R' - Y'$ and $B' - Y'$ color-difference signals) could be used to exploit the well-known "video compression" of reduced-bandwidth color-difference signals. After much debate about the sampling rate, relative luminance and chrominance sampling rates (expressed as a ratio "$4:x:y$," where 4 denotes the luminance sampling rate, and x and y denote the corresponding chrominance sampling rates for alternating lines of a frame), sample bit depth, and their impact on both picture quality and the ability to encode and decode composite video signals, SMPTE conducted extensive tests of component video coding in 1981.[13,14]

Notably, the tests showed that sampling need not be locked to the subcarrier frequency and that color-difference signal bandwidths greater than their final transmission bandwidth were essential to perform high-quality chroma keying. As a result, 13.5 MHz was selected as a common sampling rate for luminance signals in both 525/59.94 and 625/50 systems, based on the fortuitous relationship that it is an integer multiple of the horizontal line frequency in both systems and provides 720 active samples per line (**Fig. 6**). Also, 4:2:2 sampling (using 13.5 MHz luminance sampling and 6.75 MHz chrominance sampling) was recognized to provide a good balance between the tradeoff between video data rate and video signal sharpness, making it the first digital "video compression" technique to be used in TV. The "Component Video Signal 4:2:2 Bit-Parallel Digital Interface" was documented as SMPTE 125M.

Adopted in 1982, the International Telecommunications Union (ITU) Radiocommunication Sector (ITU-R) BT.601 (originally known as CCIR 601) is a family of compatible standards for component TV. It accommodates two chrominance bandwidths, which are specified in relation to the luminance signal and its 13.5 MHz sampling rate. BT.601 defines 4:4:4 (full-resolution chrominance) and 4:2:2 (half-horizontal resolution chrominance) sampling formats and allows either 8 or 10 bits/sample.

Although initially implemented as a bit-parallel digital interface[14,15] and used in the D1 component videotape format, the use of the BT.601 4:2:2 10-bit format became ubiquitous after the development of the SMPTE 259M Serial Digital Interface (SDI) in 1993, which provided a serial data stream (10-bit samples, 270 Mbits/sec being the most commonly used variety) over a single-wire interface using a standard 75 Ω coaxial cable with BNC connectors. Subsequent HDTV sampling formats [SMPTE 274M and SMPTE 296M] and serial interface standards [HD-SDI, SMPTE 292M] are direct descendants of the principles established for standard-definition digital component video.

Another sampling format that is important for digital video compression is the 4:2:0 format. In the 4:2:0 format, the density of chrominance samples along a vertical line is reduced by a factor of 2, and thus the vertical chrominance resolution in 4:2:0 is half that of 4:2:2 or 4:4:4. (For interlaced scan systems, a 4:2:0 chrominance sampling is designed to be uniformly interlaced in successive fields.) The 4:2:0 format became ubiquitously used for consumer services with the advent of modern digital video compression, as it takes advantage of the reduced chrominance sensitivity of the HVS in the vertical and horizontal dimensions. However, it is notable that even this vertical downsampling had a precedent in analog color modulation—as the SECAM system used vertical chrominance subsampling, alternately transmitting U and V signals in its line-sequential color modulation.

The Origins of Modern Digital Video Compression

As the speed and capacity of digital memory grew, storing entire fields and frames of video for signal processing became common and was an essential prelude for performing modern video compression. The representation of a video signal became commonly expressed in terms of the luminance *pixel array* size (i.e., the number of horizontal samples times the number of vertical scan lines or the video frame size) and a frame rate.

The pioneering work in modern digital video compression during the 1970s and 1980s was not initially motivated by TV, which had very high resolution and quality requirements. Rather, the initial applications that motivated development included military uses of video, videoconferencing, and multimedia playback on personal computers.

The basis for all modern digital video compression is the removal of spatial and temporal redundancy from the pixel arrays of a sampled video signal. Video compression has two key elements: (1) the reduction of *redundancy* using statistical analysis (*prediction* and *transformation* processing) and information theory (*entropy coding*), and (2) the reduction of *irrelevancy* using signal processing and quantization based on HVS characteristics (*perceptual coding*). There is no redundancy in a picture if all samples are statistically independent as they are in random noise, whereas there is a lot of redundancy in still pictures or a patch of blue sky. Perceptual coding eliminates

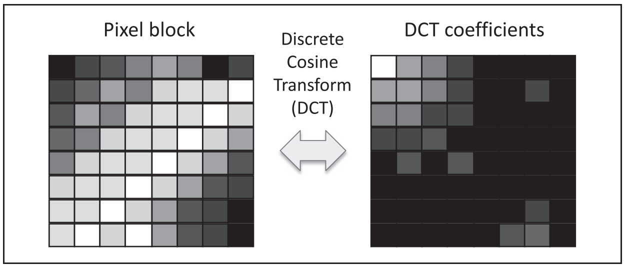

FIGURE 7. The DCT of a block of pixels produces a set of DCT coefficients. After quantization, there are many coefficients with values that can be approximated as zero, and the values can be scanned in order of increasing frequency and coded as run-length/value pairs.

information that cannot be readily seen by human observers. While a significant amount of perceptually irrelevant information was removed in analog TV, digital techniques enable further elimination of imperceptible information. This is followed by statistical entropy coding and the use of data buffering to absorb a variable information rate.

The extremely high degree of compression used in modern digital TV systems is *lossy*—they transmit a high-quality, but imperfect, representation of the original moving picture and sound. The consequence of squeezing the data that represent the pictures and sound into an insufficient data rate is the presence of *compression artifacts*.

Basic Principles of Digital Video Compression—Removing Spatial Redundancy

In a video signal, pixels that are close to one another usually have similar values. Removing this inherent spatial redundancy was the first step toward modern digital video compression. By the early 1970s, it was understood that digital images could be segmented into *blocks* of pixels that could be more efficiently represented as a sparse set of transform coefficients. A square discrete cosine transform (DCT) will decompose an $N \times N$ block of pixels into a set of $N \times N$ frequency coefficients (similar to a Fourier series), as shown in **Fig.** 7. If the pixels are highly correlated, most of the higher order transform coefficients have values that are small enough to be approximated as zero. Perceptual coding principles are used to quantize the transform coefficients, which generally results in a sparse set of nonzero coefficients that are mostly concentrated at low spatial frequencies. The quantized coefficients can then be scanned in order of increasing frequency and converted into run-length/value pairs, specifying a nonzero coefficient value and an associated run length of subsequent zero-valued coefficients in the scanning order. The run-length/value pairs can then be entropy coded using variable-length codes, meaning that, as in Morse code, shorter codeword strings are used for common pairs and longer ones are used for less common pairs.

For color images, the DCT compression must be separately applied to each color component signal. The DCT block size of $N = 8$ was selected in the major early designs, as a good compromise for capturing the local statistical content of the signal and also being relatively easy to compute. In more advanced designs, the block size of the transform has become variable, somewhat different types of transforms are also used, and the entropy coding techniques have also become more sophisticated. For the quantization of the transform coefficients, a simple scheme characterized as *scalar quantization* is generally used—for which the decoder basically just multiplies by a scale factor when reconstructing the approximate transform coefficient values. The value of the scale factor controls how coarse the approximation becomes, and adjusting the scale factor is the primary way that encoders control the tradeoff between bit rate and video fidelity.

DCT compression for still images was the basis for the Joint Photographic Experts Group (JPEG) standard [ITU-T T.81 | ISO/IEC 10918-1] in 1992, which became a key enabler for digital photography and was also sometimes used for video compression. The subsequent JPEG 2000 (a.k.a. J2K) standard [ITU-T T.800 | ISO/IEC 15444-1] used *wavelet* signal decomposition in which digital filter banks separate the image into different spatial frequency bands, which can then be quantized and coded. JPEG 2000 is used for video in digital cinema applications.

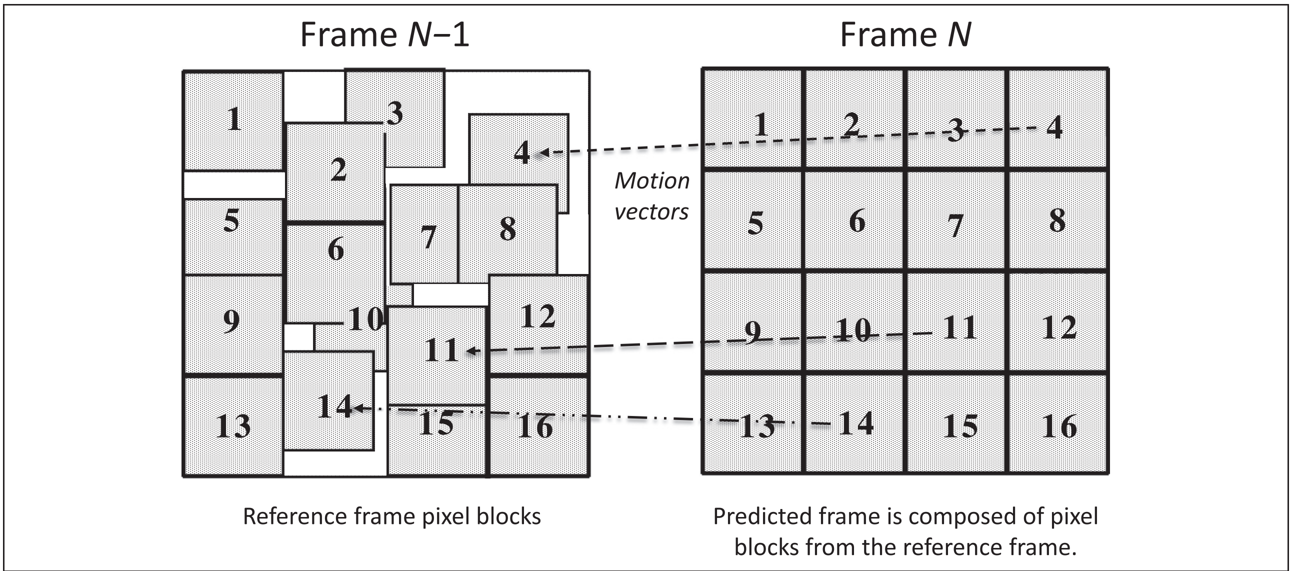

FIGURE 8. A *motion vector* is used to indicate a pixel block in a previously coded temporally nearby frame that serves as a good predictor for a pixel block that is being encoded in the current frame.

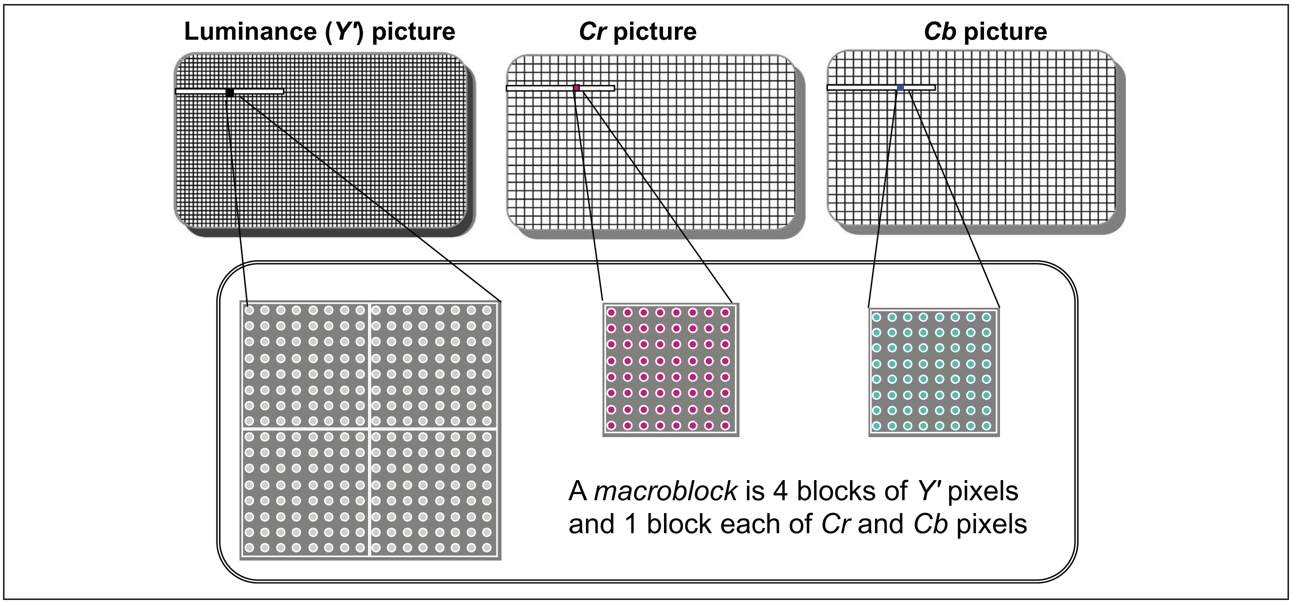

FIGURE 9. Macroblock structure, with four luminance (*Y*) and two chrominance (*Cr* and *Cb*) 8 × 8 pixel blocks.

Basic Principles of Digital Video Compression—Removing Temporal Redundancy

Just as groups of nearby pixels usually have similar values within a video frame, they are also usually similar from frame to frame. Digital video compression also removes temporal redundancy so that picture information that appears in one frame does not need to be retransmitted for subsequent frames. In areas of a picture where nothing is moving, simply subtracting the two frames removes the redundancy. However, most video consists of moving objects; thus, a best match for a block of pixels is searched for in a temporally nearby video frame that has already been encoded. The horizontal or vertical displacement used to reference a block region in the other frame for prediction of the block in the current frame is called a *motion vector*, which is illustrated in **Fig. 8**.

The predicted pixel block is subtracted from the actual pixel block, so that only the small differences, the *residual* information, need to be sent. The first commercial use of motion-compensated digital video compression for multimedia playback on a PC was demonstrated by RCA in 1987 as the Digital Video Interactive system.

The principle of reduced-bandwidth color-difference components continues to be used advantageously by using the lower chrominance sampling density of a 4:2:0 representation, and the motion in an image is generally coherent for both luminance and chrominance color arrays. Thus, a single motion vector value can be applied for all three color components when performing motion compensation. At one-quarter the sample density of the luminance signal, an 8 × 8 block of chrominance samples corresponds to the same picture area as four 8 × 8 blocks of luminance pixels, and a horizontal or vertical motion vector displacement of 1 pixel distance for the luma is a displacement of 1/2-pixel distance for the chroma. A collection of four 8 × 8 luminance pixel blocks (a 16 × 16 region in the luminance array) and two 8 × 8 chrominance pixel blocks (one 8 × 8 block for each chrominance component) that represent the same area of an image, as shown in **Fig. 9**, became known as a *macroblock*. For motion compensation in older designs, a single motion vector would be applied to the entire macroblock region.

In more modern digital video compression schemes, motion vectors can be encoded with subpixel resolution, allowing better approximation of true object motion. Advanced techniques also enable the use of variable block sizes to perform the best possible matching. In the most recent designs, the macroblock concept has also been generalized to become a larger and encoder-selectable size.

Motion-Compensated Video Coding—H.261 and MPEG-1

Modern digital video compression combines both temporal and spatial techniques. The development of the H.261 video compression standard in 1988 (with a substantial revision in 1990) by the CCITT Specialists Group on Coding for Visual Telephony, the predecessor of the group now known as the ITU-T Video Coding Experts Group (VCEG), was a major pioneering milestone in digital video technology. Targeting videoconferencing applications, it embodied practically all of the core techniques that are still found at the heart of video compression designs today—including 4:2:0 sampling, the macroblock concept (with a 16 × 16 luminance region size), the DCT transform (with an 8 × 8 block size), motion vector encoding with the same vectors affecting both the luminance and chrominance prediction blocks, scalar quantization, coefficient scanning with a zigzag scanning order, run-length/value pairing of quantized coefficients, and variable-length entropy coding. These same technologies, with various refinements, have continued to be used in all subsequent digital video compression standards. It is also substantially the same basic design that would become the JPEG still-image coding standard in 1992, aside from the aspects relating to motion handling that were not needed for that application. (There had been a prior digital video coding standard in the CCITT known as H.120 in 1984, which was revised in 1988, but its design was missing key elements needed to make it really practical for use; thus, H.261 rather than H.120 is considered the basis for modern video coding.)

H.261 uses a hybrid of motion-compensated interpicture prediction and spatial DCT transform coding. Motion vectors are determined by matching a macroblock in the actual picture with macroblocks in a nearby search area in the preceding frame. The actual pixels in each macroblock are subtracted from the predicted pixels, and the resulting "residual information" is transformed with the DCT. The DCT coefficients are quantized and, using a zigzag coefficient scanning order, represented as run-length/value pairs using modified Huffman codes. The compressed data for each interframe-coded macroblock include its motion vector and the DCT coefficient data for each of the six pixel blocks (four luminance blocks and two chrominance blocks) in the macroblock.

As H.261 was being finalized, a new group was created in 1988, called the Moving Picture Experts Group (MPEG). Its goal was to bring video-enabled multimedia into the mass market—providing a level of quality that would be adequate for consumer entertainment uses rather than having the videoconferencing focus that had governed H.261 development. Videoconferencing was still only possible then in an expensive business-to-business niche market, and the low bit rates available on the telecommunication networks of the day (generally at most 128 to 384 kbits/sec, including audio and system signaling) seriously limited its achievable quality. Moreover, since some more time had passed since H.261 had been developed, the computing resources available in low-cost products had become greater, and the experience with H.261 could be used to develop further improvements.

The MPEG-1 standard [ISO/IEC 11172-2] of 1993 was designed to compress VHS-quality digital video down to 1.5 Mbits/sec for multimedia playback from CD-ROM discs using PCs or low-cost player devices.[16] Using the core techniques from H.261, MPEG-1 added the important concepts of motion vectors with subpixel accuracy (i.e., interpolating the pixels in a prediction block), bidirectional motion prediction (combining predictions from both preceding and following video frames in display order), and the use of a "group of pictures" that could be encoded as a unit, starting with an intraframe-coded (i.e., spatial-coding-only) picture that provided a simple starting point for random access.

The Digital TV Era

During the 1980s, it was becoming obvious that the 525 and 625-line-based color TV systems of the world were reaching their fundamental limits of performance. In Japan, NHK had begun work on analog HDTV in the late 1960s and held the first U.S. demonstrations at the 1981 SMPTE Television Conference in San Francisco. In Europe, much work was done on developing multiplexed analog component technology that overcame the compromises associated with color subcarriers and similar HD versions. The broadcast spectrum was also highly sought for other uses, prompting U.S. broadcasters to petition the Federal Communications Commission (FCC) in 1987 to reserve spectrum for HDTV. In response, the FCC formed an Advisory Committee on Advanced Television Service (ACATS) and the race to establish an HDTV system for the U.S. began.

In 1990, while ACATS was considering more than 20 advanced TV system proposals that either required two 6 MHz transmission channels for HDTV or delivered less-than-HD resolution and picture quality, the FCC challenged the industry to develop a full HDTV system that used only a single 6 MHz channel. Within a year, four competing digital HDTV systems were announced, and TV began its complete transformation from analog to digital technology.

Pioneering Digital TV Systems

Many of the leading TV research laboratories recognized the significance of the digital compression technology advances in H.261 and MPEG-1, although they were used for applications that did not require "broadcast-quality" video. If digital transmission could be performed through high-power broadcast transmitters at a sufficiently high bit rate in a 6 MHz channel, perhaps digital systems could meet the FCC challenge. In order to deliver HDTV, two key elements were needed—video compression would have to deliver high-quality video at fractions of a bit/pixel and digital transmission would have to deliver more than 2 bits of data rate per hertz of spectrum bandwidth—a higher spectral efficiency than the typical computer modems of the day, at 1000× their speed and successfully coping with a terrestrial channel prone to signal fading, RF signal interference, and multipath distortion.

Four competing digital HDTV system proposals rose to the challenge.[17–20] All used motion-compensated DCT compression, but notably the Advanced Digital HDTV (AD-HDTV) proposal[18] had adapted MPEG-1, with special modifications made to accommodate interlaced video. The AD-HDTV prototype was the world's first real-time MPEG encoder—and in HD.

Digital HDTV Grand Alliance, ATSC, and DVB Standards

After comprehensive testing of two analog systems and the four digital HDTV systems during 1992, ACATS decided in early 1993 that a digital system should be the basis for the future of TV broadcasting in the U.S., but they were unable to pick a single winning system from the digital proposals. In 1993, the digital proponents decided to join forces and work together to create a "best-of-the-best" digital system under the oversight of ACATS. Key principles of agreement were that the Grand Alliance system would allow both progressive and interlaced scan formats, that it would be based upon a successor MPEG-2 video compression standard, and that it would employ a packetized transport layer like the one the AD-HDTV system proponents had developed and submitted to MPEG for standardization.[21–23] The Grand Alliance HDTV System was documented by the Advanced Television Systems Committee (ATSC) standard organization in 1995 and approved by the FCC in 1996.[24,25]

As the U.S. race for HDTV progressed, engineers in Europe also recognized the potential of digital TV and the prospects of an MPEG-2 video compression standard. The Digital Video Broadcasting (DVB) project was formed in 1993 to develop standards for cable, satellite, and terrestrial digital TV.

MPEG-2 and the Digital TV Revolution

Even as the AD-HDTV system demonstrated that MPEG-1 compression could be successfully adapted to TV broadcasting, work had simultaneously begun in the MPEG committee, also in partnership with the ITU-T Video Experts Group, to develop a successor MPEG-2 standard, specifically targeting TV (including support of interlaced video formats) as its key application. Symbiotically, the efforts of the Digital HDTV Grand Alliance, the DVB Project, and the MPEG committee progressed, culminating in the MPEG-2 video and transport standards [ITU-T H.262 | ISO/IEC 13818-2 Video and ITU-T H.222.0 | ISO/IEC 13818-1 Systems] in 1995. MPEG-2 became the catalyst for the prolific worldwide transformation to digital technology for TV service delivery to consumers. In terms of compression technology design, the primary feature of MPEG-2 video that differed from MPEG-1 was having frame-field switching features added to provide an adaptive way to efficiently compress either progressive-scan or interlaced video. This was an essential ingredient for TV at the time, as traditional 525 and 625-line interlaced formats (480/59.94i and 576/50i) and CRTs were still ubiquitous, and even HDTV was originally conceived as using interlace.

Direct broadcast satellite (DBS) was the first commercial deployment of digital TV. Although frequencies and orbital slots had been allocated, early analog DBS systems were extremely limited in the number of TV channels they could deliver. An offshoot from the AD-HDTV project applied the same "MPEG-1+" digital video compression and packetized transport technology to standard-definition TV, resulting in a DBS system with over 150 channels and a small (18 in.) receiver dish. DirecTV was launched in the U.S. in 1994 and was the world's first commercially deployed digital TV system. The DVB standard for satellite broadcasting (DVB-S) using MPEG-2 was completed in 1995 and was rapidly put into commercial service by DBS operators such as Galaxy in Australia (1995), Dish Network in the U.S. (1996), and Sky Digital in the U.K. (1998). DirecTV migrated to MPEG-2 soon thereafter.

DVD discs and players were launched in 1996 and rapidly replaced analog videocassette recorder tapes as the consumers' preferred format for home video movie rentals and purchases. DVD players set the record for the most rapidly adopted new consumer electronics product in history, reaching nearly ubiquitous household adoption in the U.S. by the early 2000s and becoming a huge success in the rest of the world as well.

HDTV broadcasts and receiver sales of the ATSC system began in the U.S. in 1998, making it the world's first digital HDTV deployment. ATSC signals were initially simulcast with analog NTSC broadcasts, which finally ceased in 2009. DirecTV launched its first HDTV channels in 2000.

The DVB project delivered its first standard for digital cable TV (DVB-C) in 1994, and in the U.S., the Society of Cable and Telecommunications Engineers (SCTE) published its Digital Video Transmission Standard for Television [SCTE DVS-031; currently SCTE/DVS 07] in 1996. Digital cable transmissions were simulcast with a conventional analog tier. By the early 2000s, most large cable operators offered a digital tier of standard-definition service, and in the mid-2000s, HDTV was gradually introduced and today is available on virtually all cable systems. As the digital subscribership share has grown, some cable systems have made the switch to become purely digital.

H.264/AVC Advanced Video Coding

Meanwhile, advances in video compression technology continued to be developed in research laboratories, and additional standards were developed as well, including the H.263 standard from ITU-T and the MPEG-4 Part 2 standard from ISO/IEC MPEG. These had some improvements of compression, loss robustness, and other features, but it was the next generation after that when the advances would reach a real critical mass. The ITU-T's VCEG issued a call for proposals in 1998 and created a first draft of a new "H.26L" standard in 1999, with the primary goal being to greatly improve compression capability. MPEG soon issued a call as well, and VCEG responded by proposing its draft design to become a joint project. The two groups then agreed to join forces and formed a partnership called the Joint Video Team (JVT) in 2001. The result would become known as the *Advanced Video Coding* (AVC) standard [ITU-T H.264 | ISO/IEC 14496-10, a.k.a. MPEG-4 Part 10].

With increasing computational capabilities, greater storage capacity, and more sophisticated compression algorithms, H.264/AVC could *double* the compression efficiency of video relative to MPEG-2 (i.e., reducing the bit rates required to deliver high-quality video by about half). In particular, new intraframe prediction techniques, variable block sizes, more accurate subpixel motion vector capabilities, multiple reference picture motion compensation, sophisticated adaptive entropy coding, and in-loop image filtering all contributed significant advances and reduced the severity of compression artifacts compared to MPEG-2.[26,27] Although the fundamental concepts remained similar to H.261, every element of the design had been examined and enhanced.

The first version of the AVC standard was completed in May 2003, and although it was initially considered a challenge to implement due to its increase in encoder and decoder complexity, it was adopted into various services—especially in places where new services were being deployed or where MPEG-2 had not yet become entrenched. SMPTE also standardized a general-purpose video coding standard, as a proposal from Microsoft became the basis for SMPTE 421M "VC-1," which was somewhat less complex to implement than AVC.

As consumer adoption of HDTV displays increased, an HD successor to the DVD format was needed. The Blu-ray Disc was launched in 2006, supporting three video formats—H.264/AVC, SMPTE 421M VC-1, and MPEG-2.

Recognizing the advances in both video compression and transmission technology, the DVB project incorporated AVC (and VC-1) as it developed second-generation standards for satellite (DVB-S2), cable (DVB-C2), and terrestrial (DVB-T2) broadcasting. Brazil's ISDB-T terrestrial broadcast was another early adopter of AVC, and DirecTV, Dish Network, and other DBS systems soon upgraded to it as well. AVC is also extensively used for video streaming over the internet, and the decoder is ubiquitously supported in modern smart phones, PCs, tablets, and smart TVs. The compression improvement of AVC over the prior designs has proved so compelling that today the vast majority of video used in the world is coded using AVC, and since most of the data on today's worldwide networks is video, the majority of data traffic in the world is now AVC video.

Since the development of its first version, the AVC standard has been extended with extra features, such as support for higher quality chroma formats (e.g., 4:2:2 and 4:4:4) and higher bit depths, multiview coding and 3-D coding with depth maps, multilayer scalable video, and multiresolution frame-compatible stereoscopic video. Indeed, the most popular variation of AVC that is used today—known as the "High profile"—was part of the *second* version of the standard rather than the first.[28,29]

HEVC and Beyond

As more time passed, the question again arose as to whether another breakthrough was feasible, and again, there was exploration by VCEG that included an experimental software platform started in 2005 for "Key Technical Areas" (KTAs), to study for potential benefit, and exploration studies in MPEG for "High-performance Video Coding." A joint call for proposals was issued, and a new Joint Collaborative Team on Video Coding (JCT-VC) of VCEG and MPEG was established in early 2010.

The result was the *High Efficiency Video Coding* (HEVC) standard in 2013,[30–32] which has also been substantially extended in several ways since its first version. As did AVC before it, the HEVC standard has again approximately doubled the compression efficiency capability of the syntax; so it represents a clearly compelling advantage over its AVC predecessor and a truly phenomenal advantage of around 75% bit rate reduction relative to MPEG-2 (for the same video quality).[33,34] Key features of HEVC include larger and more highly variable region segmentations for prediction and transform processing, more sophisticated prediction of motion vector values, more sophisticated filters for motion compensation prediction, merging of motion regions, more choices of intraframe prediction modes, additional transforms, transform skipping, further improvement of entropy coding, and an additional filtering stage known as sample-adaptive-offset filtering. It also has other important new features, such as parallelism of encoding by segmenting pictures into "tiles" and parallel processing by "wavefront" decoding of multiple rows of blocks at the same time. While encoding for HEVC is a challenge, HEVC decoding is not so dramatically more complex than for AVC—perhaps roughly 50% more complex for decoding, and perhaps less on parallel-processing architectures.[35]

HEVC has emerged at around the same time as other advances in video have also become major topics of interest, including trends toward the use of 10 bit/sample pixel precision, ultra-HD (UHD) picture resolution, and HDR and WCG video source content. As with AVC, which emerged around the same time that HDTV were services becoming widespread, the enhanced content needs may facilitate the generational transition in coding technology. HDR/WCG video, such as that enabled by the new "Perceptual Quantization" (PQ) EOTF nonlinearity scheme in SMPTE ST 2084 (finally replacing the traditional "gamma" curve of monochrome TV), can provide a much greater sense of reality for video services, and the combination of the HEVC coding format, 10-bit precision, the PQ transfer function, and new display technology may prove a compelling package for a much enhanced user experience (especially when combined with UHD picture resolution).

HEVC is in the process of being incorporated into the latest generation of TV delivery systems by the relevant standards organizations, including DVB, ATSC [ATSC 3.0, A/341 Video Coding], and SCTE [SCTE 1166-1]. It is also used in the latest UHD and HDR Blu-ray Disc format, which was announced in 2015 by the Blu-ray Disc Association.

At the time of this paper, the community is still in a relatively early phase of the adoption process for HEVC, and while it is clear that HEVC is a major advance in technology, there has been some trepidation over business risks surrounding the potential cost of licensing the patents needed for its deployment. In a related development, a movement to try to develop royalty-free video coding formats has gotten stronger. It is worth noting that patents expire, and the technology in the standards prior to AVC is now two to four decades old. Only time will tell what will be the result when another decade or two has passed.

Further extensions of HEVC have already included various key additional developments,[36] including format range extensions (known as RExt, for alternative chroma formats, higher bit depths, and high-throughput usage), multilayer scalable video (known as Scalable HEVC or SHVC), multiview coding, 3-D coding with depth maps, and—most recently—screen content coding (SCC). The SCC extensions provide a major improvement for video containing a significant amount of rendered graphics, text, or animation rather than (or in addition to) camera-captured video scenes and are especially beneficial for applications such as wireless displays, news, and other TV content with text and graphics overlays, remote computer desktop access, and real-time screen sharing for video chat and videoconferencing.[37]

Looking further out to the horizon—beyond the capabilities of HEVC and its extensions—exploration work has again begun toward the next generational change. A new Joint Video Exploration Team (JVET) of VCEG and MPEG has already demonstrated an improvement of around 20% in compression efficiency over HEVC for typical camera content using software known as the Joint Exploration Model (JEM). A joint call for proposals toward developing the next generation of video coding standard seems likely to be issued around mid-to-late 2017, with a target of developing a new standard by around the end of the decade.

> **For the foreseeable future, it seems certain that video compression, using the principles of information theory and techniques of digital signal processing to cleverly exploit the statistical properties of video signals and the characteristics of the HVS, will continue to be essential to future advances in motion imaging.**

Conclusion and Future Predictions

Retrospective

It is remarkable that many of the video compression techniques developed for analog TV, such as "gamma curve" nonlinear signals and reduced-bandwidth color components, continue to be foundational elements for virtually every facet of modern digital video production and distribution and the most advanced digital video compression standards. Other analog approaches, such as vestigial sideband modulation and color subcarriers, were rapidly obsoleted by digital TV, although analog signals are still used in many countries and in legacy baseband analog consumer interfaces. In addition, with the CRT now replaced by flat panel displays, the tradeoffs inherent in interlaced scanning seem rather quaint, and while interlaced formats remain in use by virtually all legacy digital TV systems, their use seems clearly destined to fade away over the coming decades. The longevity achieved by all of the analog techniques is indeed a testimony to the pioneering inventors of TV and their insightful application of human visual perception to video signal processing that resulted in the earliest forms of video compression.

The advent of video-speed A/D and D/A converters and fast digital circuitry brought video into the digital realm. Subsequent advances in large, fast memory, and powerful digital signal processing computation enabled the use of motion prediction and spatial transforms, which are the basis for all modern digital video compression techniques, starting with the H.261 standard. The additional advances made in MPEG-1 paved the way for pioneering digital TV efforts, and MPEG-2 catalyzed a complete transformation in TV broadcasting and consumer electronics, while JPEG 2000 ushered in the era of digital cinema. Continued advances in computing power and the algorithmic advances embodied in H.264/AVC have made it become ubiquitous and dominant in most applications. HEVC, the newest standard, will be an essential ingredient in the delivery of UHD and HDR/WCG video formats to consumers, and research efforts are now looking out to the horizon to think about the next standard beyond HEVC.

For the foreseeable future, it seems certain that video compression, using the principles of information theory and techniques of digital signal processing to cleverly exploit the statistical properties of video signals and the characteristics of the HVS, will continue to be essential to future advances in motion imaging. The spatial resolution, color gamut, dynamic range, and temporal rendition of motion pictures and TV will also continue to advance, supported by these video compression techniques to enable the delivery of ever more realistic viewing experiences at bit rates that are practical and affordable for a broad range of applications.

It is far more difficult to predict what the long-term future of audiovisual entertainment will be. After all, the pioneers of film did not envision TV, and indeed the addition of TV to the Society's name was controversial at one time. Likewise, the pioneers of analog TV could not have imagined today's HD digital world and its extensive use of sophisticated digital video compression. Today's pioneers are developing fascinating techniques, such as virtual reality and augmented reality immersive experiences and light-field digital cameras, and innovative products have begun to appear, ranging from Google Cardboard and Samsung Gear VR to the Oculus Rift and Microsoft Holens. Will the future be immersive video headgear, or will we push beyond to develop true object representations with fully free-viewpoint multiviewer holographic imaging and display systems that make us like Zeus on Olympus, looking down at a world below that we can manipulate at will?

Regardless of what direction the future takes, one thing is certain—that "video compression" of some form will be a key enabler, as it has been since the dawn of TV.

About the Authors

Glenn Reitmeier is the senior vice president of technology standards and policy at NBC Universal, leading the company's technical efforts related to industry standards and government policy. Reitmeier is a graduate of Villanova University. He began his career with Sarnoff Laboratories, where he worked for 25 years in digital video R&D. In the early 1980s, he was instrumental in developing the SMPTE and BT.601 Component Digital Video standard for television production. In the 1990s, he was a key proponent of digital television and a leader in the Digital HDTV Grand Alliance, which became the ATSC digital television standard in 1995. Since joining NBC in 2002, Reitmeier has been involved in the creation of NBC's first high-definition cable channel, Universal-HD, and the launch of DTV multicast programming. Reitmeier currently serves the industry as a board member of the Advanced Television Systems Committee (ATSC), the North American Broadcasters Association (NABA), and the Open Authentication Technology Committee (OATC); he has previously served as chairman of the ATSC and OATC boards. Reitmeier is a Fellow of the SMPTE and received its Progress Medal and Leitch Gold Medal. He is also an inaugural member of the Consumer Electronics Association's (CEA) Academy of Digital Television Pioneers and received the National Association of Broadcasters' (NAB) Television Engineering Award for lifetime achievement. He holds more than 50 patents in digital video technology and is recognized in the New Jersey Inventors Hall of Fame.

Gary J. Sullivan is a video and image technology architect in the Corporate Standardization Group of Microsoft Corporation. He has been a long-standing chairman or cochairman of various video and image coding standardization activities in ITU-T VCEG, ISO/IEC MPEG, and ISO/IEC JPEG, and in their joint collaborative teams since 1996. He is best known for leading the development of the "Advanced Video Coding" (AVC) standard [ITU-T H.264 | ISO/IEC 14496-10], the "High Efficiency Video Coding" (HEVC) standard [ITU-T H.265 | ISO/IEC 23008-2], and the extensions of those standards for format range extension, scalable video coding, 3-D/stereoscopic/multiview video coding, and screen content coding. At Microsoft, he has been the originator and lead designer of the DirectX Video Acceleration (DXVA) video decoding feature of the Microsoft Windows operating system. He has received the IEEE Masaru Ibuka Consumer Electronics Award, the IEEE Consumer Electronics Engineering Excellence Award, the *IEEE Transactions on Circuits and Systems for Video Technology* Best Paper Award, the International Committee for Information Technology Standards (INCITS) Technical Excellence Award, the International Multimedia Telecommunications Consortium (IMTC) Leadership Award, and the University of Louisville J. B. Speed Professional Award in Engineering. The team efforts that he has led have been recognized by an Academy of Television Arts & Sciences (ATAS) Primetime Emmy Engineering Award and a National Academy of Television Arts & Sciences (NATAS) Technology & Engineering Emmy Award. He is a fellow of the IEEE and SPIE.

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File-Based Workflows

By Brad Gilmer

Abstract

As we celebrate the Society's 100th birthday, file-based workflows are a common part of almost every professional media organization. In fact, it is hard to imagine how an organization could stay in business without them. The Society and its members have contributed significantly to the enabling technologies behind file-based workflows.

Keywords

Metadata, Workflows, JT-NM, TFHS, SMPTE

What Have We Gained?

What have we gained from file-based workflows? Perhaps the easiest way to answer this question is to look at the state of a typical broadcaster in the mid-1980s. Each morning, trucks from several overnight shipping companies arrived, offloading large canvas bags containing tens, potentially hundreds of video tapes. These tapes contained commercials, programs, and various video and audio elements that would be used for local production. Throughout the day, news crews came back from the field, again carrying stacks of tapes from news vans to edit suites. Video tape machines were everywhere: from pairs of machines in small rooms used for news story editing, to a row of machines in every production edit suite, to tens of machines in the on-air playback tape rooms. More tape machines sat in central technical areas waiting to make copies of video tapes.

Why were there a number of machines dedicated to copying video tapes? Because this was a critical component of tape-based workflows. When a tape entered the facility, typically it was needed in several places. Making copies was the only way to deal with this requirement. And of course, we would end up making copies of copies as part of the workflow, with the attendant loss in quality. Furthermore, only one person could work on a project at a time, because you had, perhaps, multiple source tapes and an edit master, and of course, you were editing one source into one master at a time. Think about the implications for workflow in this environment.

Fast-forward to today: In many facilities, deliveries have been reduced dramatically. If tapes are still delivered, they are almost always ingested into a server. Commercials are likely to be delivered to the broadcaster as files, and news crews shoot content, which is stored directly as files at the camera. Once the essence is available as a file, new workflows are enabled-files may be cloned (an unlimited number of bit-perfect copies may be made). Files can be stored on servers, allowing simultaneous access for viewing, editing, and approval. Files generated by news crews may be edited in the field on laptops, and the completed story can be sent back to the studio at whatever speed the data links will support. Files can be annotated with additional metadata, which enhances processing and aids in cataloging, search, and retrieval. Files can be simultaneously converted to a number of online formats for distribution on the web or through over-the-top (OTT) applications. Long-form programming stored as files may be accessed to create promotional material while simultaneously being accessed by Standards and Practices, Legal, and Marketing departments. On-air playout facilities can store weeks of programming available for playout on multiple channels with different languages. It is hard to imagine any broadcast workflow that has not been impacted by file-based workflows.

> **It is hard to imagine any broadcast workflow that has not been impacted by file-based workflows.**

Milestones and SMPTE's Contribution

Critical enabling technologies have had to come together to get us to where we are today, and SMPTE has standardized a great many of them. But in addition to these technologies, perhaps the most significant milestone along the path to file-based workflows was the creation of the EBU/SMPTE Task Force: Final Report: Analyses and Results (2554 KB) "Special Supplement 1998" to EBU

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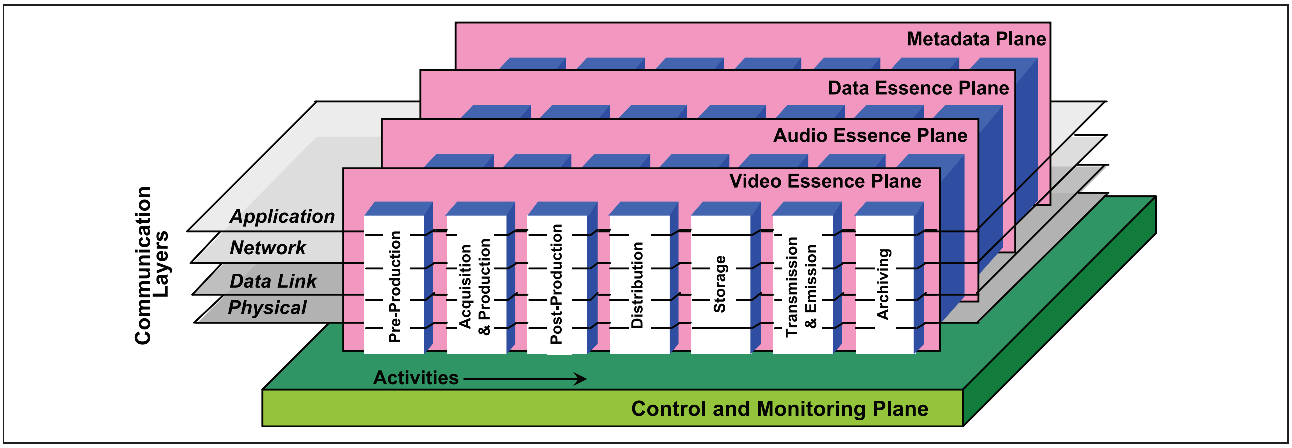

FIGURE 1. This model includes a number of important concepts, showing that the separation of different types of essence and metadata into different planes, the inclusion of an abbreviated ISO seven-layer stack, and the notion that control and monitoring is an overarching application are all core concepts and convey best practices in system design, even almost 20 years after the Task Force publication.

Technical Review (link to https://tech.ebu.ch/docs/techreview/ebu-smpte-tf-bitstreams.pdf). Its scope was to collect user requirements in the areas of digital encoding (compression), wrappers and file formats, metadata, interfaces suitable for program data transfers, and physical link and transport layers, with the ultimate goal of driving the areas of focus for the Society in the transition from an analog to a digital era. The significance of the work of this Task Force cannot be understated. It affected the overall composition of the SMPTE technical committees, it informed the projects to be undertaken, and it ushered in the era of digital video and file-based workflows.

To put it simply, our industry would not exist today without the innovations that were foretold by the Task Force.

The "Final Report: Analyses and Results" was published jointly by the SMPTE and the EBU in July 1998. Included in the report was a systems model, given as Figure 2.2, which encapsulated the entire view of this new digital world. This model remains relevant today (see **Fig. 1**).

Astounding developments are occurring with regular frequency in the field of Internet technology, much of it video-focused.

Thoughts for the Future

I have been asked to contribute my thoughts regarding the future as it relates to the Society and file-based workflows—a dangerous prospect for anyone, but especially dangerous given the progress of change over the last few years. That said, a few points stand out.

- *Leverage Internet technology*: Some people say the greatest invention of mankind is the Internet. But I believe that misses the mark. The truly great invention is Internet technology and all it embodies. Concepts of virtualization, composability, and atomic functionality are finding their way into professional media. As they do, it is incumbent on us and on the Society to make professional video and audio and its associated data, first-class citizens in that world. Astounding developments are occurring with regular frequency in the field of Internet technology, much of it video-focused. We must create Standards that enable the media professional to take advantage of these developments.
- *File-based*: Live streaming is not the subject of this article. That said, it is clear that the line between streaming and file-based content is becoming increasingly blurred, and it may be that this distinction vanishes completely in the near future. Consider, for example, that adaptive bit rate technology delivers a series files to the end viewer's device, but that the contents of those files are presented as if they were a continuous stream. Consider that a flow of video grains (a key concept contained in the output of a new task force, the Joint Task Force on Networked Media[i]) is not a continuous flow, but is based on the delivery of units of data representing a video frame. The difference between a workflow designed around the delivery of files and the delivery of grains may be merely the coarseness with which the essence is divided, and the method used to persist the content.

[i]See http://www.jt-nm.org for additional information, including the JT-NM Reference Architecture (RA) v1.0.

- *Power in the browser*: For many years, content has been originated and played back as a prepackaged, complete program. Modern HTML5 browsers make it possible to render the viewing experience at the end-viewer's device. Where this will lead in the future is anyone's guess, but you can be sure that there are some young storytellers out there who will figure out how to make use of this capability.
- *Fundamental frameworks*: As we enter the next era of professional media, and as the Society continues to contribute to this transition, it is helpful to refer to the JT-NM RA v1.0, a document created by the Joint Taskforce on Networked Media (JT-NM), jointly sponsored by the SMPTE, along with the Video Services Forum (VSF), the EBU, and the Advanced Media Workflow Association (AMWA). The JT-NM has concluded that there are several fundamental frameworks in the area of professional media networks, namely, Identity; Timing; Discovery and Registration, and Connection Management.

The Society is making an active contribution to the industry's future by developing Standards that describe how to leverage existing network timing Standards to create profiles that meet the requirements of our industry.

Identity is a key concept in Internet technology, and there are very successful patterns for identity that have been used in Computer Science for some time. The JT-NM RA establishes rules and best practices which should be followed in the area of identity.

Timing in a networked environment is critical, a fact that has been well known in the computer world for quite some time. It is tempting to think that the professional media industry has unique and, perhaps, more stringent requirements for timing than any other industry, but the fact is that military, financial, and medical applications also have critical timing requirements, and that there are fielded technical solutions and Standards in this area, and they have been in place for years. The Society is making an active contribution to the industry's future by developing Standards that describe how to leverage existing network timing Standards to create profiles that meet the requirements of our industry. This effort is achieving solid results.

Discovery, Registration, and Connection Management addresses an interesting issue in professional media networks. When you connect devices using a video router, you know what is connected to which input. The router control system allows you to connect inputs to outputs. But when you connect cameras, monitors, and other devices to an IP switch, where is the control system which used to be in the video router which allows you to route a particular camera to a particular monitor? Discovery, Registration, and Connection Management resolves this issue by providing a way for devices to be discovered on a network, to register their capabilities, and to allow a control system to connect a sender to a receiver.

Readers are encouraged to download and read the RA document published by the Joint Task Force on Networked Media (www.jt-nm.org/RA-1.0/index.shtml) for additional detail on fundamental frameworks and other key concepts for professional media applications.

Capabilities and the JT-NM Layered Model

The JT-NM RA v1.0 introduces a high-level layered model, which is used to illustrate the business context within which the RA is focused. This model can be used to convey a key concept regarding the use of Internet technology for professional media. This concept has to do with the notion of Capabilities.

At a high level, any media business provides products and services by performing Operations on media using Applications (see **Fig. 2**). Consider that these Applications require specific Capabilities in any given workflow. For example, it may be that in a given workflow, the capability to move a file from one place to another is required. A modern media platform will expose many capabilities, with the ability to move a file from one place to another being one of them.

In this simple example, we have exposed some important enabling concepts. An atomic unit of capability

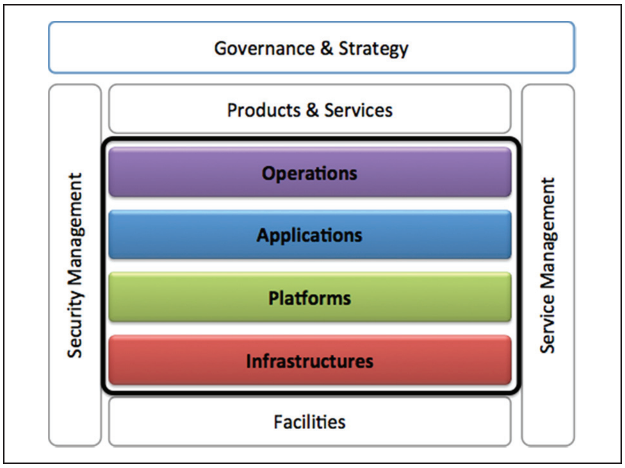

FIGURE 2. In this example, our workflow makes use of this small, atomic capability (file move), along with tens or, more likely, hundreds of other capabilities, in order to achieve its final objective. This file move capability has strong identity because it uses the Identity fundamental framework; thus, our workflow can locate and consume this capability. This is all very straightforward. But critically, once this file move capability is no longer needed in our workflow, this capability can be released back into the platform, where it can be identified and consumed in a completely unrelated workflow.

(meaning a simple, isolated function) is exposed through a platform where it can be combined with other atomic capabilities to compose a complex workflow. If the capability is required, but all of the "file move" capabilities are engaged in other workflows, virtualization allows new instances of this capability to be created on demand, rather than having extra capability preexisting in the platform which goes unused.

This may be a lot to absorb, but think about tape-based workflows. A broadcaster may have needed to have hundreds of tape machines deployed in a facility, although it was a very rare event when all of them were in use. Or consider the case where a broadcaster might have had a frame synchronizer hard-wired into a post-production room, where it was seldom used. It may have taken extraordinary patching and routing in order to make that resource available to the news room, which only occasionally required conversion of an international feed.

We are on the cusp of having facilities that can be created on demand. Capabilities are created, used, and, perhaps, paid for only when they are required. These capabilities are created as a result of demands from applications based on the workflows that are to be performed. When workflows are complete, the capabilities used in that workflow are decomposed and are available to other workflows or discarded.

This ability might seem, to you, to be way off in the future, but if you speak with any accomplished web developer using modern development and deployment environments, they will tell you that they have operations that work like this today. The challenge for the Society and for our industry at large is to make professional media a first-class citizen and to take the steps necessary to allow us to leverage Internet technology in our industry.

About the Author

Brad Gilmer is the president of Gilmer & Associates, Inc. He is a founding member of the Joint Task Force on Networked Media and executive director of the Video Services Forum and the Advanced Media Workflow Association. Gilmer is a member of SMPTE and has been an active participant within since 1984. He was the first recipient of the SMPTE Workflow Systems Medal. Gilmer was previously employed at Turner Broadcasting System in Atlanta, where he and his staff were responsible for Engineering and Operations for the Entertainment Division Worldwide.

Software-Defined Media Infrastructures

By Al Kovalick

Abstract

There are three generations of media infrastructure design patterns; analog, digital and now software-defined. This article outlines the salient aspects of software-defined networking, computing and storage. The focus is on the application of software-defined methods to support media workflows using private and public infrastructures. Considered are the fine tunings needed to use commodity hardware to achieve realtime, high quality, media transport, sync/timing and audiovisual processing. Also covered are methods to scale for workflow loading and reliability.

Keywords

Software-defined, infrastructure, media, converged systems, cloud, SDDC, web-scale, hyper-converged, SDMI, virtualization

Introduction

Technology is reshaping the world at a dizzying pace. This is no less true for the media enterprise whether large or small. Where is its infrastructure headed? How does the cloud fit in? What are the drivers of change? What could it look like in 100 years? Well, how about in five? These questions and others will be considered in this tutorial article on the fundamentals of the software-defined media infrastructure (SDMI).

Before defining and detailing the SDMI, let us start by considering ten business and technology drivers related to the data center. **Table 1** outlines each case.

Item 1 is the most impactful driver in the list. The digital economy has changed many aspects of business plan execution. Witness the same day delivery of goods, pop-up TV channels, and the so-called *gig economy*.[1] All the entries are following their own trajectory in terms of a time line to full development. Each has a value proposition, a list of benefits, and a return on investment (ROI). Most are loosely connected by item 6, the move to virtualization of resources. This is breaking the dam in terms of enabling new ways to manage, control, and utilize compute, storage, and networking assets.

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Many readers will be familiar with item 2, the move to Ethernet/IP for media systems.[2–4]

Items 3, 4, and 9 in the table are beneficial by-products of number 6, the move to software-defined infrastructures. Entries 5, 7, and 10 result from the move to Infrastructure-as-a-Service (IaaS) cloud resources, both public and private. Cloud-based service reliability can be as bulletproof as your budget will permit with all manner of duplicated resources, services, and geodiversity.

Finally, item 8 moves application execution to the cloud or dedicated on-premise servers. Users can access apps using browsers on a variety of platforms, including PC/Mac, thin clients, and tablets. The *access anywhere* paradigm is very compelling and consolidates app management and deployment. It is predicted that by 2018, 59% of the total cloud workloads will be Software-as-a-Service (SaaS) workloads, up from 41% in 2013 (Cisco Global Cloud Index 2013-2018). Also available is the Desktop-as-a-Service (DaaS, remote desktop) model to supplement any SaaS apps.

The remainder of this paper will focus on item 6 and other entries related to it. The emphasis will be on the local/campus media infrastructure, with some thoughts related to the hybrid cloud case. Also, the term "data center" in this discussion can apply to local, private, or public clouds, depending on the context.

What is Software Defined?

Software defined means different things to different people. Common themes are as follows:

- Providing "resource services" that are independent of the hardware
- Programmability of behavior
- Dynamic resource control/management

Figure 1 compares the traditional hardware-defined to the software-defined (S-D) data center. Using application programming interfaces (APIs), controllers allocate resources to match workloads. If only compute is virtualized and if networking and storage remain in hardware-based

TABLE 1. Ten trends leading to the next-generation media infrastructure.

Traditional Approaches	Next Generation
1- Slowly changing business execution processes	*Internet speed,* dynamic*,* agile, digital; more, better, faster, cheaper, data-driven
2- SDI/AES3 transport with Ethernet/IP (files)	1/2.5/5/10/25/….400G Ethernet/IP streams and files
3- Manual workflow builds	Automated /Algorithmic/Programmatic
4- Static configs	Agile, Orchestrated configs
5- Limited resources	Full resource elasticity (web-scale, cloud)
6- Traditional Data Center	Software-Defined Data Center (SDDC) (virtualized: compute, network, storage)
7- On-site infrastructure	Hybrid, geo-distributed cloud
8- Desktop installed apps	Web apps (SaaS), Virtual Desktop
9- Limited APIs	Rich product APIs, Micro-services, Service-Oriented Architecture (SOA)
10- Limited reliability methods	Reliability-to-the-budget (e.g. 5 data copies, geo-distributed storage, services)

silos, the full promise of S-D is not delivered. All resources must be API driven and software defined before S-D reaches its highest potential. According to David Floyer, cofounder and chief technology officer of Wikibon, "Software-led infrastructure is a game-changer for businesses and organizations, on the same scale as the internet was in 1995." Time will tell if this is hyperbolic speech or an accurate prediction.

Another research firm MarketsandMarkets stated, "The total SDDC market is expected to grow from $21.78 billion in 2015 to $77.18 billion in 2020, at an estimated Compound Annual Growth Rate (CAGR) of 28.8% from 2015 to 2020" (tinyurl.com/SDDC-worth). Note also that "web-scale" infrastructures (e.g., Amazon, Microsoft, Google, and Facebook) set the pace for this paradigm; thus, it is already a respected approach for data center design.

What are some of the benefits of the SDDC as applied to the media enterprise? Here are some aspects:

- Dynamically and automatically provision workflows to meet realtime user requirements
- Increase utilization of storage, compute, and networking resources; no silos
- Deliver services as needed; apps, encoding, audiovisual processing, transporting, storing, etc.
- Maintain security and compliance
- Reduce capital and operational expenses
- Scale components to meet workloads
- High availability to meet workflow needs

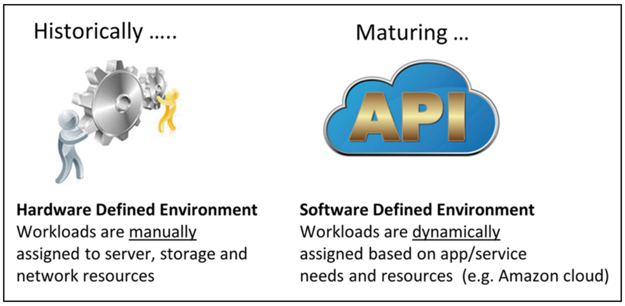

FIGURE 1. Hardware vs. software defined.

Most important is the dynamic provisioning feature. This is a hands-off approach to allocating compute and storage to meet workflow needs. This feature may include service cloning to guarantee availability in the event of a component failure. Of course, not all workflow provisioning can or should be automatic but much can.

Figure 2 shows one view of the evolution of the data center. Note that each of the "big 3" resources—computing, networking, and storage (C, N, and S)—are software defined. Let us call these methods SDC, SDN, and SDS, respectively. Each has disparate methods to implement their S-D functionality. The rollout started with SDC, followed by SDN, and lately SDS. There is no coordinated effort here but rather industry forces acting toward the same end.

For compute, this includes virtual machines or hypervisors (e.g., KVM, Hyper-V, ESXi, and XEN). These effectively enable the server hardware to be shared by many users/services securely and invisibly. Another way to share compute resources and create independent servers is by using software-based *containers.*[9] One major advantage of using containers and hypervisors is the ability to migrate workflows to other systems (local or remote) while in operation. Many servers offer CPU cores with a graphics

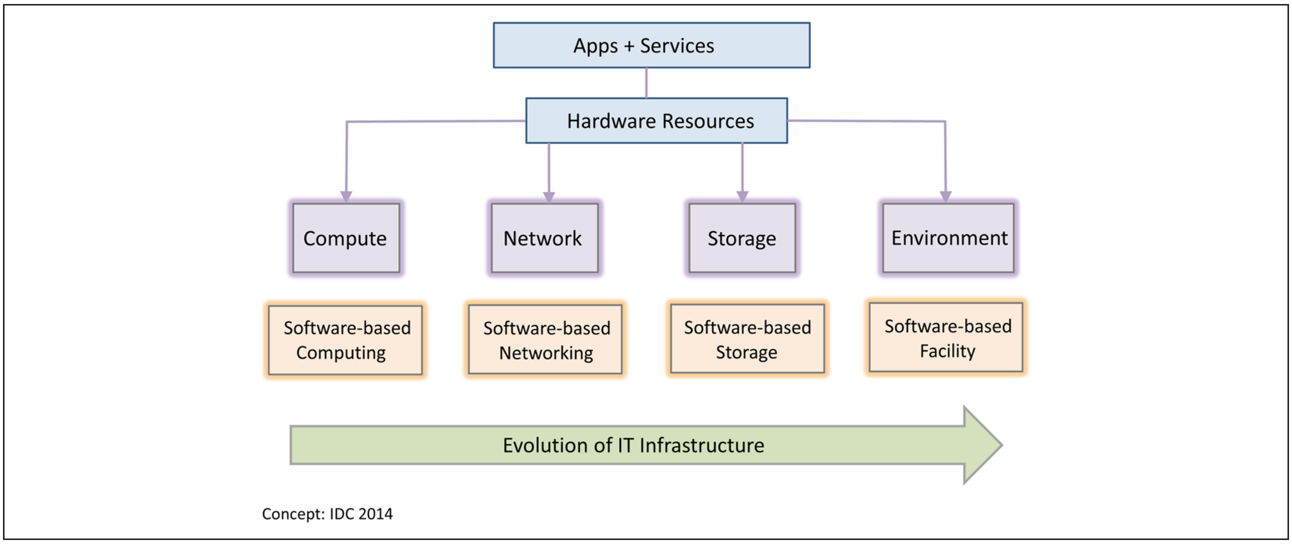

FIGURE 2. A high-level view of the evolving SDDC.

processing unit (GPU) for the most demanding video processing needs.

For networking, SDN includes router and switch control protocols, such as OpenFlow (opennetworking.org), or vendor-specific APIs. Also for networks, there are controllers from OpenDaylight (opendaylight.org), Floodlight (projectfloodlight.org), and several others. Note that networks may or not be virtualized and can still use software-defined techniques (en.wikipedia.org/wiki/Network_virtualization).

Finally, SDS is a concept for managing policy-based read/write (R/W) provisioning and management of storage resources independent of the primary hardware. SDS often uses storage virtualization techniques to separate the actual storage hardware from a virtual view of it. The "Server SAN" concept is fundamental to SDS. Each storage node has direct attached storage (DAS), and these are networked in a cluster to create a scale-out storage system. Examples of this include Ceph (ceph.com) as often used in OpenStack and ScaleIO (en.wikipedia.org/wiki/EMC_ScaleIO).

Together, SDC, SDN, and SDS comprise the fullest realization of the SDDC. Of course, associated management tools are required. Notably, if only one or two of these techniques are used, some benefits are still accrued. Leveraging S-D is not an all-or-nothing proposition. Is the SDDC the same as a private cloud? It can be. However, a private cloud is a service, as compared to a technical architecture such as the SDDC.

If you are involved in media facility design or operations, all this may seem a bit distant from your current system architecture. You may have questions such as — Is the SDDC actually being used today for media? Will it perform as well as my current media infrastructure? What migration strategies should I use to get there? Let us delve into these questions and more.

Moving Toward the SDMI

The SDDC is the future of the on-premise data center and, of course, for all private/public clouds. Presentations delivered at the SMPTE Annual Technical Conference and related papers in the *Motion Imaging Journal* point toward this eventuality.[5–7] Disney and other broadcasters are already using a private cloud infrastructure to deploy traditional linear TV channels.[8] Disney has not disclosed to what extent their cloud is fully S-D, but it could be fully S-D or a hybrid. Think of the SDMI as a more focused SDDC for media workflows. What does this mean?

Broadcast, venue events, and post media workflows require special tunings of the infrastructure when using "generic IT" (including SDDC). Below are some of the considerations for media:

- Realtime media transport. The SMPTE Technical Committee 32NF is currently working on for "single essence streaming" over IP to replace (or augment) SDI/AES3 flows.[2,3] The existing SMPTE standard ST2022-6 (multi-essence streaming) currently supports the SDI payload over IP.
- Deterministic, loss free, low latency, media transport over Ethernet/IP. SMPTE, other industry bodies, and vendors are outlining best practices for these requirements.
- Point-to-multipoint video streaming (1 to N) distribution in a facility or truck.
- Support for video frame-accurate switching. There are several proven methods available to accomplish this.
- Support of massive data rates for video processing, editing, and transport for certain uncompressed video formats.
- Ability to support scheduled "channel playout" functionality.
- Ability to support realtime media processing such as studio live production and graphics creation and overlay.
- Ability to support Precision Time Protocol (PTP, IEEE 1588v2) for conveying time and sync information.

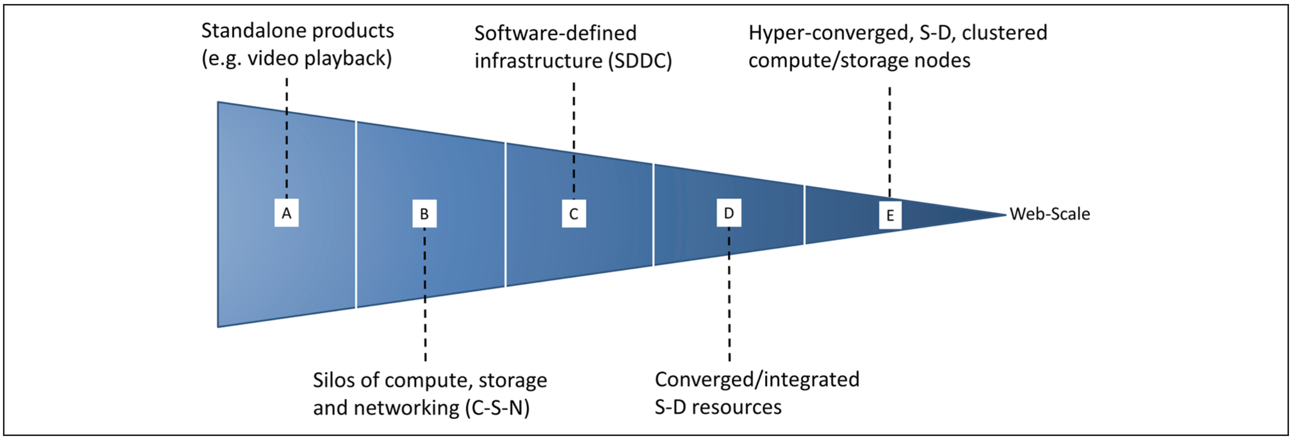

FIGURE 3. The path to a web-scale infrastructure.

Not all media workflows or nodes will need this, but some will.

- Other media-specific operations.

Therefore, for this discussion, an SDMI is an SDDC with support for most of the items in the list earlier. However, if all the supported workflows are file-based only, then most of the transport, timing, and sync aspects can be relaxed. On the other hand, if workflows support live production with many realtime streams, then timing, sync, and low latency will apply. A hybrid combo is also possible, with some nodes supporting realtime streams and others file-based workflow focused. Also, the SDMI does not need to be a standalone system but may coexist with any current media infrastructure, IT-based or not. More on this, as follows.

Figure 3 shows a hypothetical facility migration path progressing from traditional stand-alone media products (A) to a world in which all resources and services run on a "web-scale" infrastructure (E). Each step toward the right includes more integration, umbrella management, automation, and scalability. Most private cloud infrastructures could be based on C, D, or E. Many, if not all, public scale clouds fall into domain E. Domain C may be fully S-D or for only some features. For example, a system using compute virtualization and S-D storage does not necessarily require that the supporting network be SDN-based, but it may.

Today, there are media facilities (e.g., rack, campus, venue trucks, and boutiques) utilizing each of these methods. Most are still in the A only or A and B regions. Netflix is firmly planted in E, while many call-letter TV stations are only in A. D uses software-defined methods but in a converged infrastructure. E is the domain of the hyper-converged infrastructure (see sidebar). E is often called a "web-scale" architecture. To be clear, web scale can mean anything from a few to thousands of nodes in a cluster. At the high end, this is similar in concept to Facebook's or say Amazon's cloud. Thus, a small facility can have a web-scale infrastructure in principle but at the very low end of the scale range. The same principles of convergence and API control apply at any scale.

Media product vendors need to test their software products under compute virtualization and containers. Gone are the days when a vendor specifies exactly what server model to run their software. Many, not all, NAB/IBC vendors understand the need to be agnostic about platform and embrace "cloud-native" thinking. Make sure you ask vendors for tested-in-the-cloud product support. Importantly, the selections in **Fig. 3** are standards independent of actual scale. Domain A can be small (one camera, one monitor) or very large. Likewise, domain E can start as a few node clusters supporting just one application. Scale is a separate dimension that can be applied to any of the five domains. Domain E offers the best scale range.

Figure 4 shows the basis of a hyperconverged cluster. The basic unit of replication is the node with virtualized compute and DAS. A single node is nothing special.

Converged and Hyperconverged: How are they different?—A converged infrastructure combines computing hardware, SAN block storage, and networking together under one integrated management system, or "one pane of glass," while keeping the device's identities separate. Hyper-convergence goes a step further and combines the storage and compute "as one node" and no traditional SAN is necessary. When nodes are clustered together, this is called a hyper-converged infrastructure. Both methods are superior to traditional silo-based data center designs.

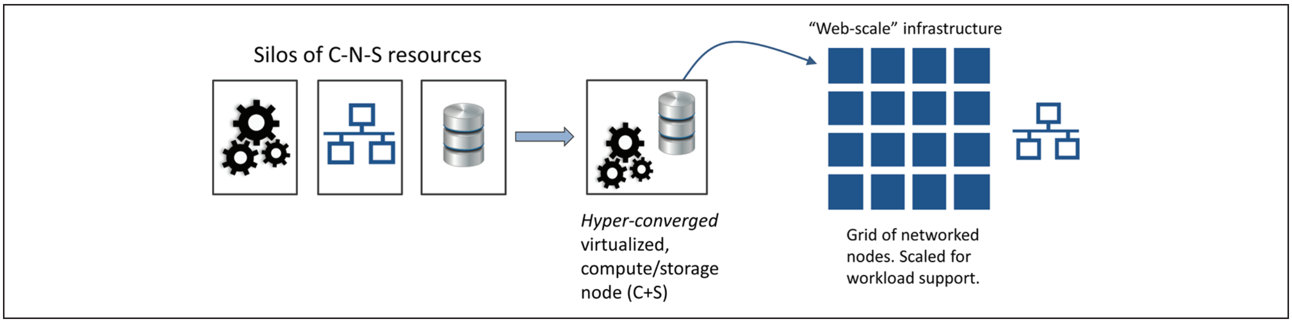

FIGURE 4. Migrating to a hyperconverged, web-scale architecture.

However, when the device is configured in a networked connected cluster of nodes, with distributed storage software, then the whole is greater than the sum of its parts. It is a collaborative pool of resources.

This is a key point; this concept enables any node to act as storage alone, compute alone, or both, depending on the needs of the installed applications. Therefore, a node can be capacity focused, performance focused (flash memory option), or a policy-based mix. A given file or data object is stored (redundant copies too) across all nodes and can be accessed by any node. This divide-and-conquer approach provides high reliability in the event of a nodal failure and a remarkable data rate throughput—ideal for media workflows.

The number of clustered nodes (16 shown in the figure) of compute/storage should match the aggregate workloads' requirements plus some headroom. There are many moving parts with, for example, *K* different installed media workloads, each with *N* processes, and each requiring compute and storage resources. Thus, some effort is required to master selecting the number of nodes to support the workloads. Start small, learn, and grow. This method is a very flexible way to build an infrastructure to meet the needs of all workflows. Need more resources? Add more nodes to a working system.

Nodes can be based on the OpenStack software solution (open source) supporting hyperconvergence. OpenStack optionally integrates with Ceph or ScaleIO SDS techniques outlined earlier. See also examples from Nutanix (nutanix.com) and SimpliVity (simplivity.com) to learn more about hyper-converged nodes and clustering.

Hybrid SDMI and Legacy in Harmony

The discussion on SDMI is a forward-looking view. There is a distance to travel from today's legacy media infrastructures to a full SDMI. There are vast differences in workflow needs among media enterprises, venue production trucks, and boutique systems that will affect where, why, and when SDMI makes sense. The main point is that the SDDC and SDMI are part of our collective future. SDMI is a work in progress. It is being used today for file-based workflows and, in a few cases, for streaming-based workflows. It is worth noting that public cloud vendors are offering S-D today, but with only meager support for realtime streaming, timing, sync, and other aspects that may be important for workflows. That said, there are ways to coerce a non-media-friendly infrastructure to implement streaming workflows but with tradeoffs in increased processing latency and frame buffering.

Here are some configurations using the SDMI/SDDC:

- Standalone SDMI, small or large file-based workflows
- Software defined as offered by public and private cloud providers
- Combination of SDMI with legacy media system and/or public or private clouds
- Full SDMI media enterprise; files/live. This is not mature in 2016.

Figure 5 is an example of a hybrid system with a mix of SDMI and a legacy media system. Both are situated locally but could be geographically distributed. The SDMI portion could be considered as a private cloud, depending on its usage model. The sizing of the respective domains depends on need. For example, the legacy portion could be 95% of the system and the SDMI at 5%, or size reversed. One of the hallmarks of hybrid systems is the bridging between legacy SDI/AES3 (including compressed) streams and Ethernet/IP streams. These bridges will exist for many years to come. Some realtime video workflows (compressed and uncompressed; UHD, 4K, 8K rasters) with compute heavy operations may require more performance than a commodity compute platform can provide. Nonetheless SDMI will take the share that makes economic, platform and workflow sense.

Another property of modern IT systems is the reliance on the services model. First, the entire S-D concept is based on powerful APIs to provision and control the pieces of an SDDC. Second, media software vendors often provide APIs to manage provision and control their products. One example of an API collection designed for media workflows is the Framework for Interoperable Media Services (FIMSTV) sponsored by the Advanced Media Workflow Association (amwa.tv) and

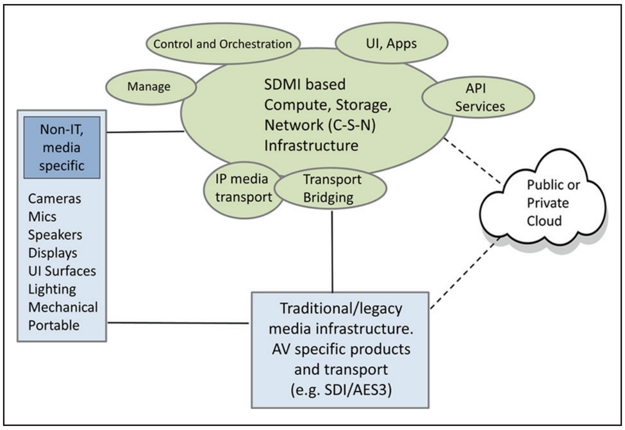

FIGURE 5. A hybrid SDMI and traditional media system.

the European Broadcasting Union (EBU). FIMS is based on service-oriented architecture (SOA) principles. A related concept is microservices, a software architecture style in which complex functions are composed of small services. Some software architects call this style "fine-grained SOA." For a comparison with SOA, see tinyurl.com/SOAMS2.

An important new area to watch is the "cloud software store." One interesting example is the Amazon Marketplace. This is like a mobile app store but for cloud code, products and SaaS apps. Amazon Machine Images (AMIs) are available for rent by the hour and optimized for the cloud. Users can test drive products before making long term commitments and then only pay for what they need. AMIs are available by industry, software vendor, and specific regions. Some forward thinking media vendors currently offer products in the Marketplace and expect many more do so.

Final Words

The software-defined infrastructure is drawing a metaphorical line in the sand. Its principles are forging a path toward web-scale infrastructure for media designs both large and small. By 2017, web-scale IT will be an architectural approach operating in 50% of global enterprises, up from less than 10% in 2013, according to Gartner, Inc.[10] The SDMI will mature over time and gain more design wins. It will coexist with traditional media systems for many years. What to do now? Set your sails in the direction of software-defined systems, toward a future in which business requirements leverage a media infrastructure with agility and scale.

Acknowledgments

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About the Author

Al Kovalick has worked in the field of media infrastructure and file-based workflows for the past 25 years. Previously, he was a digital systems designer and technical strategist for Hewlett-Packard (HP). While at HP, he was the principal architect of HP's first video-on-demand server. Following HP, from 1999 to 2004, he was the chief technology officer at Pinnacle Systems. More recently, Kovalick served at Avid Technology as a strategist and Avid Fellow. In 2012, he founded Media Systems Consulting in Silicon Valley, specializing in media infrastructure and related technologies. Kovalick is an active speaker, educator, and author. He has presented more than 50 papers at industry conferences worldwide. He holds 13 U.S. patents. He is the author of the book *Video Systems in an IT Environment* (2009, 2nd ed.). Kovalick has a BSEE degree from San Jose State University and an MSEE degree from the University of California at Berkeley. He is a SMPTE Fellow, a Director of Education, a recipient of the SMPTE David Sarnoff Medal, and a member of the Tau Beta Pi Engineering Honor Society.

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Displays: From Fantasy to Reality in a Century

By Peter H. Putman

Abstract

Although the Society's formal involvement with television didn't begin until 1950, it has kept pace with all of the advancements in display technology since then; from the earliest days of color television to the SMPTE-170M standards for CRT monitors in the 1980s, the advent of digital television and flat screen displays in the 1990s, and the 21st-century generation of Ultra HDTV displays with high dynamic range and wide color gamut capabilities.

Keywords

Cathode-ray tube (CRT), Digital Light Processing (DLP), Liquid-crystal display (LCD), Organic light-emitting diode (OLED), Ultra high definition television (UHDTV)

Introduction

We live in an age of go-anywhere, do-anything mobile electronics, a world with display screens built into everything from phones and tablets to major appliances, a time when televisions (TVs) have become ubiquitous commodities. However, it is useful to remember that the "T" in SMPTE was not always there.

The focus of the Society of Motion Picture Engineers (SMPE) at its inception in 1916 was exclusively and rightly focused on the art and science of projected film, and it continued that way for 34 years. "Going to the movies" was the only way to view large-screen entertainment for millions of Americans, an experience that was enhanced with the introduction of synchronized sound in the late 1920s and color in the 1930s.

In 1916, the concept of TV was still very abstract and futuristic, and regular radio broadcasts were still a few years in the future. However, only one decade later, the research and development of low-resolution monochromatic TV displays by Philo Farnsworth, Vladimir Zworkyin, and John Logie Baird elevated the concept of electronic moving pictures, synchronized to sound, from fantasy to reality.

In 1916, the concept of TV was still very abstract and futuristic, and regular radio broadcasts were still a few years in the future.

By the mid-1930s, manufacturers were already showing TV receivers for home use. Many used mirrors with vertically mounted cathode ray tubes (CRTs), and there were several demonstrations of projection TV, using CRTs to light up screens that measured as large as 3 ft. in width.

Still, for the vast majority of people, TV remained an expensive curiosity. Some research and testing was done on the delivery of color TV images, but further development and acceptance was delayed by World War II. For the average person, color was something you saw only in movie theaters.

The Landscape Changes

Consumer acceptance of TV grew rapidly after the war, and in 1950, the Society recognized it needed greater involvement in the science of capturing and displaying TV images. Hence, it changed its name to the Society of Motion Picture and Television Engineers and embraced this new communications medium—and the timing could not have been better: Nearly six million TV receivers were already in U.S. homes at that point, and studios worried that "TV" would eventually kill off movie theaters.

The advancements began rolling out. A practical technique for transmitting and viewing color TV images had already been developed by CBS Laboratories in 1940 using a synchronized color wheel at the receiver, and although it eventually lost out to the color subcarrier process developed by the Radio Corporation of America (RCA), we still use color wheels today in small projectors equipped with digital micromirror devices developed by Texas Instruments (**Figs. 1–2**).

In 1953, the National Television System Committee (NTSC) adopted a standard for color TV broadcasts and reception, using the RCA color subcarrier system that would be backward-compatible with the existing NTSC black-and-white broadcast TV format already in use. A gamut of colors was defined for TV receivers that, until recently, was the largest ever specified for electronic displays.

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FIGURE 1. This July 1945 edition of Radio News described a color TV scanning system using a spinning, synchronized color wheel.

Unfortunately, the ability of color CRTs to reproduce all of those colors and maintain a sufficient level of brightness fell short. The first RCA color TV sets could reproduce the NTSC gamut—modeled after the colors in movie prints—but only at low brightness levels.

To achieve higher brightness, TV manufacturers used phosphors that did not produce colors quite as saturated. Combined with the fussiness of hue controls on consumer TVs and video monitors, the resulting colors were more often than not inaccurate—but that did not matter to the vast majority of TV viewers at home, who still viewed TV on monochrome displays. (Only 3% of all homes had a color TV by the end of 1964.)

Over time, the CRTs in home TVs grew in size. Some early TV sets had small screen sizes, although you could buy 21 in. console models from the likes of GE, Bendix, Philco, and RCA for as low as \$180; about \$1500 in today's dollars (**Figs. 3** and **4**). (And they even came with a separate phono jack for your record player!)

And Away We Go (In Color!)

That all began to change in 1965, with the NBC TV network announcing a full slate of color programs. They were followed quickly by rival networks ABC and CBS, with the last black-and-white daytime TV program airing in 1967. The abundance of color programming led to increased demand for color TVs, and market penetration finally hit 50% in 1972—two years after the first practical liquid crystal displays (LCDs) appeared in calculators made by Casio and Sharp.

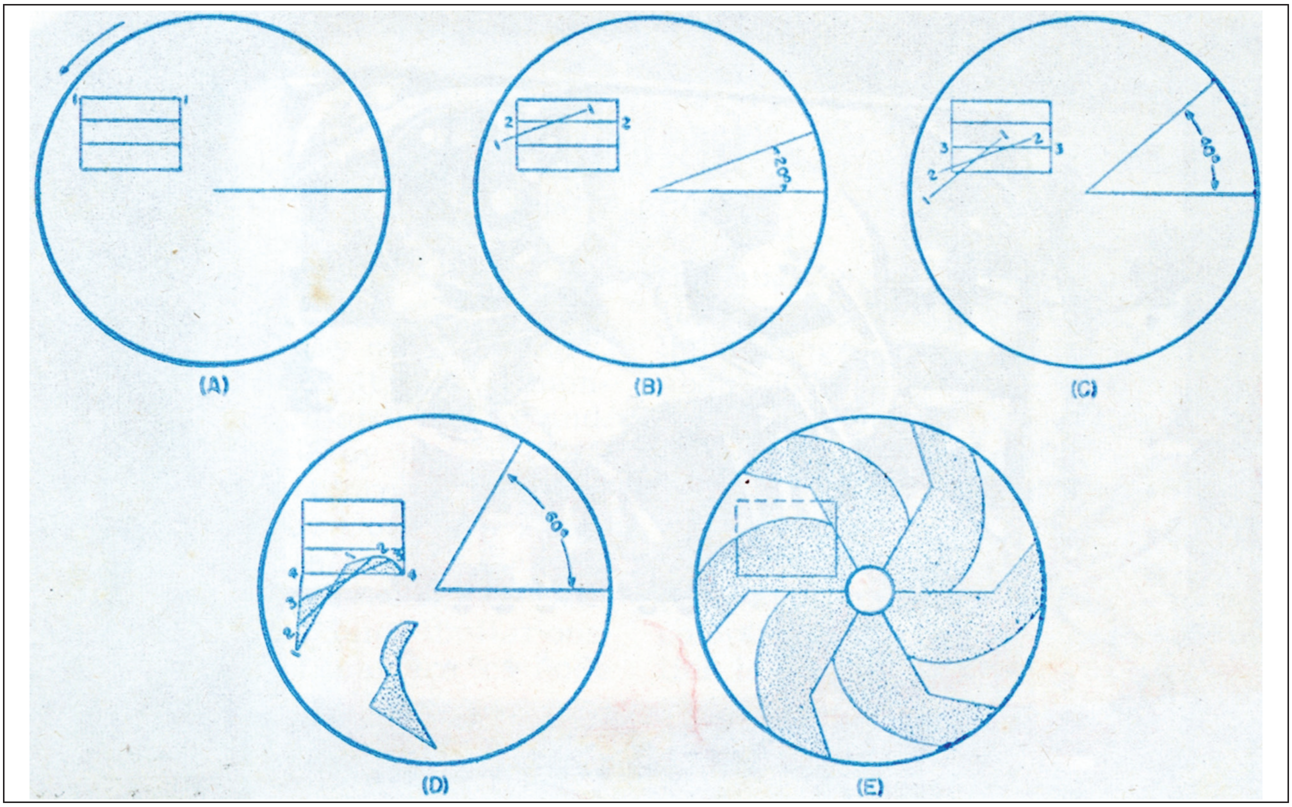

FIGURE 2. A description of the scanning color wheel technique proposed by CBS in 1945.

FIGURE 3. This advertisement for an RCA 17-inch black-and-white television ran in a 1953 issue of *Life* magazine. ($179.95 would be $1,624.98 in 2016 dollars.)

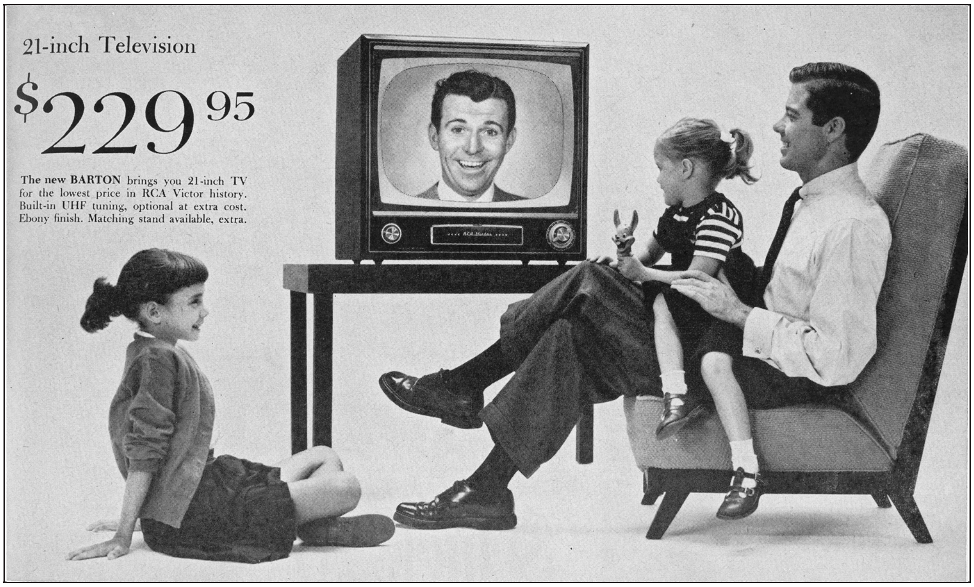

FIGURE 4. This advertisement for an RCA 21-inch black-and-white television ran in a 1953 issue of *Life* magazine. 21 inches was a very large screen size at the time, and the $229.95 price works out to $2,076 in today's dollars.

Color TV sales continued to climb in the 1970s as black-and-white set production was phased out. Picture tubes grew in size and color reproduction improved, thanks to more stable solid-state circuitry and improved filtering. Moreover, the first projection TVs for home and commercial use started to appear, characterized by high-gain screens and narrow viewing angles.

In the late 1960s, Conrac Corp. and RCA tried to get a handle on accurate color reproduction in professional CRT monitors by defining a set of color coordinates for red, green, and blue phosphors that resulted in a much smaller color gamut than the 1953 NTSC standard.

However, this color gamut was much easier to reproduce consistently across a broad range of monitors, and the Conrac/RCA coordinates for red, green, blue, and reference white were incorporated into the SMPTE 170M standard in 1987. We have come to know them over the years as SMPTE "C" phosphors.

Now, It Gets Interesting

New contenders for next-generation displays were emerging. While CRT displays continued to dominate the world of direct-view and projection monitors into the 1990s, the final act for CRTs was already being written with the maturation of plasma displays, the emergence of liquid crystal imaging for large panels and for portable video projectors, and the development of digital TV.

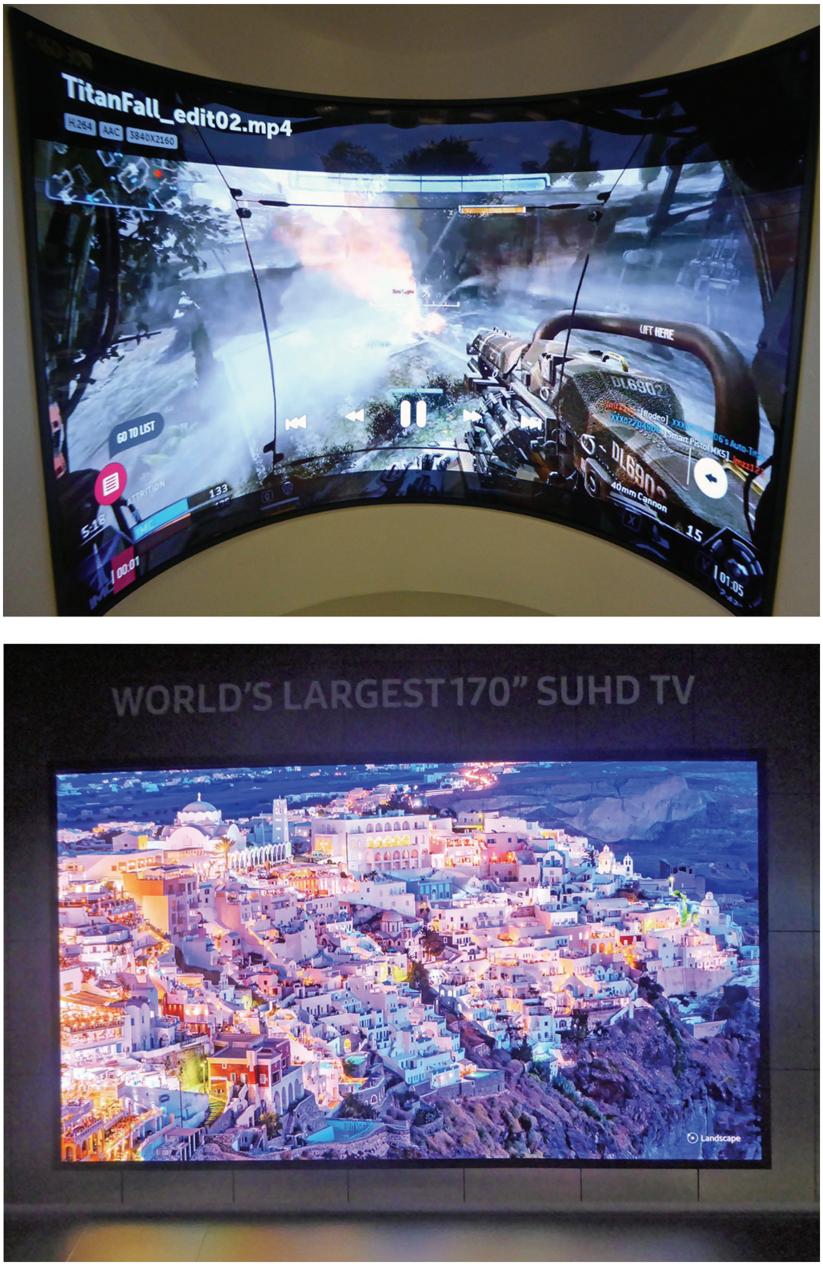

FIGURE 5. We've come a long way since the first color television sets! Top: LG's 65-inch curved OLED Ultra HDTV. Bottom: Samsung's 170-inch HDR Ultra HDTV.

In 1964, two professors at the University of Illinois—while having dinner—came up with the idea of sealing a noble gas mixture between two microscope plates and discharging a high voltage through the mixture. The result was the world's first single-pixel plasma display.

Within a few years, that science experiment had evolved into a room full of equipment to create a 150-pixel color plasma display. By the 1980s, the first practical monochrome plasma displays for computers had come to the market, although they were very costly and required a lot of power to operate.

In 1993, Fujitsu and Hitachi introduced big-screen plasma displays with high-resolution pixel counts and a wider aspect ratio than the usual 4:3 format used for TVs and computer monitors. The latter products had moved from simple dot-matrix displays to full-color imaging with the development of the Video Graphics Array (VGA) and eXtended Graphics Array (XGA) standards in the 1980s. Moreover, for the first time, our attention began shifting from "lines of resolution" to "pixel counts" when we talked about imaging resolution in displays.

Another new imaging technology—the LCD—was getting ready to grab the spotlight. Companies such as Sharp, Samsung, and LG were hard at work to boost manufacturing yields and bring LCD TVs to the masses. Ironically, the basic principle of liquid crystal light-shuttering—birefringence—had already been observed in nature in the 1880s!

The convergence of four technology trends in the 1990s—digital video, fixed-pixel displays, high-definition video, and wider aspect ratios—created unprecedented disruption not only to the way we capture and view TV images but, ultimately, to cinema projection as well.

The start of digital TV broadcasts in 1997 prompted some manufacturers to introduce even larger and wider CRT monitors and TVs, with RCA's 38 in. and Mitsubishi's 40 in. offerings standing out. Even so, CRTs were reaching the practical limits of their image resolving capacity, ceding ground each year to plasma monitors.

Along the way, digital video production had come into play, accompanied by a new color gamut (ITU Recommendation BT.601) for digital composite video, a gamut that closely followed that of the older SMPTE-C coordinates. The launch of digital broadcasting resulted in yet another gamut—ITU Recommendation BT.709—as video followed the lead of computer graphics cards and moved away from a composite signal with subcarrier to a component signal with discrete luminance and color difference channels.

At this point, the nexus of TV manufacturing—which had shifted from the U.S. to Japan in the 1980s—was on the move again; this time, it was from Japan to Korea. And the shift away from labor-intensive CRT display manufacturing to large-scale "fabbing" of plasma display panels, and later of LCD panels, rewrote the book on TV sales.

Prices began to fall rapidly as pixel counts and screen sizes increased. By the turn of the 21st century, a 50 in. "reference" quality plasma cost as much as $20,000. Five years later, that same product had dropped to $5,000. The widespread adoption of high-definition (HD) formats for broadcasts and cable TV by 2005 further stimulated sales of HDTVs.

Tempus fugit! By 2005, LCD TVs and monitors had started undercutting both plasma TV pricing and market share. Unlike plasma, LCD panels could be economically manufactured in just about any size with high resolution. They also had the advantage of presenting substantially brighter (although not necessarily color-accurate) images with lower power consumption.

The proliferation of lower-cost flat-screen, fixed-pixel displays led to their adoption for use in editing, color grading, and other reference monitor functions. And this trend led to SMPTE's involvement in studying and making recommendations for this new crop of monitors to be used in critical viewing applications.

Stepping on the Gas

Although advances in display technology from 1990 to 2010 dwarf what happened in the 94 years since SMPE was born, they take a back seat to what has transpired since 2010. At that point, plasma display technology was on its way to extinction, and LCD imaging had clearly won the technology war. Two major Japanese manufacturers had dropped out of the TV business completely, with three more to follow.

We also heard the first rumblings about ultra-high-definition (UHD) imaging and displays with pixel resolutions of 3840 × 2160 and 4096 × 2160. Sure enough, they materialized in 2012 as behemoth 84 in. LCD monitors costing $20,000 and more. However, economies of scale and a new shift of TV manufacturing away from Korea and Japan to China have resulted just four years later in Ultra HDTVs as large as 98 in. and as small as 42 in.

As this is being written, it is possible to buy a 55 in. Ultra HDTV with "smart" internet connectivity for as low as $500. Manufacturers are cutting back on inventories of Full HD (1920 × 1080) TVs in favor of Ultra HD models. Add in two exciting developments—high dynamic range and wide color gamut—and you have a new TV system that is as far removed from our 1970s NTSC color TV system as Pluto is from the sun!

And it will not stop there. There are now 5K (5120 × 2880) computer monitors for sale, and eight different manufacturers showed 8K (7680 × 4320) TVs at the 2016 International Consumer Electronics Show—some as large as 120 in. Lower fabrication costs have even resulted in super-wide, panoramic LCD monitors for computers and curved screens for immersive TV viewing (**Fig. 5**).

As usual, SMPTE will be in the thick of things, having already convened study groups to make recommendations and set standards for the formatting and delivery of high dynamic range content, along with specifications for faster signal transports to carry UHD (and beyond) video to next-generation displays—whatever their size, shape, and pixel counts turn out to be.

About the Author

Peter H. Putman is the president of Roam Consulting L.L.C. He is a contributing editor for Sound and Communications magazine and publishes HDTVexpert.com, a web blog focused on high-definition television, digital media, and wireless and display technologies. Putman holds a BA degree in communications from Seton Hall University and an MS degree in television and film from Syracuse University. He is a Senior Academy instructor for the InfoComm International and was named ICIA's Educator of the Year for 2008. He is a SMPTE member and education director, and holds industry certifications from ICIA (Certified Technology Specialist) and the Imaging Science Foundation (ISF).

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Temporal Engineering: Archiving and Preservation

By James Snyder

The heart of archiving and preservation assures that humanity's cultural record will survive beyond the current generations. As engineers and technicians, we deal with technical and economic challenges every day. This challenge is different: It is engineering to survive time itself. Our additional task is now temporal engineering, and in addition to our other tasks, we must learn to be temporal engineers. SMPTE is there, as it has been for 100 years. We and 100 years of our predecessors have much to be proud of, but we must temper ourselves in the knowledge that there is still much to do.

To know our society today is to see its records in as complete a form as possible.

Preserving our cultural heritage consists of two basic principles: do no harm and preserve as much as possible. At times, the principles contradict because they both require resources in a world without infinite resources. Part of our challenge is making the tool kits and skill sets as widespread, easy to learn, easy to use, and consistent worldwide as practical. The tool kits are defined by well-documented international standards: As long as the written record of how a recording was made exists, that recording has a chance at replay and survival.

At the Library of Congress, one of the first principles we learn is the lesson of the Library of Alexandria in ancient Egypt. It held the collected knowledge of the ancient world that surrounded the Mediterranean Sea and beyond. Created by Ptolemy I of Egypt in the 3rd century BCE, it lasted until it was burned down during the Roman conquest of Egypt in 30 AD. Many ancient writers reference the Library, giving us tantalizing clues as to the knowledge and cultural artifacts it held. The object lesson for those who preserve is that we must **always** assume that a collection is in danger and create ways of ensuring its survival.

We have a modern analog to that today: There are many works that are reflections of our times, both positive and negative. To know our society today is to see its records in as complete a form as possible. To accomplish that goal, we must plan for the physical degradation of time, as well as fire, sabotage, neglect, and even societal upheaval. Those creating audiovisual works today may not realize that what they are doing is important or will last, but neither did early film makers, radio and audio recording artists, or early television artists. How many of us today have said, at least once in our lives, "I wish I could watch/listen to <fill in the name of a missing work here>." The people who created that work probably did not think it important in most cases, or they only realized years later, possibly after it was too late. Assuming our work is not important is to miss the point of history: It is up to future generations to decide and not us. Let us not self-edit for them.

"Do no harm" means that we preserve the original work in its original form, or the digital equivalent, whenever possible. In the analog era, SMPTE set standards for motion picture film visual and aural records that preserved as much of the original information as was practical. As sound and visual recording on film improved, projection standards from SMPTE set the standard for viewing. SMPTE analog television standards created the highest quality analog video recording that could be achieved with its Type-C videotape format and SMPTE C definitions for cathode ray tube phosphors.

In the digital era, "do no harm" means using recording methods that do not throw away any of the original information. From the beginning in the 1970s, SMPTE has led the way to achieving the goal by setting digital standards that can capture everything that recordings from the analog era captured. The SMPTE 259M serial digital interface and the D1, D2, D3, D5, D6, and D7 digital videotape recording standards helped set the stage for the high definition (HD) and, now, the 4K/8K era and beyond. With its digital cinema work on high dynamic range and wide color gamut, SMPTE is at the forefront in creating new standards that expand recording beyond

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what the human eye can see and the human ear can hear. SMPTE has led the way to file-based content creation through the suite of Material eXchange Format (MXF) standards that are still evolving today.

The most important piece of this preservation puzzle is metadata. Metadata are data about the essence. They are the digital equivalent of the label on and paper lists inside a tape case or film canister. Many think of them as simple technical or descriptive data that enable production and distribution systems to do their work, but they are so much more. They are the descriptions that tell us what a production is about, who worked on it, what the intellectual property rights are, whose works were used within it, and everything that makes a work searchable and usable once the folks who produced it have released their work into the world. Metadata standards are still a work in progress and involve SMPTE and many other groups in distribution, consumption, and, finally, long-term archiving for future generations to see long after our generation has departed this earth. We are in a marathon race in which the goal is survival over time, and we have to hand over the best, well-documented baton to our successors, the next set of runners. That is temporal engineering.

"Preserve as much as possible" means we must save as much of the cultural record as our resources permit. It is the greater of the two challenges since, at this point in time, economics require lossy compression at many points in capture, production, distribution, and consumption.

SMPTE is there as well, leading the way with the Archive eXchange Format (AXF) standard for how data sets are organized, stored, and transmitted. In cooperation with other industry groups, SMPTE's efforts at metadata creation, storage, and carriage through production and distribution chains are doing the work that must be done to describe, search, and use the works of today in the future.

In motion pictures, in which 130 years of motion picture film has been substantially replaced by electronic capture, editing, and distribution, SMPTE is leading the effort to create the film reel of the future: The Interoperable Master Format MXF standards, Digital Cinema Packages, and Academy Color Encoding System implementations will be the "film reels sitting on shelves" of this generation, but there is still much to do: we must preserve the actual film still on shelves as long as it can physically last. However, as it too starts to decay beyond usability, we must make sure the storage technologies of the future will be there to carry on those images and sounds. That is temporal engineering: creating the data standards to write to future storage systems and making sure the media they are written on last for as long as possible at the most affordable price.

In the end, many times what survives into the future are only those works that can be paid for. The works that people or organizations cannot afford to pay to preserve are self-edited out of history. The loss of most of our silent films worldwide is a testament to that reality: the 2013 Library of Congress report, "The Survival of American Silent Feature Films: 1912–1929," documented that 70% of silent films no longer exist. Lost to history, never to be seen again. Another "Library of Alexandria fire."

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We are at a major turning point in the creation of mankind's cultural records. Physical recording has shown its limitations. Although progress has been made in defeating that ultimate destroyer—time, we must accept that no one solution lasts forever. It is our job to make the copies we create today last as long as we can and that the information our successors need to make the next copy is there when they need it. That is also temporal engineering.

Temporal engineering is also purely and simply a materials sciences challenge. It is creating systems that store our audiovisual records for long periods of time at an affordable price. It means thinking outside the five- to ten-year window we have all learned in our careers. It means accepting that data sets are the focus, not just the storage systems that hold them. It means designing data storage in which the data themselves are designed to survive regardless of the storage systems they sit on over time.

The Society of Motion Picture Engineers (SMPE) was created 100 years ago to allow the interchange of film materials and then, later, to standardize how sound, projection, and the production processes worked. When electronic imaging came along in the 1940s, we added "Television" to our name. Data are now our warp and woof. Making sure they live longer than us is now our mission.

1912 saw a key change in the history of intellectual property: the Townsend Amendment to the U.S. Copyright Act. Until 1912, motion pictures could not be copyrighted because only works printed on paper could be registered for copyright. Prior to 1912, some enterprising people at Edison and other studios began printing their movies on to 35 mm strips of photographic paper to register them for copyright. This is the Paper Print Collection of the Library of Congress, which contains 3300 works, many of which no longer exist in their original motion picture film form. The 1912 Townsend Amendment meant motion pictures now had copyright protection, allowing companies to make their investments in production pay off much more easily.

By 1916, the motion picture was embroiled in a strangling intellectual property–based engineering and legal battle. The Motion Picture Patents Company (MPPC), a successor to the Edison patents licensing system, held a stranglehold on the patents that created motion pictures. The patents on equipment, sprocket holes, and film stocks were almost entirely held by an organization that is meant to prevent anyone from creating or showing motion pictures without paying ongoing fees to the MPPC. As one might imagine, it stifled the spread of motion pictures as an entertainment medium. SMPE was founded to create well-documented international standards that everyone could use without paying an ongoing license fee. It revolutionized the industry.

A key aspect to the long-term survival of any creative work is how it is instantiated: What physical form does it take? The best way to ensure long-term survivability of any work is to create it, or at least save it, in a form that is well-documented and uses technologies that are well-documented throughout the world. That is exactly where SMPTE now plays a key role. We, the members and participants of SMPTE, now wear the mantle Charles Francis Jenkins and the founders of SMPTE created for us 100 years ago. It is up to us to wear that mantle well, make it better, and set the stage for handing our baton over to the next generation. Let us do our best at this interesting endeavor.

We, the members and participants of SMPTE, now wear the mantle Charles Francis Jenkins and the founders of SMPTE created for us 100 years ago.

About the Author

James Snyder is an Emmy Award–winning digital media engineering, data and media archiving, preservation, and production and project management specialist. His 36 years of experience includes television, film, radio, internet, and data technologies from traditional analog to cutting-edge digital audio, video, and data technologies. His career includes the commercial, noncommercial, and government sectors. He was awarded a 2007 Technology Emmy for his work on the Advanced Television Systems Committee (ATSC) digital television standard. Snyder serves as the senior systems administrator for the Library of Congress' National Audio-Visual Conservation Center on the Packard Campus for Audio Visual Conservation in Culpeper, Virginia (http://www.loc.gov/avconservation/packard/). His responsibilities include all audio, video, and film preservation and digitization technologies, including long-term planning and implementation, long-term data preservation planning and implementation, technology services to the U.S. Congress and organizations on Capitol Hill, as well as standards participation and technology liaison with media content producers worldwide. He has worked for many organizations in media, entertainment, engineering, and communications, including MCI, Verizon, Intelsat, PBS, the ABC Radio and Television networks, Harris Corporation, the Advanced Television Test Center, Fox News, Communications Engineering Inc., Reuters, and Discovery Communications. He has consulted on many types of projects for organizations, including Sarnoff Corporation, Turner Engineering, CBS, NBC, ABC, Fox, the News Corporation, FedNet, and multiple agencies of the U.S. federal government. He has worked on key projects in the creation and standardization of the ATSC digital television standard, the HD Radio digital radio standard, the AXF (SMPTE 2034) standard, as well as the first consumer commercial HDTV satellite service Unity Motion. Snyder is member of a number of industry organizations and serves as an officer and on standards committees in SMPTE. He serves on technical committees of the Advanced Media Workflow Association and the Academy of Motion Picture Arts and Sciences.

A Contribution received from the author July 2016.

From One to Many: A Short History of 20th Century Multichannel Cinema Sound

By Tom Scott

Abstract

This paper traces many of the steps in the development of multichannel cinema sound from the single channel mono optical cinema sound of the 1930's to the dawn of the Digital Cinema of the 21st century.

Keywords

CDS, Cinema Digital Sound, CinemaScope, Cinema sound, Cinerama, DC-28, Dolby Stereo, Dolby Digital, DTS, Fantasia, Fantasound, IMAX, Quintaphonic, Sony SDDS, SVA, Todd-AO, 70mm magnetic, 5.1, 7.1

Introduction

The current state of cinema sound is the product of a series of evolutionary changes in the latter half of the 20th century that brought us from monaural cinema sound to a proliferation of multichannel delivery systems at the dawn of the 21st century. This is a short history ending at the revolutionary change from heavy cans of celluloid to digital file delivery to the cinema.

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Optical reproduction, as codified by the Academy of Motion Pictures in 1938, allowed widespread distribution of films with adequate interoperable sound tracks across the U.S. and around the world. Electrical reproduction of 78 rpm music recordings for the home gave audiences a glimmer of fidelity, and the desire for higher fidelity in cinema sound had to be satisfied.

Disney Throws Down the Surround Sound Gauntlet

For his movie *Fantasia*, Walt Disney wanted the symphonic score to rival the sounds heard in live orchestral concerts and surpass that stationary sound by moving sound sources around the theater. You can picture Walt imagining Paul Dukas' *The Sorcerer's Apprentice* marching those throngs of bewitched brooms over and around the enthralled audiences. The sound system Disney engineers created arguably demonstrated the very first cinema surround sound. There has been much written about this monumental engineering feat of recording breakthroughs—the invention of the pan pot not the least of them—but the theater playback system was truly gargantuan for the time. Three sound channels played from a separate sprocketed optical sound track, providing amazing true stereo from behind the screen. Then, for certain scenes, the left and right channels were steered by gain control amplifiers triggered by tones on a fourth track, into speakers on each side, the back corners, and the ceiling over and around the auditorium.

For the 1941 release, the full system, branded Fantasound and built by RCA, was installed in only two theaters: New York's Broadway Theater and Los Angeles' Carthay Circle Theater. Reputedly costing $85,000 each in 1940 dollars, those installations would be well over a million dollars apiece in today's currency! RCA built eight smaller "roadshow" systems with manually selected audience speakers at about half the cost but that still demonstrated ground-breaking, high-fidelity, three-channel stereo. Considering that this was during World War II, the achievement was particularly stunning, and the entertainment value during the war years must have been great for morale.

Bigger Picture, Bigger Sound, Big Price Tag

Fred Waller's Cinerama system debuted in the same New York Broadway Theater in September 1952, with a triple-wide picture played from three synchronized 35 mm projectors onto a giant curved screen made of perforated strips. A separate sprocketed 35 mm magnetic player delivered seven channels of sound to five screen channels and audience surround sound. *This Is Cinerama* succeeded as a novelty, and several dozen films were made to screen in true Cinerama and later in anamorphic 70 mm

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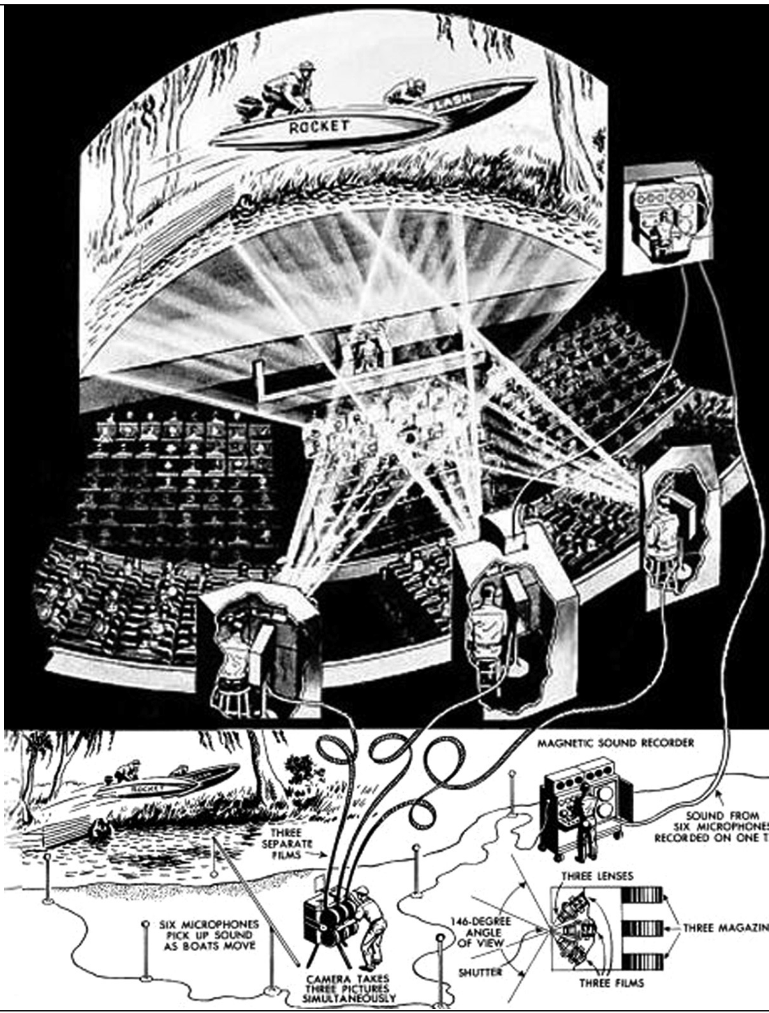


Cinerama diagram showing "how it is done": three cameras, three projectors, and separate sound.

Cinerama branded venues. However, the expense of the equipment for making and projecting the films precluded the system from becoming widely circulated. Still, the much-publicized big-sound big-picture experience ignited a desire for much more of the same.

Bigger Picture, Bigger Sound, Lower Price Tag

In 1953 Twentieth Century Fox was able to feed exhibitors' desire for a lower priced big-screen and big-sound experience with their development of CinemaScope. Anamorphic 35 mm filmed prints, striped or "painted" with magnetic material, gave audiences widescreen and discrete four-track sound: three screen speakers and a mono surround track. *The Robe* was the first release to employ CinemaScope in 1953, a spectacular blockbuster debut, but the format was not without problems. The magnetic heads wore out quickly, the magnetic oxide striping sometimes did not stick, and the process of "sounding" (recording every print at play speed) posed substantial expense. Every print was essentially handmade. Furthermore, devoting most of the film width to picture and accommodating the magnetic track with slightly smaller sprocket holes left no room for an optical track. This meant that prints could not be moved to second-run mono-optical-only houses, and eventually Fox would reduce the picture size to accommodate an optical track.

Todd-AO: Even Bigger Picture, More Sound

Mike Todd and American Optical raised the ante in 1955 with Todd-AO. It employed 70mm prints, whose large image area and 1:2.2 aspect ratio gave a very high resolution, and a very widescreen picture. Across such a widescreen, three speakers produced uneven coverage; thus, the 70 mm stock was striped with six channels: five screen speakers and one auditorium surround channel. Played at 30 frames/sec, the first production, *Oklahoma!* set new image and sound quality levels. The enormous success of that film led Twentieth Century Fox to buy the rights to the system.

The 70 mm film with six discrete magnetic tracks became the peak cinema delivery system for the next three decades. It was truly the Cadillac format of the time,

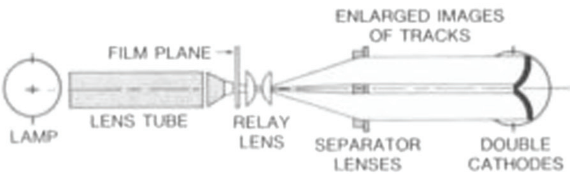


Fig. 3
John Frayne's Optical Reproducer

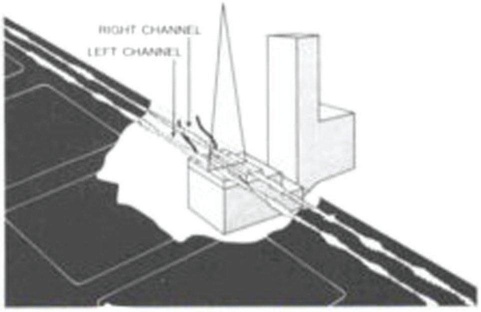


Fig. 4 Diagram of reproducing system for stereophonic photographic soundtracks

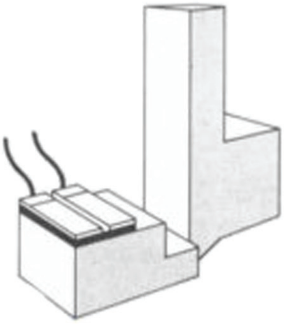


Fig. 5 Diagram of a two element photocell for reproducing stereo soundtracks

Diagrams courtesy Ron Uhlig & SMPTE

Image from Ronald E. Uhlig, "Stereophonic Photographic Soundtracks," *J. SMPTE*, 82(4):292-295, Apr. 1973.

despite the elevated costs of the film stock and the expense of striping and recording the magnetic tracks. Distributors of major releases would often make a number of "70's" for the big cities and fill in with less expensive mono optical 35 mm wide releases.

Biggest Picture?

In 1971, the first IMAX permanent installation in San Diego was followed by many museum and special venue installations. Featuring very large screens viewed from relatively short distances, the picture quality provided patrons with a glimpse of extremely high-quality visuals to come, and the six-channel magnetic sound may well have been an exciting first taste of high-quality multichannel sound for family theater-goers visiting IMAX systems installed in museums and planetariums.

IMAX films do not carry an embedded sound track. Instead, to maximize the picture area on the horizontally played 15 perforation 70 mm film, a six-channel 35 mm magnetic full-coat film was recorded and reproduced on a separate sprocketed player locked to the projector. The speakers are arranged behind the screen in typical L-C-R fashion, but an additional high center channel is provided to give height information, particularly effective as the IMAX seating is close to the screen. Audience surround is supplied from the back left and back right corners of the theater.

To obviate the expense and bother of the regular replacement of worn mag film, the sprocketed players were supplanted in the early 1990s by a Digital Theater Systems (DTS)-based six-track digital sound system, still locked to the projector, playing audio off a series of proprietarily encoded discs. This has eventually given way to a system using a hard disk drive that carries six channels of uncompressed digital audio.

Enter the Matrix

In 1975, the Who's rock opera *Tommy* employed a special variation of magnetically striped 35 mm prints, developed by John Mosely. The systems deployed used DBX noise reduction and, in an attempt to surround the audience with sound, used the Sansui matrix encoding system developed for quadraphonic records, a short-lived fad where four channels were combined to two audio signals using an analog sum and difference technique on LP music discs. For the film, special playback decoders were installed to decode three tracks of the 35 mm magnetic prints to yield five "Quintaphonic" outputs: Track 2 provided the center channel directly, but matrix-encoded Tracks 1 and 3 were decoded in the theater to give four more channels: a left front and left back and a right front and right back. The equipment was used only for that one film, but the prints would play on systems without matrix playback—and matrix encoding and decoding was poised for much bigger things.

Dolby Stereo Optical

In 1973, Kodak's Ron Uhlig published an article in the *Journal of the SMPTE* describing a method, based on the 1955 work by John Frayne, of recording and playing two optical tracks in the space occupied normally by a

Selling tickets with sound? How many dollars per track did you pay to hear *Star Wars*? Picture credit: SFGate.

mono optical track on 16 mm film. For educational films for schools, Kodak wanted to create a competitor to the U-Matic videotape, which featured two audio channels. Frayne's work had been unsuccessful because of poor dynamic range. However, Ioan Allen of Dolby Laboratories had been applying Dolby noise reduction to mono optical films with encouraging results since 1972. Combining Dolby NR to the stereo optical tracks that Uhlig described formed the starting point for the stereo variable area (SVA) prints that would forever seal the fate of expensive 35 mm magnetic four-track releases.

Aided by Dolby noise reduction, Allen was able to relax the roll-off of the Academy curve for better high-frequency response, and by applying quadraphonic matrixing, Dolby engineers first encoded three tracks and then four tracks onto the two SVA tracks. The modest separation of the analog matrix techniques could result in some of the screen sound leaking from the surround speakers near the rear audience. This was obviated by the addition of an analog CCD delay that could be varied depending on the length of the theater, assuring that sound from the screen reached listeners first and masked any dialog leakage. *Lisztomania* was the first release in Dolby SVA in 1975, but a fortuitous release in 1977 rocketed the system to prominence. Thousands of theaters howled for a print of *Star Wars*, originally released by Fox in only a few dozen theaters, most of which were 70 mm prints [we will get into those next]. The fact that the analog optical Dolby Stereo 35s could be high-speed printed meant that the voracious demand was filled as rapidly as Dolby could ship and install their Cinema Processors, the all-in-one boxes that replaced all the sound gear between optical pickup and the power amplifiers.

70 mm Heyday

Star Wars 70 mm prints were special as well. The main channels carried A-type noise reduction. Tracks 2 and 4 of the six magnetic tracks, called "baby-boom" tracks, were devoted entirely to bass information behind the screen that wowed audiences with the rumbles of the spaceships and the space battles.

The 1970's and 1980's may have been the high point of 70 mm releases, but consider the pros and cons. Yes, you got six discrete, high-fidelity, noise-reduced tracks with 6 or 8 dB more dynamic range than Stereo SVA, and magnetic distortion curves are much more forgiving than optical clipping when loud sounds exceed 100%. But stock was expensive, and print sounding (recording) had to be done at play speed for fidelity. These "handmade prints" required lots of expensive labor and also required print checking before shipping, as the "painted on" mag tracks might have bald spots or dropouts. A 70 mm print in 1980 could cost more than $20,000, whereas a stereo optical 35 mm print might be less than $2000.

There was one more 70 mm variation that must be mentioned. For the 1979 release of *Apocalypse Now*, Director Francis Coppola and Sound Designer Walter Murch searched for ways to envelop the audience with the sounds of battle and had set up the Northpoint Theater in San Francisco as a testbed. Dolby's Ioan Allen and Max Bell, who had been considering special 70 mm techniques for *Superman*, came up with the idea of using the "baby boom" Tracks 2 and 4 to carry both stereo bass tracks below 250 Hz and above 500 Hz, sharing the channels with left-back and right-back stereo "split-surround" tracks. The tracks were separated on playback by electronic crossovers, and the two surround tracks' response was filled out with mono sound below 500 Hz taken from the mono surround on track 6 that was included so the prints would be backward compatible with unmodified "baby boom" equipped venues. *Superman* came out first and was a big success, but the *Apocalypse Now* 70 mm tracks, especially tuned and groomed at the Northpoint to fit the format exactly, set new heights for feature film sound.

The Last Gasp of Optical?

Ray Dolby had another analog trick up his sleeve in 1986 as he and his team perfected an even better noise reduction scheme that would replace A-type modules in recording studios and film equipment all over the world. Spectral recording, or SR, offered an additional 10 dB of noise reduction, and some of those decibels could be used to both increase dynamic range and to reduce distortion. In theaters, it was an easy change as the SR cards were pin compatible with the earlier A-type. Finally, the dynamic range of SVA could approach that of magnetic prints, and the fact that SR encoded optical tracks are with us to this day, better than 30 years on, is an unmistakable reminder of the genius of Ray Dolby.

Let Us Go Digital

In 1988, 400 million CDs were manufactured by 50 pressing plants around the world. CDs overtook vinyl, and listeners were becoming accustomed to the idea that "digital was better." Ray Dolby, fresh off the triumph of SR, had assembled a small team of engineers to examine how the seemingly massive amounts of data in digital audio might be reduced with an eye to uses in radio and TV broadcast. For several years, Dolby had been supplying AC-1 (AC for audio compression) and then AC-2 for satellite links and studio-to-transmitter links. These devices showed that full-range stereo digital audio could be reduced from 1.5 Mbits to only a few hundred kilobits and still maintain good fidelity to the human ear.

In 1992, Dolby announced a digital cinema sound system that employed the next-generation scheme, AC-3, to provide a 5.1 channel coding at a bit rate of 320 kbits/sec with the digital audio data printed on a track of near microscopic speckles between the sprocket holes, replete with a tiny Double D logo, in an area of the film print that was surprisingly resistant to damage. The first trial Dolby Stereo Digital AC-3 film was *Star Trek VI* in December 1991, in only three theaters, followed by the formal announcement for the wide release of *Batman Returns* in the following year. By adding a standard analog stereo optical track, the digital prints could be backward compatible for theaters without digital playback gear. Because the optical track employed SR noise reduction, the format became known as SR-D and is now called simply Dolby Digital.

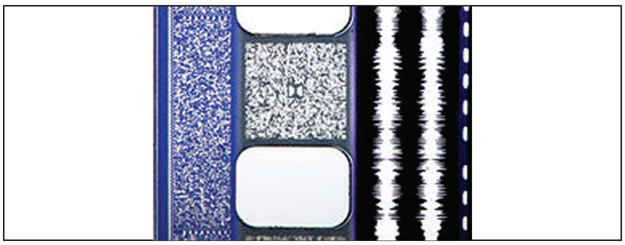
In those heady days of early digital sound, it seemed like everyone had to have their own digital release format.

In those heady days of early digital sound, it seemed like everyone had to have their own digital release format. In the revolving cast of characters in this short history, a few came and went rather quickly. Kodak, a company with lots of engineering strength, saw digital coming to the cinema. They combined a special fine-grained negative film they had developed that could carry high data density with a coding and error correction scheme from Optical Radiation Corporation, and they produced a system that could record and deliver six digital audio channels with "CD quality," as well as an SMPTE timecode and MIDI channel that might eventually be used to synchronize and trigger any number of in-theater effects. The digital track could be printed on both 35 mm and 70 mm stocks. In the case of 35 mm, the track was in the area normally used for the optical SVA track; in 70 mm, the prints were not striped with magnetic tracks. In either case, there was no analog fallback in case of digital failure—they had a lot of confidence in their system.

Paramount embraced the system, dubbed Cinema Digital Sound (CDS), first for a few installations for *Dick Tracy*, then for more for *Days of Thunder*. Nine films were released in the format, including *Terminator 2* (1991) and concluding with *Universal Soldier* (1992), before quietly slipping away.

Double System Is Back, and It Is Digital

At about the same time, in 1990, Terry Beard set about creating a digital playback system that could had be



A close-up of a 35 mm release film release print with all four sound systems: (from left) Sony SDDS track outside the sprocket holes, Dolby Digital between the sprocket holes, the Stereo Optical track with Dolby SR noise reduction, and (right) the DTS Synchronizing timecode track.

synchronized with 35 mm and 70 mm films. He employed a simple timecode that could be printed in the guard band between the picture and the SVA sound track to synchronize a “double-system” player based on CD data. Steven Spielberg was working on *Jurassic Park* and hoping for 70 mm discrete six-track sound on a 35 mm print budget. He heard a sample of the system and convinced Universal (no strangers themselves to investing in special sound equipment, recall Sensurround?) to invest with him in Terry’s company, DTS, and to commit to buying equipment for up to 900 theaters for the *Jurassic* release.

The system employed synchronized dual CD-ROM drives containing APT-X data reduction encoded audio to provide a wide frequency response, high dynamic range, digital 5.1 track playback system that could be easily retrofitted to cinemas previously equipped with speakers and amplifiers for 70mm.

A less expensive two-channel system with a single CD-ROM drive was also offered that would serve for four-channel (LCRS) optical-playback-equipped theaters. Although DTS was a “double system” that required shipping the correct sound-track discs along with the 35 mm film, the lightweight CD-ROMs were often shipped in the same 35 mm film cans.

However, clever optical mastering made possible a single film negative that provided all four different technologies on one print and made single inventory multiformat distribution feasible.

Sony SDDS Brings Back the MGM “5 in front”

The staff of the post-production facilities at MGM fondly remembered the massive impact of five full-range channels behind the screen for big musical productions like *Ben-Hur*. They encouraged their new owners, Sony, to embrace one front, two surround, and one low-frequency effect (LFE) channel as a target for their digital cinema offering. The Sony Dynamic Digital Sound (SDDS) technology employs optical recording on the release print like Dolby Digital, but with 7.1 channels arranged as five front channels behind the screen, left and right surrounds, and an LFE channel. The first SDDS film was *The Last Action Hero* in 1993.

The extra work required to release three different sound tracks was an expense and bother to film production companies, and it could be a nightmare for individual theater operators. Sending the right release format to each theater would require extensive bookkeeping, testing, and reshipping when mistakes were made. Differing licensing fees for each technology provided further bother. However, clever optical mastering made possible a single film negative that provided all four different technologies on one print and made single inventory multiformat distribution feasible.

In 1999, Dolby Laboratories and Lucasfilm announced a new enhancement to Dolby Digital called Dolby Digital Surround EX. This format delivers 6.1 optical channels, adding a center rear source by matrix decoding the left and right rear (side) channels, adding another source of sound inside the theater. The first movie to feature the EX format was *Star Wars I—The Phantom Menace*. These prints are backward compatible for 5.1 channel venues without the surround matrix decoding.

Welcome to the 21st Century

That may well have been the last big innovation for sound on celluloid because, in 2000, the first SMPTE DC28 meetings, chaired by Soundelux’s Curt Behlmer, began discussions that led (eventually) to the Digital Cinema Initiative (DCI) and the SMPTE standards that enabled the all-digital distribution of feature films. The DC28 Cinema Audio committee was sure they would finally have enough channels with 16! Who could possibly ever need more channels than that?

Of course, you know the answer to that… but we don’t want to steal the thunder of the next *SMPTE Journal* issue, the Progress Issue, where we will hear all about the challenges of the ongoing developments of Object Based and Immersive Audio for Cinema, still pursuing the goal of Walt Disney’s *Fantasia* 75 years ago: moving sound enveloping the audience.

About the Author

Tom Scott is an Editorial Director, Motion Pictures, for SMPTE. He has been involved with sound for motion pictures since 1978, employed at American Zoetrope, Dolby Laboratories, Saul Zaentz Film Center, and Skywalker Sound. He has been the recipient of two Oscars, Academy Awards for Best Sound, on the films *The Right Stuff* and *Amadeus*. He is currently employed as the vice president of technology at Onstream Media in San Francisco, California.

The History of SMPTE and Digitization

By S. Merrill Weiss

Abstract

SMPTE has been involved with the process of digitization, in one form or another, for over half the period of its existence. For more than the last four decades, the Society has been engaged actively in the process of transformation of its constituent industry segments from use of analog to use of digital technologies. SMPTE's involvement has matured from reporting on work done elsewhere in research and commercial settings, to conducting research directly, to developing technologies and standards for use by the industries it serves. The fields in which SMPTE has been engaged in the process of digitization have evolved from various control applications, to digital video and audio signal coding, to various forms of data transport, to signal data compression, to generation and use of metadata, to treatment of content as files, to all of the aspects of data workflows and content management. To deal with the very significant set of SMPTE contributions to the digitization of the motion imaging industries, this paper takes a more-or-less chronological approach. Many of the developments cited are from the author's personal recollections.

Keywords

SMPTE, EBU, History, Digitization, Control, Digital Control, Video, Digital Video, A/D Converter, D/A Converter, Memory, Digital Videotape Recorder, DVTR, D-1, Television, Digital Television, Composite Video, Component Video, Electronic News Gathering, ENG, Machine Control, Tributary, RS-422, RS-485, NRZ-I, Serial Digital Interface, SDI, Composition Play List, CPL, Output Profile List, OPL, Ultra High Definition, UHD, Interoperable Master Format, IMF, Archive eXchange Format, AXF, AXF Object, AXF Bundle, Broadcast eXchange Format, BXF, eXtensible Markup Language, XML

Introduction

Much of the history of the Society of Motion Picture and Television Engineers in the second half of its first century revolved around the movement of the motion picture and television industries from analog to digital technologies. Digitization of motion imaging and related aspects of the processes applied to motion imaging content grew through application of semiconductor, software, and networking technologies that developed in the surrounding environment. At times, the motion imaging domain followed what was occurring in the outside world; at other times, the motion imaging realm was the leader in technological development that other sectors followed.

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Digitization started in the world of SMPTE slowly, filling applications that could be performed only digitally. Often, those applications involved creating, through digital signal processing, analog signals that could not be obtained using analog methods. As time and technology progressed, digital methods were used to replace analog methods to achieve higher quality analog results at lower cost. Ultimately, systems became fully digital, and analog technology was completely replaced with digital processes for everything except signals that had to propagate without wires: viz., light into camera lenses, sounds into microphones, radio signals from transmitters to receivers, light reproduced by displays, and sounds reproduced by loudspeakers or headphones. Even then, digital methods were developed that improved every one of the inherently analog functions necessary to communicating images and sound.

Institutionally, digitization affected SMPTE and its activities first slowly, in limited areas, gradually expanding its envelope until it became all-encompassing. At the start, an occasional paper would be presented at a conference and/or in the *SMPTE Journal* with a novel approach to performing a function using digital methods. Over time, papers and articles were more about digital processes and

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less about analog processes until the analog processes disappeared. Similarly, in the SMPTE standards effort, work began on a single digital technology in a single committee, later to be joined by another technology and another committee. Ultimately, almost all of the standards-writing committees came to deal with digital methods, and just a few are left dealing with analog techniques, either to maintain methods that are needed for preservation or reproduction of content or to create new ways of transmitting light, sound, or radio signals that always will remain analog in nature.

This examination of digitization as it impacted SMPTE and its work over the decades and as SMPTE impacted the course of digitization generally will proceed chronologically. Along the way, some attempts will be made to point out the larger trends that were occurring that might not have been visible at the time to those engaged in the inexorable movement from analog to digital technologies throughout the world that is SMPTE.

Early Stages of Digitization (Late 1950s and 1960s)

The first instances of the concepts of digitization involving SMPTE in some way appear to be papers presented at the Society's convention in Detroit in October, 1958, and appearing in the *Journal of the SMPTE* in 1959. As most of the early indications of the coming of digitization to the SMPTE domain, they appeared as papers at conferences and in the *Journal* reporting on research taking place in academia or industry that made use of the availability of primitive digital computers or components. The first two were concerned with mechanical methods for language translation (published in April, 1959) and with a method for reducing the bandwidth of television signals using a hybrid of analog means for transmission of the low-frequency portions of video signals and digital methods for transmitting and reconstructing the higher frequencies in images. Authors of the latter paper (published in August, 1959) included William F. Schreiber and others then at Technicolor in Hollywood. Dr. Schreiber's name would be associated with digital image compression and other technologies over the next four decades, as he moved to the Massachusetts Institute of Technology (MIT) Department of Electrical Engineering, where much research in digital image processing was conducted over the years.

Despite the natures of the early notable presentations on digitization of processes of interest to SMPTE members, most of the work in the area during the 60's involved aspects of measurement and/or control. In keeping with what was going on in the world at large, the primary subjects addressed at conferences and in the *Journal* involved either camera tracking at missile ranges or automatic control of switching systems at television networks and stations. The technologies related to missile range tracking cameras largely concerned photography of missile launches and tended to be funded by NASA as part of the moon-bound space race. At the same time, computer technology was becoming sufficiently low in cost and sufficiently reliable that it could be applied to early efforts at what came to be called TV Master Control automation. During this period, however, the first video-capable analog-to-digital (A/D) and digital-to-analog (D/A) converters were being developed at BBC Research and Development (**Fig. 1**), starting the march toward what would become a ubiquitous use of digital methods over time..

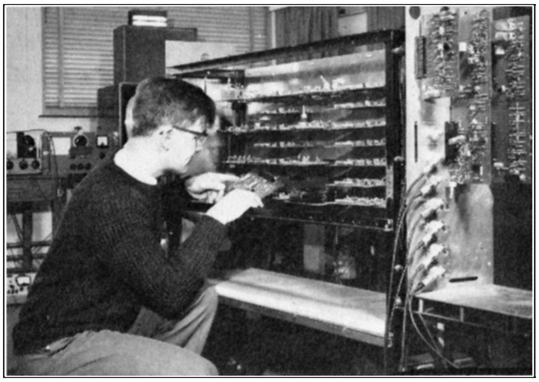

FIGURE 1. First BBC television analog-to-digital converter (1966).

By the end of the 1960s, digital technology was being used to apply image processing to the pictures being sent back to Earth from space probes flying by or orbiting the Moon, Mars, and other heavenly bodies. In particular the application of transform coding made its appearance for purposes of bandwidth reduction and spacecraft power saving, using Fast Fourier Transforms (FFTs) at both the sending and receiving ends of very-long-distance microwave links to return photography from the probes. In addition, by that time, digital control was being applied to color television cameras, which previously had required large numbers of wires carrying analog signals from camera heads to camera control units and analog control voltages in the opposite direction. The number of analog signals was indicated by the designation TV-81 for the cables, which had 81 conductors, 6 of which were coaxial cables for image signals and the remainder of which were primarily for power and analog control and communications functions. With digital control of cameras, only a few pairs of conductors were needed to carry all of the multiplexed data for full control of the same functions and more.

Digitization of Video and Control and the First Active SMPTE Work (1970s)

Early in the 1970s, electronic components started to become available that would allow processing of television signals using digital technology in commercial applications. Most necessary were A/D and D/A converters that would operate at video rates. A/D converters were more difficult to design and construct than were D/A converters. Early versions were built from individual components and small-scale-integration (SSI) integrated circuits. They had small word sizes (often starting at 6 bits) and low sample rates (in the multiple-megahertz region). By the mid-1970s, converters were available that were capable of up to 8-bits of amplitude resolution (256 levels) and sample rates in the 11–12 MHz range. The first commercial applications to video processing were timebase correctors (TBCs) for use with helical scan videotape recorders (VTRs) and frame synchronizers for allowing synchronization between sources without having to genlock studios to each remote source in succession.

Enabling Electronic News Gathering

The first widely used digital TBC was the CVS 504, released in 1974, which was used with U-Matic videocassette recorders (VCRs) to make them suitable for broadcast signal playback. The combination of U-Matic VCRs and TBCs, along with transportable (often backpack) cameras, enabled the development of Electronic News Gathering (ENG) in the mid-70s. Inclusion of microwave links on ENG trucks began the incorporation of live reporting into newscasts that is prevalent today. By the end of the decade, the film processors that had populated nearly all television stations producing news had vanished, to be replaced with ENG. While, at the start, only the TBCs in ENG involved digital technology, over time, ENG became fully digital as other elements of the system moved in that direction. Frame synchronizers, as represented by the NEC FS-10, also introduced in 1974, initially were used for Olympics telecasts and other major events but migrated to more common uses over time as their sizes and costs were reduced. Ultimately, they became widely used for ENG live shots to avoid genlocking.

Digital Videotape Recording

Also in the early 1970s, the first work was beginning on full-fledged digital videotape recorders (DVTRs). John L. E. Baldwin of the Independent Broadcasting Authority (IBA) in the U.K. conducted measurements in 1971 that showed that videotape could hold as much information in digital form as it could in analog form, but with better quality. He presented his results in 1972 and 1973. By 1976, Baldwin and the IBA were demonstrating digital recording using a sample frequency of two times the color subcarrier frequency of the European phase alternate line (PAL) analog system on borrowed analog SMPTE B-Format transport platforms. By the time of the Montreux Television Symposium in 1979, Ampex, Bosch Fernseh, and Sony all were demonstrating experimental digital VTRs.

Initial Digital Video Standardization Efforts

Shortly after the appearance of the first professional digital products, it became apparent that multiple, cascaded conversions of content from analog to digital and from digital back to analog form again would result in deterioration of the quality of the material. As a consequence, SMPTE set up its first activity to begin exploration of what would be needed to support the recognized coming expansion of digital technology in television operations. The SMPTE Study Group on Digital Television, chaired by Charles Ginsberg of Ampex, was formed in late 1974 to explore what might be possible and to make recommendations for future work. As a consequence of the Study Group's work, in early 1977, SMPTE established the Working Group on Digital Video Standards (WG-DVS), chaired by Robert S. Hopkins of RCA.

The WG-DVS started with an effort to standardize an interface for *composite* digital video, i.e., sampled NTSC signals. It was understood that the Nyquist Criterion required that the sampling frequency be greater than twice the highest frequency component contained in the signal being sampled. It also would simplify sampling if the sampling clock were locked to the subcarrier frequency and ran at an integer multiple of the subcarrier frequency. Since the NTSC subcarrier frequency is 3.5795454545… MHz, convenient multiples were 3 times and 4 times that value ($3f_{SC}$ and $4f_{SC}$, respectively), equaling 10.7386363636… MHz and 14.3181818… MHz. At the time, A/D and D/A converters and memory devices all were expensive, and significantly more so at higher frequencies. This led to a great deal of debate about which of the two sampling frequencies to use. Sampling at $3F_{SC}$ would result in a sampling structure that did not repeat on every field and frame of the interlaced image raster. Sampling at $4F_{SC}$ would produce a structure that conveniently repeated on each field and frame but the components for which would cost well over one-third more.

Numerous techniques were developed to accommodate $3F_{SC}$ sampling, including methods such as Phase Alternating Line Encoding (PALE), which resulted in a *quincunx* pattern (equivalent to the shape of the "5" pattern on a 6-sided die) in the sampling structure. While the argument continued, electronic component prices dropped as integration of circuitry expanded. By 1979, TRW was producing an integrated A/D converter that was reasonably-priced for the application. Once an equipment manufacturer (John Lowry of Digital Video Systems —DVS) showed up at a Working Group meeting and indicated that TBCs and frame synchronizers based on $4F_{SC}$ sampling were available in the marketplace (and at competitive pricing), the debate ended, and a decision was reached to adopt $4F_{SC}$ for the composite digital television interface standard. A document was produced that provided for use of 25-pin D-subminiature connectors with 12 parallel twisted-pair conductors and a ground interconnection, using balanced Emitter-Coupled Logic (ECL) devices and levels for the interface.

At about the same time that agreement was being reached on a potential *composite* interface standard, discussions began within the European Broadcasting Union (EBU) and spread to SMPTE about the possibilities for international program exchange that would be enabled by use of *component* coding of television signals. Use of *components* (i.e., three separate signals such as the red, green, and blue [RGB] primaries, luminance and two color-difference signals, or other combinations that avoided use of a subcarrier) could facilitate transfer of material between emission standards, which was an acute problem in Europe, where the use of both the PAL and SECAM systems constituted a barrier to the free flow of program content. Even program exchange between NTSC and the other composite coding methods would be aided by elimination of the subcarrier and the damage that it caused to images if there were agreement on use of a common set of components. Consequently, in 1979, a Special Task Force on Digital Video Standards, chaired by Frank Davidoff of CBS, was formed to provide liaison to the EBU and other worldwide organizations to consider the adoption of a common standard based on component coding.

As work proceeded on interface standards, it was recognized that standardization also would be required for the recording of content in digital form if the capabilities of analog facilities and operations were to be replicated in digital systems. Given that the only method available for the recording of video in that era was videotape recording, all of the prototypes and demonstrations of digital recording that began appearing involved tape recording. As a consequence, the Society formed, in 1979, a Study Group on Digital Tape Recording, chaired by William Connolly of CBS. With the number of committees active on digital television subjects by the end of the decade of the 1970s and with the shift from composite to component coding, in very early 1980, the SMPTE New Technology Committee, to which all of the digital subject matter committees reported, established a Task Force on Component-Coded Television, as an extension of the earlier Task Force on Digital Standards and again chaired by Frank Davidoff, to serve as a coordinator between the various SMPTE committees involved and as a steering committee for them and also to serve as a liaison body to other worldwide standards groups that were interested in digital television.

Digital Control

While work proceeded on digital video standards, another SMPTE effort began in 1978, in a Working Group on Digital Control of Television Equipment (WG-DCTE), chaired by Bob McAll of Vital Industries, to develop a common control interface and data protocol for "machine control." Initial efforts were based on an extension of the techniques then in use for control of routing switchers, which was a natural approach, given that many of the participants were manufacturers of routing switchers. The scheme under initial consideration used unterminated coaxial cable running at 9.6 kb/s, with the ability to accommodate up to 16 devices on a cable, with a maximum length of about 200 feet.

Fairly early in the process, there was a presentation given (by this writer) proposing an alternative scheme for machine control. It was a system that had been developed for a new studio facility for KPIX, the Westinghouse Broadcasting Company television station in San Francisco. The system used new data communications technology that had been developed under the rubric ANSI/TIA/EIA RS-422 and could operate at much higher speeds, over longer distances, and incorporating many more devices on a cable than could the initial unterminated coaxial cable proposal. The alternative proposal could run on audio pairs in multi-pair cables, allowing easy operation over parallel networks that permitted equipment assignment to control points through simple distributed routing of the connections to pairs related to the respective control points. Devices called "tributaries" were employed at each machine to be controlled, and the tributaries used microprocessors programmed as state machines from a protocol and management perspective. In fact, the proposed scheme employed a modification of the RS-422 standard that adopted a tri-state connection for transmission on the audio pairs, enabling the connection of up to 256 devices to each of the parallel networks. As the decade ended, the RS-422-based approach had replaced the unterminated coaxial cable scheme as the focus of the committee's work. (Later, tri-state RS-422 was documented by EIA/TIA as RS-485.)

Addressing Fundamental Needs & Moving to Implementation (1980s)

The 1980s opened with two major developments related to digitization. In October, 1980, a test was conducted at KPIX that proved the operation of the RS-422-based machine control scheme. KPIX had a functioning system that, at the physical layer, matched the then-proposed SMPTE physical layer standard. The KPIX system comprised 17 tributaries, each simultaneously connected to 6 separate, parallel data cable loops. The loops were approximately 1,000 feet in length. By opening the loops and tying them together in series, a loop was created that was 6,000 feet long and that had effectively 102 tributaries connected to it. The system operated at 38.4 kb/s and was shown to be highly reliable. The scheme ultimately was adopted as SMPTE 207M (now SMPTE ST 207) and still sees widespread use – over 35 years later, as this is being written.

Not so successful was the communications and control protocol that was developed in the WG-DCTE effort. Rather than adopting the protocol in use at KPIX, an effort was made to create a much more generalized method that used polling of tributaries. Development of the polling scheme and obtaining consensus agreement to it took a very long time. In the meantime, the industry had a great need for machine control capability and could not wait for the SMPTE work to finish. As a consequence Ampex and Sony each developed its own communications and control protocol, both of which used the underlying SMPTE 207M physical layer standard but which otherwise were incompatible. Equipment to do the controlling and to be controlled, for instance editors and VTRs or VCRs, had to be purchased or configured for the specific protocol with which it would be used. Unfortunately, this was a tremendous missed opportunity and showed that there is a time window within which standards must be developed, or they will fail. The time window opens when necessary technology becomes available and closes when the industry moves on by filling its own needs on a nonstandardized basis since it can wait no longer for a standard.

The second major development in the early 1980s also involved KPIX. During the week of the SMPTE Winter Television Conference held in San Francisco in February, 1981, a series of tests and demonstrations was conducted at the station that ultimately led to the world of digital video as we know it today. Throughout 1980, the Special Task Force on Digital Video Standards conducted liaison discussions with the EBU and other organizations. In April, 1980, the EBU conducted demonstrations of a system described as 12:4:4, with the values representing the sampling rate used for each of the components—luminance and two color difference signals—expressed as an integer number of Megahertz. Recognizing that 12:4:4 would not be acceptable in North America, efforts were made to find a set of parameters that could be used on a worldwide basis—even if some accommodations had to be made for the differences in scanning systems that would remain. The SMPTE WG-DVS, by then under the chairmanship of Kenneth P. Davies of the CBC, undertook to produce an experimental demonstration in conjunction with the 1981 SMPTE Winter Conference and spent much of 1980 and early 1981 preparing for it. Since the demonstration would be conducted at the time of the 1981 Winter Conference, it only made sense to hold it at a venue in San Francisco, where the conference would be held, and KPIX offered to make a studio available for the purpose (**Figs. 2**, **3**).

A number of principal parameters had to be determined for inclusion in a worldwide standard, if one were to be achieved, and a number of capabilities needed to be demonstrated. Principal among the parameters were the sampling frequency or frequencies and the relative coding rates for the three components. Other factors were the picture quality achievable with the various combinations of the principal parameters, performance obtainable using production tools such as chroma-keying, quality of interface achievable to and from composite signals, quality of interface achievable to common carrier systems, the filter shapes to be used for alias reduction when sampling signals in the digitization process and for reconstruction of those signals in analog form, and the practicality of

FIGURE 2. Overview of equipment area, first SMPTE demonstrations of component-coded digital video, San Francisco, 1981.

digital tape recording. The First SMPTE Demonstrations of Component-Coded Digital Video, as they were called (although they became the only such demonstrations), set out to accomplish as many of these objectives as possible. They ultimately achieved results for all of the aspects of the digital signal except the final design of the filter responses and the common carrier interfaces, both of which were handled by the Working Group after the demonstrations.

Because of the well-understood potential for major changes in the way the television industry operated technically that could result from the tests and demonstrations, there was a very large attendance and participation. Over 330 members of the television technology elite from all over the world traveled to San Francisco either to participate in the subjective assessments that led to statistical evaluation of the various parameters and techniques or to attend the demonstrations of the system, or both. The subjective assessments evaluated a 12-point matrix involving three sampling frequencies and four hierarchical coding sampling ratios. The sampling frequencies were horizontal-line-locked values at approximately 12, 13.5, and 14.2 Msamples/second, or Ms/s, based on multiples of 768, 864, and 912 times the horizontal line frequency of

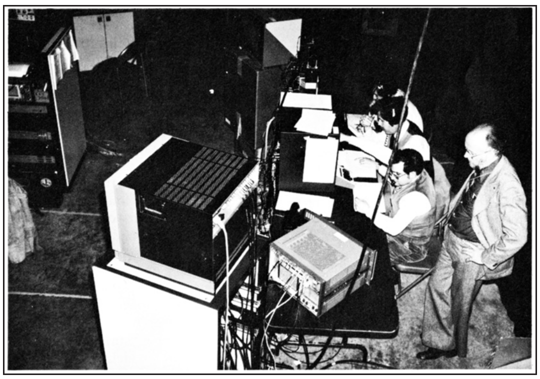

FIGURE. 3. Control desk view, first SMPTE demonstrations of component-coded digital video, San Francisco, 1981.

the 525-line/59.94 Hz system, respectively. These frequencies all were treated as approximately 4 times the color subcarrier frequency of composite signals, which formed the basis for a somewhat different descriptive scheme than had been used by the EBU for its demonstrations of component coding. With luma sampled primarily at approximately $4f_{SC}$ (but also at $2f_{SC}$), and with the color difference signals (basically R-Y and B-Y) sampled at 1×, ½×, and ¼× the roughly $4f_{SC}$ luma sampling rate, the coding sampling ratio choices that were evaluated were designated as 4:4:4, 4:2:2, 4:1:1, and 2:1:1.

Along the way to deciding what characteristics and parameters to evaluate during the San Francisco tests, it was recognized that there was a magic number that, if used for sampling the signals, could work equally well for the interlaced video field rates of 50 Hz and 59.94 Hz. The magic number was found by Stanley Baron, then of Thomson CSF and was any integer multiple of 2.25 MHz. 6 times 2.25 MHz is 13.5 MHz, and it was decided to include that value among those tested. (15.75 MHz also was considered but was determined to be too difficult to implement economically at the time or in the then-near future.) The magic nature of the 2.25 MHz frequency was that it is the lowest common multiple of the two line rates used with the 50 and 59.94 Hz field rates, i.e., 15.625 kHz and 15.734… kHz (being the 144th and 143rd multiples, respectively). The use of a multiple of 2.25 MHz permitted the same sampling frequency to be applied to both 50 and 59.94 Hz systems, with different numbers of samples per line, and, of course, different numbers of lines per field or per frame. Nevertheless, use of common equipment was enabled by such a choice. Luckily, the testing showed that 13.5 MHz sampling was a nearly optimal choice from an image performance perspective, and it and other multiples of 2.25 MHz became the foundation for all of the digital video systems, at all sorts of image spatial resolutions, up to the current time.

Evaluating the 12-point matrix meant producing tests in each of the points combining a set of sample rate and sample coding ratio live, in real time. This was necessary because there was no proven technology available at the time for recording the material with sufficient accuracy and reliability. Indeed, one of the first prototypes of a component digital videotape recorder was incorporated into the system to permit examining the potential for such recording capability. Because of the lack of both digital recording methods and digital versions of all of the processing equipment needed for the tests, the entire system was assembled using an analog component (RGB) system, and recording of the system output was done using a 3-machine RGB analog recorder assembled for the purpose.

One of the processes included in the system was color matting (a high quality method comparable to chroma keying), and its use turned out to be the deciding factor with respect to the image coding sampling ratio. A single image told the story. It involved a composite of a foreground image created in the studio on a live camera and any of several background images from a flying spot scanner. The foreground included twisted crepe paper, which, when seen in two dimensions, varies repeatedly between wide, nearly elliptical shapes and points where the crepe paper appears just to touch as it crosses over from front to back as seen by the camera (**Figs. 4**, **5**). As seen directly on a display, the foreground looked quite natural in all three sample coding ratios. It turned out, however, that, in the color matting process, when an insufficient sampling rate was used in the color difference channels, the touching points of the crepe paper pulled apart so obviously that it was quite evident even to untrained observers. That effect occurred at the 4:1:1 and 2:1:1 levels but not at the 4:4:4 and 4:2:2 levels (**Fig. 6**), resulting in selection of 4:2:2 as the initial standard and the primary mode of operation for digital television in the studio. The standards for digital television ultimately provided for operation at all three levels of sample coding ratios.

FIGURE 4. Foreground for color matte experiments, from live signal, first SMPTE demonstrations of component-coded digital video, San Francisco, 1981.

A number of important lessons were learned from the 1981 demonstrations of component coded digital video

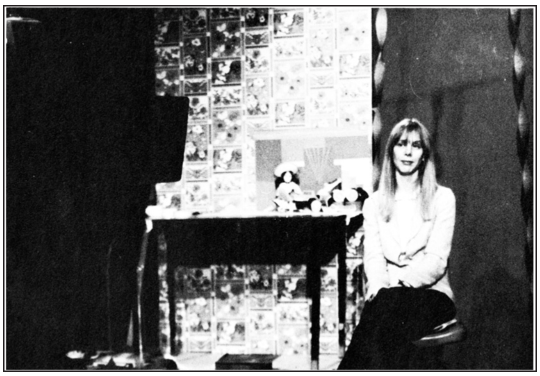

FIGURE 5. Scenes used for live studio camera, including "busy scene," crepe paper, & model, first SMPTE demonstrations of component-coded digital video, San Francisco, 1981.

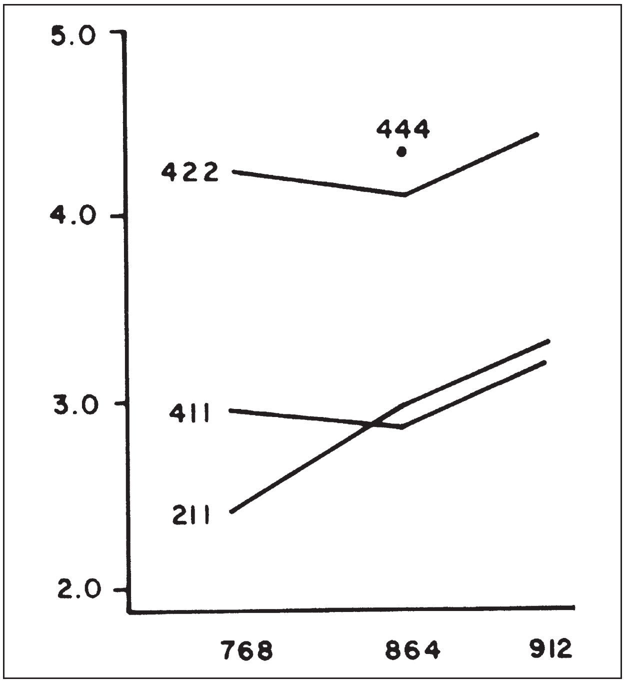

FIGURE 6. Results of color matte process, impairment value averages vs. no. samples/line, first SMPTE demonstrations of component-coded digital video, San Francisco, 1981.

that have been significant in SMPTE standards development ever since. First, in deciding on the characteristics of video and other imaging systems, just looking at native images on a screen is insufficient. Images must be processed in the ways they will be in real production and post-production operations because such processes can be sensitive to image characteristics that are not directly evident to the human visual system. Such processes can make visible what is not normally visible to the eye. For a thorough treatment of the 1981 Component Digital Video demonstrations, please see the *SMPTE Journal*, October, 1981 issue, which is largely devoted to the event, its various experiments, and their findings.

An outcome of the San Francisco event was a consensus within the television industry worldwide to adopt 13.5 MHz sampling, with a sample coding ratio of 4:2:2 for both 50 Hz and 59.94 Hz operation, with 720 active samples per line, with 8-bit PCM coding, and with a number of other specified characteristics. SMPTE, the EBU, and other organizations worked together to achieve adoption at the CCIR (now ITU-R) of Recommendation 601 (now ITU-R BT.601) to specify the sampling and coding of television images. SMPTE developed its own standard based on Rec. 601, first designated RP125, then SMPTE 125M, now SMPTE ST 125, that also specified word-serial, bit parallel interfaces using DB-25 connectors and parallel twisted pair cables. It was several years before the first systems could be implemented using RP125 because other elements of a system still were needed.

One of the principal elements needed for a complete system was a digital videotape recorder. As mentioned previously, the Society had started work on standardization of such a machine in 1979. The work continued until standardization of the D-1 format was reached by the Working Group on Digital Television Tape Recording (WG-DTTR) in 1985. The WG-DTTR had worked together with the MAGNUM group of the EBU and others to achieve worldwide consensus on the design of the many components of a recording system. These included selection of 19 mm tape width, design of a tape cassette system capable of different sizes and recording times, design of a tape transport system and a data layout on recorded tracks on tape, and design of the data encoding and error correction systems for processing of the recorded and recovered video and audio data. Prototypes of D-1 machines were first demonstrated in 1986, and deliveries began in 1987, using the DB-25 connector interface of SMPTE RP 125.

Shortly after the initial D-1 machines were introduced, the first fully-digital post production operation in North America was constructed at Limelite Studios in Miami. The Working Group on Studio Video Standards (WG-SVS)-successor to both the WG-DVS and the Working Group on Component Analog Video Standards—was invited to hold its next meeting at Limelite Studios in recognition of its work in the field. Upon arrival at Limelite, its vice president of engineering, Marcos Obadia, pointed out a problem. When a shallow blue ramp was generated and viewed, obvious contouring (banding) was visible to the viewer. The readily available solution to the problem was to use the two spare pairs in the DB-25 connector and cable to increase the bit depth of the data from 8 bits to 10 bits. Before finishing its meeting, the WG-SVS prepared a draft of a revised RP 125 based on a 10-bit interface, with the only difficult question being whether to make the additional 2 bits the MSBs or the LSBs. (The LSBs won.) There were immediate objections from European colleagues in the development of the Rec.601 consensus, some of whom felt that it was inappropriate to make such a change so soon after adoption of the standard.

Thus began an industry-wide discussion on the need for 10-bit operation and possible alternatives to overcoming the visibility of contouring in certain types of images. The principal alternative that was proposed (largely by the BBC and Quantel, each of which had its own version) was the use of dithering in the data to reduce the visibility of the contours. Dithering essentially is the addition of noise to the signal to mask the appearance of errors caused by the coding of the data. Dithering had been used successfully in the digital coding of audio, and it was held that it could be similarly used for video. Papers were presented at SMPTE conferences and published in the *SMPTE Journal*, demonstrations were given at WG-SVS meetings, and positions were taken on both sides of the issue by knowledgeable engineers. It took a confluence of factors finally to resolve the matter.

During the period in which the DVTR was developed, it was recognized that the DB-25 connector and parallel twisted-pair cables of the RP 125 interface were too cumbersome for widespread use. Aside from the bulk of the cables and connectors, which would affect the size of equipment, when contemplating routing switchers, for example, it was hard to imagine having to switch 9 parallel paths (8 data and 1 clock) at a time instead of one higher-speed path per connection. Moreover, it was desirable to be able to reuse the existing coaxial cable infrastructure of television facilities if a transition from analog to digital operations were to be economical. To enable such applications of coaxial interconnects, a bit-serial interface would be required in lieu of the word-serial, bit-parallel interface of RP 125. By 1984, an approach had been developed jointly with an EBU committee for a method using 8b/9b coding (i.e., mapping 8-bit data into 9-bit code words) to reduce the occurrence of long runs of 1's or 0's, thereby reducing low-frequency energy and DC on the interface, making both capacitive coupling and line equalization practical. With 8-bit sampling at 27 Ms/s total (including both luma and chroma) the result was a data rate of 243 Mb/s.

There were a number of problems with the 8b/9b system, though. First, 243 MHz turned out to be an international aircraft distress frequency. Worse, its fundamental, 121.5 MHz, was the primary international distress frequency, with satellites and commercial aircraft monitoring it continuously. Worse still, Bosch Fernseh had a laboratory under the flight path into Frankfurt Main airport, and they received a visit from the German spectrum police to tell them that they were creating false alarms on the emergency locator receivers of practically every plane landing at the airport from their direction. It turned out that the problem was a panel in a piece of equipment that had not be closed properly, but nevertheless the incident caused widespread concern in the industry about the use of 243 Mb/s as a clock rate for a serial digital interface that would see very widespread use worldwide.

Another difficulty with the 8b/9b approach to a serial digital interface was the fact that a company had promised to develop a chip set and make it available to the industry. The chip set had been described as comprising two devices—a read-only memory (ROM) for code look-up, combined with a serializer chip to convert from parallel to serial and vice versa. Such a chip set should have been workable, except that no chips had been made available after a significant time had passed (measured in years). The industry was in desperate need of a solution.

Fortuitously, a techno-political solution emerged from an alternate proposal. As chairman of the WG-SVS, the writer was approached by representatives of a different company with a different scheme for serializing and transmitting parallel data. The method was non-return-to-zero, inverted (called NRZ-I). NRZ-I had the properties that its output bit rate would match its input bit rate and that there was no impairment of reception due to inversion of signal polarity in distribution devices. With the use of 8-bit data and a 27 MHz word clock, the serial data rate would be 216 Mb/s, overcoming the potential radio frequency interference issue that accompanied use of the 8b/9b coding system. The problem was that the company offering the alternative did not know how to present it successfully in the SMPTE process, given the obvious potential political ramifications. Upon questioning, it turned out that the semiconductor process proposed could run at a 240 MHz clock rate. When asked if the process could run at 300 MHz, the answer was yes, and when asked when, the answer was in about 6 months. Six months later, another meeting on the subject took place, and the process was by then running at 300 MHz. So, the specifications were laid out in answer to the earlier inquiry about how to proceed with proposing the alternative: 10-bit operation at 270 Mb/s for component signals, 10-bit operation at 143 Mb/s and at 177 Mb/s for composite signals in NTSC and PAL (4× the subcarrier frequency in each case)—all in a single chip.

The 270 Mb/s technology, in particular, offered a techno-political solution to several problems. First, it got away from the worrisome 243 Mb/s potential interference generation. Second, it created a serial interface operating with 10-bit data without touching the 8-bit parallel interface of RP 125; those who wanted to continue operation with 8 bits in the parallel world could do so. They also could operate with 8 bits in the serial world if they left the two LSBs set to zero. (There clearly would be 10-bit parallel interfaces to the serial interface chips, but they would be internal to equipment and not standardized.) Third, there needed to be no loss of face to those who had proposed the 243 Mb/s approach since it could remain available for use in 8-bit systems if someone chose to produce the necessary chip sets. Fourth, chips could become available to the industry much more quickly than otherwise would have been the case, and, indeed, that turned out to be the situation. Thus a number of technical and business (political) problems were solved with a single techno-political solution. The result was SMPTE ST 259, now the well-known Serial Digital Interface, or SDI.

By the end of the 1980s, then, all of the fundamental pieces of the puzzle were in place to permit full-scale, raster-based, digital video operations. The transition from analog to digital operation had been described from early in the decade as utilizing islands of digital equipment in an analog sea at the start and gradually expanding those islands until there were analog lakes in a digital landscape, and eventually the lakes would dry up and disappear. Except for those lucky enough to build green-field operations, that is how it turned out for most facilities. At the same time, it must be noted that the digital facilities rolled out in that period largely were just digital replacements for analog equipment and maintained the processes and workflows that went with them. The real impacts of digital technologies on the operations of the television business were in the future.

Also by the end of the 1980s several other developments had appeared on the horizon that would further change the face of the industry and ultimately have an impact on its digitization. High definition television (HDTV) had emerged from the laboratories (largely of NHK in Japan), initially in analog form. In fact, HDTV first had been shown in North America, in San Francisco at the SMPTE Winter Television Conference, on the very weekend in 1981 during which the SMPTE Demonstrations of Component Coded Digital Video were held just a couple miles away. As HDTV continued to progress, worry grew among U.S. broadcasters that there might be an influx of HDTV television receivers with no way for broadcasters to deliver content to them. As a consequence, an effort was started to persuade the U.S. broadcasting regulator (the Federal Communications Commission—FCC) to initiate activity leading to a way for U.S. broadcasters to transmit HDTV signals. That activity (called the Advisory Committee on Advanced Television Service—ACATS) began in 1987. While it started out as an analog-centered development process, it soon turned digital in nature and came to depend significantly on SMPTE standards.

Extensions to High Definition and Preparations for Workflow Impacts (1990s)

By the early 1990s, there was a beginning of recognition of the impending convergence of the technologies of electronic media, computers, and communications. In that light, in 1991, meetings were held between SMPTE engineering management and their counterparts at the IEEE Computer Society. It was decided to make an effort to facilitate the convergence through development of tools that could be used by both groups' constituencies. To that end, a Working Group on Headers and Descriptors (WG-H&D) was established within the SMPTE Engineering Committee structure. The working group's objective was to develop techniques to permit transportation of digital video and audio data intermixed with unrelated data in a general purpose digital communications channel.

The WG-H&D took some time to determine where it best could contribute to the needs of both organizations' members. In the end, it set out to develop a set of Universal Headers and Descriptors that could identify content communicated as data and that could carry information about that data. It turned out to be the first of what would become many efforts to rationalize the world of electronic media content with the world of data, and it also turned out to be the first time the SMPTE standards development organization would brush up against what came to be called metadata in its pure form, although it had been dealing with such ancillary data for quite some time. True to the form that often would follow, the headers and descriptors work got locked in a tangle between the proponents of two divergent positions, neither of which would compromise its position. In this instance, the two parties both came from the IEEE Computer Society in the person of representatives of Apple Computer and the Massachusetts Institute of Technology (MIT).

The headers and descriptors logjam continued for quite some time, measured in years. A change in chairman of the Working Group to someone with decades of experience and numerous instances of finding compromise between parties with divergent positions did not help. Finally, a chance crossing of paths found the solution. The chairman of the parent committee to the WG-H&D happened to attend a paper presentation at a cable television conference in which the presenter proposed a new form of cable set top box based on a new form of middleware code that would be derived from the SMPTE Headers & Descriptors work. After the session, the parent committee chair approached the speaker and asked if he really meant to use the SMPTE Headers & Descriptors work. He did. Then, he'd better come join the committee and help sort out the tangle between the two opposing parties while there was still time to save the effort, he was told.

Thus came about the joining of the WG-H&D by Robert Thibadeau of the Carnegie Mellon University Robotics Institute. After his attendance at a couple meetings and getting the lay of the land, Thibadeau suggested a change in objectives. Instead of trying to define a set of Universal Headers and Descriptors that could work in every environment and address every need, why not develop a set of Universal Labels that could be used within the contexts of headers, descriptors, or any other data structures that might need identifiers and/or labels that could be registered, published, and extended as necessary? Such Universal Labels could be attached to any meanings that were needed, could be used to reference documents or functions within documents, could specify use of enumerated parameters, or whatever else they might be called upon to do. Moreover, they could be published on line so that machines could be enabled to obtain their values and their meanings automatically, without human intervention. It turned out that the capabilities of Universal Labels were more powerful than Headers and Descriptors possibly could have been, and they laid the groundwork for at least the first and second generations of metadata methodologies that were to come within the SMPTE standards context. Universal Labels ultimately were documented in SMPTE ST 298.

By the mid-1990s, the movement to digital television was in full swing in practically all areas of SMPTE television standards activities. Across the SMPTE technology spectrum, committees and projects were under way on extending the Serial Digital Interface to HDTV operation at 1.485 Gb/s, on serial digital fiber interfaces, on digital audio interfaces for television, on ancillary data, on jitter measurements and mitigation, and on monitoring and diagnostics in digital video systems. In the middle of the decade, a new Committee on Packetized Television Technology was formed to deal with standardization of matters related to television carried in packetized form, including digital video compression techniques and parameters, interfaces and protocols for packetization, switching and synchronization of packetized television data streams, system design, and the like.

Despite all of the ongoing efforts, it was recognized that what then was in process within the SMPTE standards development activity was just a continuation of the analog past, implemented digitally, and did not consider the new possibilities that digital technology opened up. To deal with the future opportunities, a joint task force was set up again by SMPTE and the EBU. The Task Force for Harmonized Standards for the Exchange of Program Material as Bit Streams (TF-HS) also included members from the Association of Radio Industries and Businesses of Japan (ARIB) and had the goal of setting the worldwide direction for the transition in production, post production, distribution, and emission from raster-based to bit-stream-based television. It rationalized the convergence of television, computers, and communications with the aim of providing direction to the development of standards for the next 1–2 decades. The Task Force included 200 experts from four continents, meeting 18 times over about two years, to produce two thorough reports. An initial report on "User Requirements" was released in April, 1997, and published in the *SMPTE Journal* of June, 1997. A final report of "Analyses and Results" was released in September, 1998, and published in the *SMPTE Journal* of the same month. They remain highly recommended reading. Among the fundamental concepts established by the Task Force is Content = Essence + Metadata, with Essence being the rawprogram material included in Content and Metadata being data about the rawprogram material. The Final Report explains this and many other concepts in considerable detail.

Consequences of the work of the TF-HS covered a broad range of technology but also instigated changes in the structure of the SMTPE standardization organization itself. The Task Force having adopted many of the concepts of the ISO layered structures model, the SMPTE committee structure was refashioned to take on a layered approach itself. Thus, committees were given assignments at different layers within the system structure, with defined interfaces between them and with responsibility to make-workable interfaces to the standards produced by other committees. Much of the standardization work triggered by the TF-HS took into the 2000s and beyond to bring to fruition, but amazingly, the direction set by the Task Force and the roadmap it created served the industry for the 1–2 decades that those establishing it hoped it would. Indeed, 18 years after it finished its work as this is written, it still points in the direction that the industry continues to take. The Task Force has proved, in fact, to have been one of the most successful technology assessments and planning activities that the Society ever has undertaken.

The remaining years of the 1990s following completion of the Task Force effort largely were devoted to getting work under way that had been scoped by the Task Force reports. In particular, work began on creating containerized content vehicles as were to be defined in standards for the Material eXchange Format (MXF), which has become a very widely used system for wrapping content elements together in such a way that they can be treated as a single object but can be used to produce outputs that differ depending on the needs for a given final product. MXF can include video, audio, other types of essence, and metadata, all in a single wrapper from which essence can be output in different combinations while retaining desired time relationships to one another due to the timing metadata carried for each of the essence content elements, for example. MXF depends heavily on the use of Universal Labels to facilitate its use of metadata through register functionality.

Following the Task Force Road Map (2000s)

The Task Force for Harmonized Standards for the Exchange of Program Material as Bit Streams spawned numerous standardization activities within SMPTE. Among these were the Material eXchange Format (MXF) protocol just mentioned, the Broadcast eXchange Format (BXF), and, somewhat later, the Archive eXchange Format. MXF originally used a Key-Length-Value (KLV) approach to carriage of metadata, with MXF Keys being essentially SMPTE Universal Labels. MXF more recently has been reformulated so that it can be expressed in the eXtensible Markup Language (XML) developed within the information technology world, as well as with KLV.

MXF became one of the principal enablers of file-based workflows over roughly the decade following its initial completion. Along the way to its finalization, many interoperability tests and "plugfests" were conducted to confirm that all participants were interpreting the many semantic elements in the same way and were formulating the syntactic expressions correctly. Of course, in the same manner as for most software-based systems, work on improvements to MXF continues. In some ways, MXF suffered from a plethora of solutions to almost any problem to be solved. MXF became a large toolkit, as multiple participants in the standardization effort contributed techniques for inclusion in the standard. The result was that there were so many choices for accomplishing any particular purpose that it became difficult to select one and have it be compatible with content produced elsewhere where different choices had been made. Many of the choices are represented by different Operational Patterns, which determine how content is configured when it is saved in a file. As a consequence, as the decade neared its end, efforts were undertaken in multiple groups, both within and outside SMPTE, to select subsets of MXF methods for specific purposes. These came to be called Application Specifications, which are constrained sets of the underlying MXF specification. Work on a few Application Specifications began in the late 2000s, with more in the 2010s.

To support MXF and other methods involving metadata, registration functionality was required. To support such registration capability, a SMPTE Registration Authority (SMPTE-RA) was established, committees were launched to deal both with the concepts and the mechanisms of registration, and work was undertaken to develop an online presence for the SMPTE-RA, through which automated access to published SMPTE registers could channeled. The SMPTE-RA also became the registrar for MPEG-2 Registration Identifiers through an assignment of the responsibility by the ISO/IEC JTC1 SC29 (MPEG) committee. With the SMPTE-RA in place, it became possible to build the development of register-based standards into the regular SMPTE documentation processes. Rules for registration-based documents were devised and incorporated into the SMPTE Administrative Guidelines. Procedures were established, and streamlined over time, for the assignment of specific Universal Label values to particular applications while maintaining normal SMPTE due process approval procedures.

BXF was among the first SMPTE standards to be built on the eXtensible Markup Language (XML). BXF provides for message exchange between subsystems in broadcast facilities to enable management and automation functions in the content delivery, traffic, master control program release, and other operations in television broadcasting. BXF was developed as an extension of functionality originally devised in the Advanced Television Systems Committee (ATSC) but ultimately turned over to SMPTE for further development. While the intention from the beginning was for BXF to subsume the ATSC functionality, the two have remained separate as the BXF capabilities have long since surpassed what the ATSC scheme could do. The intention remains to bring the ATSC operations into the BXF environment, but, through the time of this writing, other priorities always have been needed first. At some point in the future, the two schemes, both based on the same basic XML schema, will be consolidated. In the meantime, BXF was designed to grow in organic stages, and, by the mid-2010s was at version 5.0 of its documentation.

Early in the 2000s, work began to apply to cinema many of the concepts developed for or in use by television, in combination with many technologies from the world of information technology (IT). The assortment of technologies came to be called Digital Cinema (D-Cinema) and included methods extending from production through post-production, to special effects, digital intermediates, and delivery to theaters. D-Cinema involves delivery of content electronically, as encrypted files, to servers that are connected securely to the digital projection equipment for each theater. Along with the content for features, pre-show content and event cinema content can be delivered to theaters for presentation. Features and pre-show content technicallycan be delivered by satellite, over the Internet, through physical delivery of hard drives, and by other comparable means. Only event cinema necessitates real-time or near-real-time delivery. Features and pre-show content typically are intended to be delivered as encrypted Digital Cinema Packages (DCPs), with the content keyed to particular security elements (Media Blocks) in licensed servers and projectors. Keys to decrypt the content are delivered as Key Delivery Messages (KDMs). By the mid-2000s, the D-Cinema standards were sufficiently complete that conversion of some theaters could begin. By the end of the decade, D-Cinema standards and technology were sufficiently mature that mass migration of theaters from film projection to digital projection could and did proceed at a rapid pace.

During the 2000s, raster-based television systems made another advance from 1080-line interlaced high definition images to 1080-line progressively scanned images—so-called "Full-HD" images. This change required a 59.94 Hz frame rate, as opposed to the 29.97 Hz frame rate of the previously implemented interlaced scheme. The result was the need for double the data rate (or bit bandwidth) of the delivery channel in production and post production processes. As a consequence, the Serial Digital Interface (SDI) system was extended further, in new standards for the purpose—first using a pair of 1.5 Gb/s links in parallel, synchronized ("dual-link") operation and then using a single link operating at 3 Gb/s. The new SDI variants essentially multiplexed together two HD-SDI streams in a way that made it easy to control the relative timing of the two components of the 3 Gb/s stream in the same way that function had been handled in the original HD-SDI structure. The standard was well received, equipment became widely available, and the use of 3 Gb/s proliferated in new installations and infrastructure refreshes done during the period.

Another of the "eXchange Formats" spawned by the work of the TF-HS is the Archive eXchange Format (AXF). Its development began in the mid-2000s and continued into the mid-2010s. AXF fundamentally defines a wrapper designed to permit creation of AXF Objects that can carry multiple, related files in a single structure. The structure provides an internal, light-weight file system, enabling establishment and maintenance of hierarchical relationships between files and folders, as would be typical in a file system. By virtue of the AXF structure, however, AXF Objects are abstracted from the hardware, operating systems, file systems, and applications on which they originally were created. Such abstraction protects the content by making it possible to recover the content of AXF

Objects without requiring use of the archive systems that created the archives, or even of any archive system. Relatively simple utilities can be created to recover AXF Objects just from the standards documentation, and successful interchange of AXF Objects was demonstrated using a system developed in such a "clean-room" environment. This means that AXF Objects are protected from obsolescence of the systems on which they were created, the failure of archive system vendors to keep their systems operable on later generations of equipment, or even the disappearance of the archive system vendors altogether. Consequently, there can be no unintentionally orphaned archives.

AXF provides for unlimited storage of content. The sizes of files are unlimited, the numbers of included files in AXF Objects are unlimited, the numbers of AXF Objects stored on specific media are unlimited, and so on. Tools are available in AXF to deal with all of the storage and maintenance functions that are needed for archives. For example, media spanning through definition of Spanned Sets can provide unlimited storage space, thereby enabling the unlimited numbers and sizes of the files stored in AXF Objects. Once created, AXF Objects are treated as immutable, but they nevertheless can be modified by the creation of versions through use of Collected Sets that enable compilation of Product Objects from multiple members of those Collected Sets. Subsequent AXF Objects in a Collected Set carry any new files required by processing instructions to ADD, REPLACE, or DELETE files found in earlier AXF Objects in the Collected Set. Through this arrangement, all content to recreate any version of a Collected Set remains available, and any version can be recreated through a simple compilation process up to the version desired.

In addition to its various other features, AXF supports a wide range of metadata that can be associated with each of the files contained within an AXF Object or with an AXF Object itself. Each of the files stored in an AXF Object has a File Footer created as an XML data structure. A File Footer has certain specified required and optional metadata, and it also has provisions for user-added metadata of any sort a user may wish to preserve. Additionally, AXF Objects provide Generic Metadata Containers that can be repositories for any metadata that a user may wish to associate with an overall AXF Object rather than with a particular file. All of the relationships between metadata and either the associated files or the AXF Objects are maintained through the entire preservation process by virtue of the positioning and binding of the metadata within the AXF Object structures.

Supporting Large-Scale Versioning and Just-in-Time Post-Production (2010s)

An important change in the production and delivery of content that occurred largely in the first half of the decade of the 2010s was the requirement for many specialized versions of motion pictures or of television programs to be created and delivered. Some of the versions were needed to support multiple languages, while other versions were needed to support different presentation environments, such as theaters versus airplanes or presentation in one country having editorial restrictions versus presentation in another country that had no such restrictions. The first implementation of large-scale versioning was in D-Cinema, where collections of assets in DCPs could include one or more Composition Play Lists (CPLs) that permitted many variations of final product from a single distribution. The answer to the need for so many different versions (some productions require as many as 80 languages, just to start, which, when multiplied by all of the other variations can lead to 35,000 versions or more) has been the Interoperable Master Format (IMF). IMF provides a mechanism for describing the assembly of content versions from the components necessary to create them. Thus, all of the components necessary to create all of the versions of a particular television program or motion picture can be made accessible to a system that will construct a completed product for delivery. As a completed product is needed, it can be constructed in the form needed based on a set of instructions for the particular version. Such sets of instructions will have been created in advance for each version to be offered for delivery. The sets of instructions comprise CPLs to combine and synchronize track files and Output Profile Lists (OPLs) to define the output processing needed to deliver content in desired sets of formats. IMF can be useful not just for reducing storage space for large sets of versions of large content items; it also can be used to assemble content for just-in-time delivery by video-on-demand services when a variety of versions must be delivered.

Another trend in the 2010s was development of methods for carriage of television signals using Internet Protocol (IP) methods. The SMPTE 2022-series documents, in particular, provided methods for delivery of video, audio, and other data in packetized form that could be transported either through conventional IP data routers and channels or through specialized equipment that was better suited to the purpose and would deliver higher performance. The 2022-series documents included methods for packetization of content data and also for error protection of the data as it traversed networks that subjected it to losses of content. At the middle of the decade, efforts were under way to find methods for application of IP technology in studio settings and to meet studio functional needs. Primary among these was the requirement to switch between packetized IP sources sufficiently synchronously as to be useful in program production or in content delivery operations. At the time of this writing, solutions still were being sought.

At the middle of the 2010s, considerable interest in and work on raster-based content transport continued as the SDI family was being extended further. Driving the need for extension was a movement toward Ultra High Definition (UHD) television by the consumer electronics industry. UHD-TV was defined in two versions—UHD-1 and UHD-2, representing image sizes of 4× HD resolution and 16× HD resolution, i.e., corresponding to 3840 × 2160 pixels and to 7680 × 4320 pixels, respectively, and generally referenced as 4K and 8K UHD. For 4K UHD, carriage could be in SDI extensions running approximately at 6 Gb/s and at 12 Gb/s. For 8K UHD, if all parameters were pushed to their extremes, up to 192 Gb/s could be needed, but current systems operating at 8K resolution were not pushing the extremes, thereby reducing the required total bit-rate, and also were operating using parallel (multi-link) data transmission channels to increase achievable data rates.

Finally, continuing in the mid-2010s was work on a new use for the Archive eXchange Format (AXF)—an extension to AXF to enable its use in production and post-production workflows.

The extension for use in workflows was to facilitate the management and transfer of files and the collection of metadata long before there was any need for archiving of the multiple files likely to be associated with any given production project. A "Wrapped" AXF Object collects all of the content needed for archival purposes, stores it together in one place in a defined structure, and also provides for additional metadata desired to be retained by the user. An "Unwrapped" AXF Bundle is a structure that provides a Manifest of files included in the Bundle, a set of pointers to the locations of the files (which need not be stored together in one place), a File/Folder XML structure to establish relationships between the multiple files, even though they may be stored in various locations, and a sidecar file structure and binding mechanism for collecting and transporting metadata related to the files in the Bundle or to the Bundle itself. The scheme solved the problem of binding metadata to essence and keeping them bound during processing and also provided instructions on how the metadata from AXF Bundles was to be used to populate the File Footers and Generic Metadata Containers once the content was wrapped into AXF Objects. The AXF Bundle structure and its sidecar files essentially provide the opportunities to create "digital birth certificates" for essence as it is created and, in fact, even to collect provenance information "pre-birth," then to retain that metadata through the entire production and post-production processes until the content is ready to be archived in an AXF Object, at which point its storage within the AXF Object is prescribed.

Summary

As has been shown, the digitization of technical systems and content within the scope of SMPTE went on for roughly half of the Society's first century of existence and continued into its second. Starting from small, tangential references and descriptions in the *SMPTE Journal* and continuing until practically everything with which SMPTE became involved was digital in nature, the transition was inexorable and complete. There was no part of SMPTE or its areas of interest that were untouched by the digitization of the motion imaging industries. The Society and its members made some mistakes and learned a lot along the way, but ultimately they were successful in the conversion from analog to digital technologies and methods and from raster-based to file-based workflows during that half-century. Obviously, there was more to come.

About the Author

S. Merrill Weiss is a consultant in electronic media technology and electronic media technology management. His career spans 49 years in electronic media and related fields, with 40 years in management and consulting. He has been involved in development of SMPTE standards for 39 years, participating in work on nearly all of the digital technologies with which the Society has been involved. He has been a Working Group or Technology Committee chair for the last 34 years and a member of the Standards Committee for 28 years.

Weiss served as producer for the 1981 First Demonstrations of Component Coded Digital Video and designed the microprocessor-based machine control system that became the foundation of the physical layer of the SMPTE-standard ESbus machine control protocol. He also served four years as Engineering Director for Television and was co-chair of the joint SMPTE/EBU Task Force for Harmonized Standards for the Exchange of Program Material as Bit Streams. He chairs development of the Archive eXchange Format (AXF).

Merrill was elevated to SMPTE Fellow membership status in 1987. He received the David Sarnoff Gold Medal Award in 1995 and the Progress Medal in 2005. He received the NAB Television Engineering Achievement Award in 2006 and the ATSC Bernard J. Lechner Outstanding Contributor Award in 2012. He won the IEEE BTS Matti S. Siukola Memorial Award in both 2012 and 2013. Weiss holds four issued US patents and two international patents. He is a graduate of the Wharton School of the University of Pennsylvania.

A Contribution received from the author July 2016.

SMPTE Centennial: Closed Captioning and Video Description—A Brief Historical Perspective

By Mark Turits

Abstract

To mark the occasion of the SMPTE Centennial year in 2016, this article covers some of the history and milestones in accessible media for the film and television industries that have made closed captioning and video description a reality for deaf and hard of hearing, as well as for blind and visually impaired consumers around the world. The FCC recognizes the SMPTE Timed Text (SMPTE-TT) standard as a "safe harbor" interchange and delivery format. SMPTE also makes its standard for closed captioning of online video content (SMPTE 2052) available free of charge. Contributions in this area by SMPTE and its members have been recognized in the U.S. with awards presented to SMPTE by the Federal Communications Commission (FCC) and the National Academy of Television Arts & Sciences (NATAS) Emmy Awards.

Keywords

Broadcasting, digital audio broadcasting, digital multimedia broadcasting, digital video broadcasting, satellite broadcasting, TV broadcasting

Introduction

As we celebrate SMPTE's first 100 years, SMPTE members can take great pride in their many contributions to the science, technology, and creativity that have advanced the film and television industries, including making closed captioning and video description a reality for deaf and hard of hearing, as well as blind and visually impaired consumers around the world.

The Early Years

When SMPTE was founded 100 years ago in 1916, during the silent film era, hearing and/or visually impaired consumers did not have access to early mass media via closed captioning and video description.

Silent films were partially accessible to deaf or hard-of-hearing moviegoers through the use of subtitles to indicate dialogue, sound effects, and other information for which there was not yet a technical means to deliver audio. However, live music and live sound effects, essential elements of these early creative works that provided atmosphere and emotional cues, were available only for the hearing audience.

With the 1927 release of *The Jazz Singer* as the first feature film to utilize the new technology of synchronized sound, blind consumers suddenly had access to motion pictures, although this was limited to the audible portion of the movie, which provided no description of the visuals on the screen (e.g., actor's faces and emotions, scene settings and locations, and action).

When SMPTE was founded 100 years ago in 1916, during the silent film era, hearing and/or visually impaired consumers did not have access to early mass media via closed captioning and video description.

Captioning for Film

In 1950, the private nonprofit Captioned Films for the Deaf (CFD) was established to provide limited access to motion pictures by providing subtitled Hollywood films to deaf people.

Although the program was initially a success, more financial support was needed than could be provided by private funds, so advocates for the deaf and hard-of-hearing lobbied Congress, and in 1958, the CFD program became federal Public Law 85-905. The private corporation dissolved, federal funding was made available, and the new federally run CFD commenced operations.

This program continued to evolve as new consumer technologies came into the marketplace (e.g., VHS videotape, DVDs, and streaming video). It developed an increased focus on accessible media for K-12 students, and in 2006, it began serving students with vision and hearing loss. With another name change to the Described and Captioned Media Program, this program is now administered by the National Association of the Deaf.

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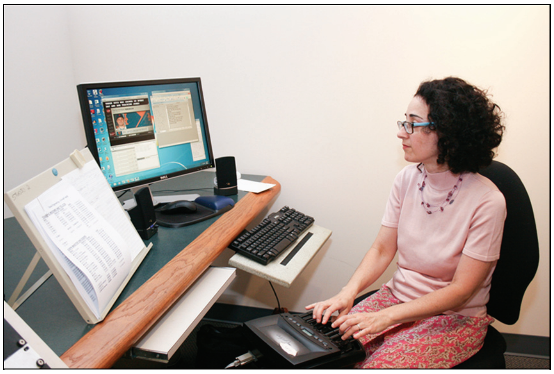

FIGURE 1. Realtime live stenocaptioning setup. *Photo courtesy: National Captioning Institute*.

FIGURE 3. Early standalone STB TeleCaption 4000 Closed Caption Decoder. *Photo courtesy: National Captioning Institute*.

Closed Captioning for Television and the Internet

In January 1972, the National Association of Broadcasters established a subcommittee to develop standards for a television captioning system for the deaf and hard-of-hearing. This led to the first on-air demonstration of a completely captioned television program in February 1972 at Gallaudet College (now Gallaudet University), when the National Bureau of Standards and ABC presented *The Mod Squad*.

In December 1976, the Federal Communications Commission (FCC) granted permanent authority to the Public Broadcasting System (PBS) and other broadcasters to televise closed captions, utilizing line 21 of the vertical blanking interval. PBS engineers then developed the caption editing consoles that would be used to caption prerecorded programs, the caption encoding equipment that broadcasters and others would use to add captions to their programs and prototype decoders.

In 1979, an independent nonbroadcast and not-for-profit entity, the National Captioning Institute (NCI), was created to further develop television captioning and, most importantly, to develop consumer television closed-caption decoding equipment with the mandate to have decoders manufactured and sold.

On 16 March 1980, off-line closed captioning debuted in the U.S. This was followed in 1981 with realtime live closed captioning, which by 1982 was in regular use (**Figs. 1** and **2**).

FIGURE 2. Off-line captioning setup. *Photo courtesy: National Captioning Institute*.

The original TeleCaption decoder developed by NCI went on sale in 1980, in the form of a set-top box (STB), and it was also built into a limited number of televisions sold by Sears (**Fig. 3**). While the aggregate sales of all these units were estimated to have been about 350,000, they fell far short of the potential consumer market that at that time was estimated to have been more than 22 million people.

This all changed when Congress passed the Television Decoder Circuitry Act of 1990, which mandated that, beginning in August 1993, television receivers sold in the U.S. with picture screens 13 in. or larger have built-in decoder circuitry designed to display closed-captioned television transmissions. Within a few years, virtually every television set sold in the U.S. had the capability to display closed captioning.

During the 1990s, the number of captioned television hours in the U.S. continued to grow on broadcast and cable television. By the mid-1990s, close to 100% of broadcast television programming was voluntarily closed captioned.

In 1996, Section 713 of the Telecommunications Act of 1996 required a phased-in period beginning 1 January 1998. By 1 January 2006 and thereafter, 100% of a programming distributor's new nonexempt video programming must be provided with captions. This applied to broadcast and cable program distributors, as well as locally produced programming (e.g., local news and sports) by affiliates of the major national broadcast television networks (e.g., ABC, CBS, Fox, and NBC), in the top 25 television markets, as defined by Nielsen's designated market areas.

On 8 October 2010, President Obama signed the 21st Century Communications and Video Accessibility Act (CVAA), which addressed both closed captioning and video description. This act expanded requirements for video programming equipment and required closed captioning on certain internet programming. Since a phased-in period that began in 2012, video programming that aired on television with closed captions must also be closed captioned when distributed on the internet as a full episode. This has also been extended to include various

FIGURE 4. Respeaking closed captioning setup. *Photo courtesy: Ericsson Inc*.

FIGURE 5. Video description: Video description recording session. *Photo courtesy: Bridge Multimedia*.

categories of program clips. It also required that any equipment, including computers and mobile devices, that shows TV programs must also be capable of displaying closed captions.

In February 2014, the FCC issued a Report and Order, which established new standards and rules for ensuring quality closed captioning in terms of accuracy, synchronicity, completeness, and placement, as well as outlining captioner and video programmer best practices.

There is an emerging technology for generating closed captioning called "re-speaking" (**Fig. 4**). Instead of a stenocaptioner entering in realtime a phonetic transcription with a 22-symbol keyboard, a single speaker repeats or "parrots" the program dialog, sound effects, and musical lyrics, along with punctuation and other essential program-related caption elements, commands, and macros, into a microphone where it goes through a speech-to-text engine which has been trained to recognize the individual respeaker's voice. When performed properly, the resultant realtime captions can be equivalent to those performed by a traditional stenocaptioner.

Video Description

Video description is audio-narrated descriptions of a television program's key visual elements, including actions, costumes, gestures, and scene changes. These descriptions are inserted into natural pauses in the program's dialogue. Video description makes television programming more accessible to individuals who are blind or visually impaired (**Fig. 5**).

A carefully written script is prepared by a trained describer, read by a professional narrator, and mixed in a professional audio production suite for broadcast-quality results. A full mix, consisting of the main program audio, is combined with these narrated descriptions that are typically then laid back onto a designated audio track (e.g., secondary audio program or SAP), which can be accessed by those consumers who require this service.

In the U.S., in 2000, the FCC adopted rules requiring larger broadcasters to provide 50 hr per calendar quarter of video-described programming, but in 2002, a Federal Appeals Court struck down the requirement, saying the FCC had no statutory authority to adopt the rule.

Under the CVAA, Video Description rules were reestablished in 2012 to ensure the accessibility, usability, and affordability of broadband, wireless, and internet technologies for people with disabilities. Congress reinstated the mandate to provide 50 hr per calendar quarter, or approximately 4 hr per week, as required by the FCC to affiliates of the top four commercial broadcast networks (ABC, CBS, FOX, and NBC), which are located in the top 25 television markets, and the top five nonbroadcast cable networks (currently Disney Channel, History, TBS, TNT, and USA).

In the U.S., on 1 July 2015, the requirement to provide video description was extended to affiliates of the top 4 broadcast networks located in the top 60 television markets.

Subscription TV systems (offered over cable, satellite, or the telephone network) with 50,000 or more subscribers must also carry video description.

Other broadcast networks, many PBS stations, nonbroadcast cable networks, and streaming services also voluntarily provide varying amounts of video-described programming.

Closed Captioning and Audio Description for Motion Pictures and Theatrical Exhibition

Closed captioning and audio description (another widely used term, interchangeable with "video description") for the motion picture and theatrical exhibition industries have also become increasingly available in recent years.

Technology with applications more specific to theatrical exhibition is utilized to make feature films and other content accessible to audiences with disabilities. In the U.S., the National Association of Theatre Owners (NATO) and the Motion Picture Association of America (MPAA) continue to work with national advocacy groups representing the deaf and hard-of-hearing and blind and visually impaired consumers to voluntarily advance this effort. In November 2014, an agreement was announced to file joint recommendations with the Department of Justice (DOJ) regarding its Notice of Proposed Rulemaking (NPRM) on captioning equipment in U.S. movie theaters.

On 18 November 2015, this resulted in the DOJ adopting a Second Report and Order on Reconsideration and a Second Further NPRM to implement these rules.

International

Closed captioning and video description are also available to varying degrees on a voluntary and regulated basis in many other countries. While it is more prevalent in North America, the U.K., other parts of Europe, and Australia, accessible media is emerging throughout the rest of the world.

Before the debut of closed captioning in the United States, Teletext was developed in the U.K. as a precursor to the World Wide Web. Teletext as subtitles for deaf and hard of hearing consumers were also provided for many years by services such as Ceefax in the U.K., Antiope in France, Telidon from Canada and NABTS, the North American Broadcast Teletext Specification in the U.S., which was short lived 1983–1986.

SMPTE's Contributions

SMPTE and its members have contributed much to all of the technological developments and workflows which have enabled closed captioning and video description.

SMPTE has been a leader in advancing the accessibility of closed captions in the world of broadband/internet-based video. In 2011, a Broadband Content Captioning ad hoc group (AHG) was established in the SMPTE Technology Committee on Television and Broadband Media (24TB).

The FCC recognizes the SMPTE Timed Text (SMPTE-TT) standard as a "safe harbor" interchange and delivery format. This means that captioned video content distributed via the internet using SMPTE-TT is compliant with the CVAA.

As part of this effort, SMPTE also makes its standard for closed captioning of online video content (SMPTE 2052) available free of charge.

SMPTE-TT is used in production environments to repurpose television content for internet use and is employed by a growing number of video services and internet video players. SMPTE-TT is the basis for subtitles and captions in the Digital Entertainment Content Ecosystem's UltraViolet™ format for commercial movie and television content, and it shares a common base with subtitles for internet-delivered television in the U.K. and other European countries.

On 19 December 2012, SMPTE was honored by the FCC with a Chairman's Award for Advancement in Accessibility for its development and contribution of the SMPTE-TT standard for captioning of video content distributed via the internet.

In January 2016, the National Academy of Television Arts & Sciences (NATAS) awarded SMPTE an Emmy Award for Technology and Engineering for its work on "Standardization and Pioneering Development of Non-Live Broadband Captioning." The award was presented to SMPTE, Netflix, Home Box Office (HBO), Telestream, and the World Wide Web Consortium (W3C) during the 67th Annual Technology & Engineering Emmy Awards Ceremony.

Given the achievements in closed captioning, video description, and other aspects of accessible media in SMPTE's first 100 years, SMPTE's next 100 years hint at even more advancements in this important area.

About the Author

Mark Turits is Vice President for Captioning and Video Description for the CBS Television Network division of the CBS Corporation. He joined CBS in 1996. From 1988 to 1996, he was Manager for Captioning at the ABC Television Network division of the Disney/ABC Television Group, and from 1987 to 1988, he was Production Manager at the former part-ABC-owned Worldwide Television News Corporation (WTN). His career began at Showtime Networks, Inc., in Network Operations, from 1981 to 1987, and included oversight for closed captioning quality assurance. He has a BFA from The Cooper Union for the Advancement of Science and Art. A SMPTE member, Turits is also a member of the SMPTE Television and Broadband Media (24TB), Broadband Content Captioning ad hoc group (AHG), and was an appointed member of the FCC's Video Programming Accessibility Advisory Committee (VPAAC).

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Forty Years of Television Progress: Television Technology Highlights from 1976 to the Present

By James E. O'Neal and Harvey Arnold

Abstract

The July 1976 SMPTE Journal celebrated television's technological growth and development with a time line and article ("101 Years of Television Technology") by Richard S. O'Brien and Robert B. Monroe that depicted and described significant milestones between 1875 and 1976. In celebration of the Society's 100th anniversary, the authors wish to continue that time line to cover the 40 years that have passed since publication of the O'Brien and Monroe article.

Keywords

Broadcasting, digital video broadcasting, satellite broadcasting, TV broadcasting, digital video broadcasting, digital images, optical fiber communication, optical fiber networks , telecommunication network, TV, cable TV, digital TV, analog TV, HDTV, IP networks, TCPIP, audio-visual systems

Introduction

The Society of Motion Picture and Television Engineers marked a significant milestone in mid-1976; the organization was rapidly approaching the 60th anniversary of its founding, and to commemorate this event, the July issue of the *SMPTE Journal* that year carried several articles of a historical nature reflecting on the progress made during the past 60 years or more in various areas of technology associated with the film and television (TV) industries. One of these—"101 Years of Television Technology," authored by Richard S. O'Brien and Robert B. Monroe, with input from Charles E. Anderson and Steven C. Runyon—provided a time line of significant developments and events occurring between 1875 and 1976, along with a fairly detailed description of some of the more important progress in the field of TV associated with these developments.

Time and progress do not stand still, and as our Society now approaches its 100th anniversary, it seems only fitting that the timeline compiled by O'Brien and Monroe should be updated and extended into 2016.

Time and progress do not stand still, and as our Society now approaches its 100th anniversary, it seems only fitting that the time line compiled by O'Brien and Monroe should be updated and extended into 2016, as some very radical and far-reaching changes have taken place in the industry in the intervening 40 years.

In the 1976 article, the authors examined 15 different categories:

— Ideas
— Mechanical TV
— Electronic TV
— Field sequential color
— Compatible color
— Camera tubes
— Display devices
— Longitudinal and miscellaneous videotape recording technologies
— Transverse scan videotape recording technology
— Helical scan videotape recording technology
— Film technology
— Transmission and distribution
— Broadcasting
— Film
— Digital technology

Obviously, some of these categories, such as longitudinal video tape recording, did not survive for very long and hence there will be no discussion of such technologies. However, several of the subject areas identified by O'Brien and Monroe still remain valid well into the 21st century.

State-of-the-Art TV Circa 1976

Concurrent with the publication of the July 1976 *SMPTE Journal*, the U.S. marked the 200th anniversary of its founding with large celebrations occurring from coast to coast. Americans and others around the world were able to watch these parades, speeches, firework displays, and allied events in full color and in real time via both the domestic and international geosynchronous

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FIGURE 1. A 1970s vintage remote truck.

satellites that were in place then. In beginning our trek across the past four decades, a useful point of origin would be a description of the TV equipment, technologies, and techniques used in covering this bicentennial celebration.

As most action took place outside studios, mobile production vehicles had to be deployed, and this required a great deal of planning in terms of parking, electrical mains connectivity needed to supply the demands of the large amount of power-consumptive equipment in the truck (generators were something of a last resort then), and audio/video connectivity with the station or network carrying the remote programming (**Fig. 1**). This usually required weeks to establish microwave paths and relay points, or to work with local telephone companies and the AT&T Long Lines division to set up signal pathing prior to the planned broadcast.

Although "minicams" were beginning to appear on the TV landscape in 1976 (**Fig. 2**), they were not yet in widespread use; the majority of such a special event coverage would have been accomplished with conventional studio cameras and lenses (typically 10:1 zoom models). Camera heads weighed in the 100 lb (45 kg) range (or more) and required the services of several muscular individuals to mount on tripod or pedestal heads. In some cases, the hire of a small crane was necessary to place a camera on an elevated vantage point. Connectivity between cameras and their associated control and shading units in the truck was achieved via heavy and bulky multiconductor cables (TV-81) that contained a mix of six coaxes and upwards of 70 individual conductors. These cables had the girth of an extra large garden hose and weighed so much that it was impossible for the average person to lift and carry a 100 ft (30 m) length. (Triaxial cable for camera connectivity was available in 1976 but was not in widespread use.)

Cabling inside the truck or trailer was equally involved, as most camera processor units required sync, horizontal/vertical drive and blanking, color subcarrier, and "burst flag" signals to be delivered via individual coaxes. Equally cumbersome was the process of timing camera and other signals to the production switcher, which involved

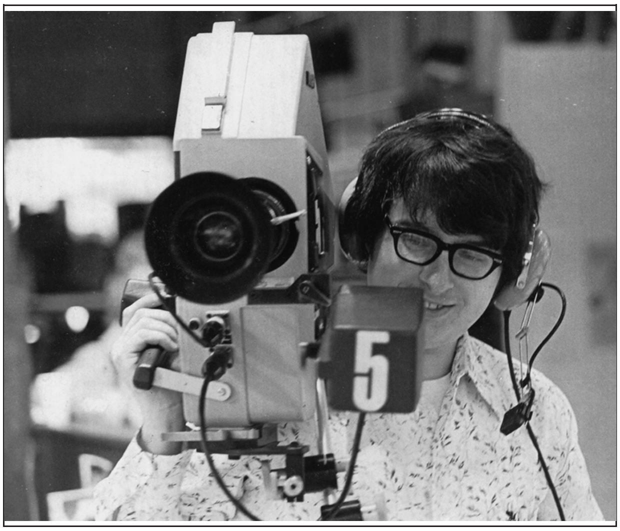

FIGURE 2. RCA's TKP-45 "minicam" was released in 1975 and saw much during the 1970s and beyond. With lens and viewfinder, it weighted 25 lb and required an external power source.

identifying the piece of equipment with video with the longest internal processing delay and adding lengths of coaxial cable or "lumped delays" to other signals to match their arrival at the switcher to that signal. This was a laborious process that involved the removal of small portions of cable in a "cut and try" procedure to ensure not only that there was no horizontal shift between video sources but also that the color subcarrier was correctly phased. Fortunately, this operation had to be done only once when the outside broadcast (OB) vehicle was being initially equipped; however, if pieces of equipment were substituted or otherwise replaced, this "cable pruning" had to be repeated.

Once the truck's cameras were deployed (five or six was usually the upper limit even for a large OB trailer due to size and weight of the support equipment and heavy coaxial cable), they had to be lined up before being placed on air. This involved the services of both a camera operator and a technician inside the vehicle, with numerous adjustments necessary to ensure good horizontal and vertical scan linearity, registration of images between color channel pickup tubes, and "matching" of individual camera colorimetry and grayscale tracking to ensure that there were no color shifts between units. Such "setup" operations could take hours and had to be checked at regular intervals prior to "air" to make sure that nothing had drifted. Once the show began, the camera "shader" was kept busy adjusting black and white levels as cameras moved and subject matter and lighting conditions changed.

Production switchers in 1970s vintage mobile production vehicles were not especially large or sophisticated, possibly having a dozen or so inputs and perhaps two or three mix effects (M/E) buses (**Fig. 3**).

Audio mixing equipment was, in most cases, equally small in scale and unsophisticated.

Video and waveform monitors were kept to a minimum due to the bulk and weight of their cathode ray tubes (CRTs).

Communication between operating personnel was usually limited to a "party line" system, with switching between two buses: "engineering" and "production." Intercom "belt packs" were nonexistent; camera operators plugged their headsets into jacks that were part of the camera head, with connectivity to the truck part of the camera umbilical.

Video/audio routing within the van was usually limited to patch panels or perhaps some "10-X"-type pushbutton switchers being fed from distribution amplifiers.

As mentioned, OB video and audio signals were relayed to network centers or local broadcasters by microwave radio links or telephone company–supplied coaxial and twisted-pair cables. Video arriving at these distribution or transmission facilities was typically passed through a processing amplifier to replace synch and color burst signals that might have become degraded in transmission. As this incoming video was asynchronous to in-plant signals, broadcasters had two methodologies available when it was desired to mix this remote video with local sources. While frame synchronizers were available in 1976, they were few in number due to cost. A more common way of bringing in-house and out-of-house video into synchronization was to "genlock" the plant synch generator to the remotely generated video. (This was not without some amount of concern though, as it caused perturbation of studio synch signals during the locking period; and had the external video/sync signal been interrupted, even more perturbation resulted.)

Although electronic character generators were available in the mid-1970s, they were not universal, and some operations still resorted to adding "lower thirds" text from 35 mm photographic "slides" containing images of "press-on" lettering or hand-drawn artwork. These slides were scanned via a telecine camera.

The addition of other enhancements and embellishments to video from the field was equally limited, as digital video effects generators were still in their infancy, very expensive, and basically limited to "squeezes" and rotation.

Signals flowed in both OB vans and studio facilities in analog format, with any digital circuitry basically limited to signal processing and sync generation operations.

FIGURE 3. Video switching operations in a 1970s vintage remote production truck.

FIGURE 4. A typical studio control room in the 1970s. (The studio lighting control console is on the left, the production switcher in the middle, and the audio mixer on the right.)

"Packaged" bicentennial content was relayed to network affiliates across the U.S. via AT&T Long Lines, which relied on a hybrid network of microwave radio and coaxial cables spanning the country. Satellite connectivity was available, but due to the limited number of spacecraft and transponders and the size and expense of earth stations, this was quite a costly and involved proposition. However, this was the only choice available for relaying programming to broadcasters in other countries wishing to carry celebration events in real time.

Signals left the U.S. in 525/60 NTSC format, and if the foreign broadcaster they reached operated with a different standard (i.e., 625/50 Phase-Alternation Line [PAL] or Séquentiel Couleur Avec Mémoire (sequential color and memory [SECAM]), standards conversion was necessary. Electronic conversion was available, but optical converters (cameras shooting monitors) were still in use at some facilities. Again, due to complexity and cost, standards convertors were usually found only at large network or telecommunications facilities.

Signals transmitted from either U.S. domestic or foreign broadcasters reached home viewers via over-the-air transmissions or, in some cases, via cable systems. Consumer NTSC, PAL, and SECAM viewing devices all utilized tricolor CRT displays (the very wealthy might own an early video projection system, but this was CRT-based as well), and accompanying audio was limited to a single channel. In addition, while some viewers of this unfolding 200th birthday spectacle might have desired to preserve portions of the TV coverage for later viewing, the number actually being able to do this was very limited due to the very high price of recording devices and media available to consumers in 1976.

Such was the TV landscape 40 years ago.

FIGURE 5. A 21st century "expando" remote production vehicle. Its capabilities would dwarf those of even a large TV station in the 1970s.

Let us "fast-forward" to 2016 and examine how outside events of a U.S. 240th birthday party might be covered by TV.

Remote Broadcasts Circa 2016

Large remote vans would still be used for some of the bigger celebrations; however, the van's equipment and its capabilities would likely overwhelm operators from 40 years earlier (**Fig. 4**). Gone are the big and finicky cameras and their large and heavy cables, which have been replaced by much smaller and lighter units that provide up to 4 K resolution and need very little in the way of operator setup and attention. Lighting is no longer the limiting factor it once was either, with today's cameras being able to make very acceptable pictures with very low levels of subject illumination. Connectivity is via lightweight copper or fiber-optic cable for fixed cameras, and wireless radio-frequency (RF) links for handheld units. Camera lenses have changed drastically too, with zoom ranges of 100:1 not atypical with color and tonal rendering that would have been unimaginable in 1976. Equally unimaginable would be the image stabilization and autofocus features that are commonplace today, as well as the resolving power needed for high-definition (HD) and ultra-high-definition (UHD) TV.

Vacuum tubes are not to be found at all: camera pickup tubes have been replaced by tiny solid-state imaging devices, and the CRTs formerly used in picture and waveform monitors are now only items of historical interest. Flat-screen displays driven by multiviewer signal combiners allow the director and others in the truck to view as many signals as they desire. Coverage of events is much more interesting and compelling too, as many more cameras can be deployed due to these technological advances.

The production switcher has grown proportionally to accommodate such multiple video sources. The typical 2016 OB van switcher and its capabilities would completely dwarf those of even the largest studio switchers available in 1976.

Videotape recorders (VTRs) are missing entirely from the van of today; there is far more recording and playout capability available in the form of clip servers than could have been accommodated or even imagined in an OB vehicle 40 years ago.

Signal routing capability in a typical large production vehicle of today is far, far greater than that available even in network centers four decades ago, with switching and manipulation of multiple levels of audio and other signals.

The intercom system has grown too, with a switching matrix all its own and multiple buses. Connectivity with camera operators and others with belt packs is accomplished wirelessly. Intercom audio quality is equal to that of program circuits.

Audio has changed too, with very large digital mixing desks being the norm to accommodate multiple source "surround" requirements.

Some of the latest trucks have even dispensed almost entirely with the bulk and weight of traditional coaxial and shielded twisted-pair cables by moving to IP connectivity.

Getting a signal back to a broadcast center has been greatly simplified by the use of satellites and associated small and lightweight uplink packages. Fiber connectivity crisscrosses the nation and the oceans as an alternative to satellite linkage. Smaller celebratory events might even be covered by a single camera operator with wireless connectivity via bonded cellular technology, or even by the use of established Wi-Fi "hot spots."

Although a complete and workable TV production system existed in 1976, it was manpower-intensive, very expensive to operate, and lacked the capabilities that exist even in today's consumer equipment.

The Modern TV Revolution

Although a complete and workable TV production system existed in 1976, it was manpower-intensive, very expensive to operate, and lacked the capabilities that exist even in today's consumer equipment. Just as O'Brien and Monroe did in their 1976 *SMPTE Journal* article, we will examine some of the technological developments and changes that have moved TV forward. We should like to note, however, that to fully document every element contributing to the digital HD system that we enjoy (and largely take for granted) today would require far, far more space than is available in these pages. To discuss all of the developments that have occurred in the past 40 or so years and explain their origin and significance in creating modern TV would require hundreds of thousands of words and a correspondingly great number of pages. We will limit our discussion accordingly, highlighting just a small number of those developments. Even this is a difficult task, for, quite surprisingly—especially in today's world of instant access to a very impressive amount of stored information—there are some noticeable gaps, making it difficult in some cases to establish key dates of developments or even those responsible for them. While a great deal of investigatory effort has gone into making the time line presented with this article as accurate as possible, there are some cases in which a date has had to be approximated due to conflicting information in reference sources. Quite surprising, too, is the lack of photographs available for documenting much of TV's progress during

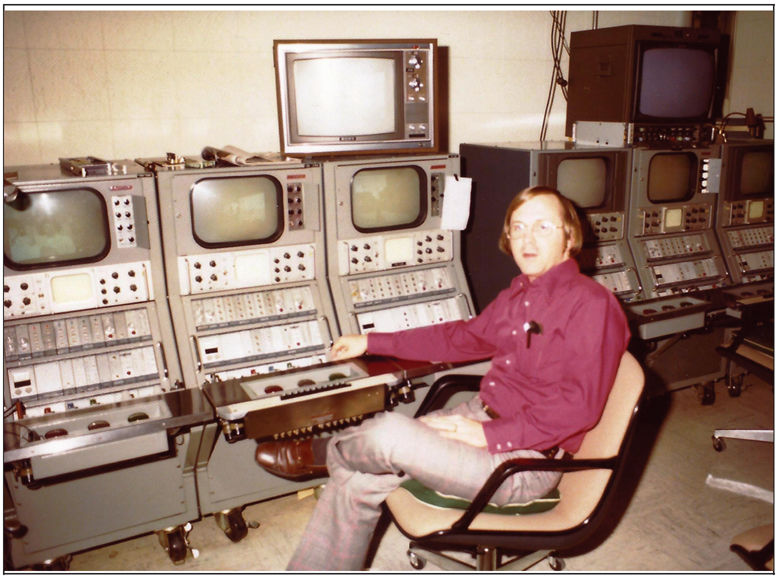

FIGURE 6. Color camera setup and shading operations in the 1970s. (These camera control units (CCUs) were used with Norelco PC-70S cameras.)

the past four decades. We had hoped to provide many more photographic illustrations to accompany our history, but despite a very involved search, very little has turned up in the way of usable artwork. A common response has been that original photographs have simply been discarded, as they were thought to have been of little value.

Where Did It Start?

The main catalyst for moving beyond the era of analog TV is most certainly traceable to the development of the integrated circuit in the 1960s, and especially to the microprocessor devices that were created in that movement. In 1976, Intel's third such device (and second 8-bit processor), the 8080, was barely two years old, and prices were quite high (more than $1,700 in today's money), making it more of a curiosity than an element to be incorporated in circuit designs. However, Intel soon began to license the technology, and other manufacturers (notably Motorola, RCA, and Signetics) released their own microprocessors, and prices fell sufficiently to make the device attractive to a number of designers, including some in the broadcast sector. Equally pricey at that time, and not especially reliable, were solid-state "memory" devices—random access memory or "RAM" chips. However, this situation changed too, and within a few years, more broadcast equipment manufacturers were moving to digital designs and using software-driven approaches to signal processing and numerous other operations, including video editing, camera setup, special effects generation, graphics creation, and much more. Today, it is virtually impossible to find any broadcast product that does not employ one or more microprocessors.

Camera Technology

Another form of integrated circuit that has helped to move TV forward is the charge-coupled device (CCD). It was originally developed as a shift-register type of storage in the late 1960s, but soon found its way into imaging applications. Prior to the arrival of the CCD imager, the 1 in. "Plumbicon" lead oxide pickup tube was considered an industry standard, with several companies licensed to manufacture such devices (**Fig. 6**). By 1976, a slightly smaller (2/3 in.) version had also emerged and became the device of choice for portable electronic news gathering/electronic field production (ENG/EFP) cameras. In the following years, designers of camera pickup tubes kept improving and innovating, with the development of technologies such as the diode gun Plumbicon, bias lighting, the Saticon, and the High-gain Avalanche Rushing amorphous Photoconductor (HARP) pickup tube target structure. However, the role of such imaging devices in TV was destined to change, and by the 1980s, work had been underway for some time on a solid-state imager based on CCD principles. An early first manifestation of these research and development efforts in the commercial TV arena came at the 1983 SMPTE conference, with both RCA and NEC demonstrating CCD-sensor cameras (**Fig. 7**). Rank Cintel also presented a paper on a CCD telecine implementation and demonstrated a working model. The following year, RCA had improved the technology to the point that the company began taking orders for CCD ENG cameras. The trend away from tube imagers continued to grow, and by 1990, CCD cameras completely overshadowed tube types at the annual National Association of Broadcasters (NAB) Show, with only one manufacturer

FIGURE 7. Larry Thorpe with the first "chip" imager broadcast TV camera, RCA's CCD-1. It was first shown at the 1983 SMPTE conference.

FIGURE 8. Typical 1970s era TV station master control room.

showing a new tube model that year. In just a few more years, it would be impossible to even purchase a new tube-type TV camera.

Imaging devices were not the only things changing in the TV camera world. There was also a push for improved image quality and better audio (**Fig. 8**).

Ideas and Advanced Technologies

Initially, such efforts centered on optimizing existing color TV systems. It was recognized that the presence of the necessary color subcarrier component in NTSC and PAL systems was responsible for much image degradation due to the necessity for restricting high-frequency luminance information in TV receivers in order to minimize luminance/chroma interactions. A major improvement in display devices resulted from the implementation of comb filtering technology in this area. Another approach—again recognizing the degradation caused by chroma subcarrier component—took the form of keeping red, green, and blue (RGB) video signals unencoded for as long as possible in the content production chain. This movement, termed "CAV" (component analog video), blossomed during the 1980s, with equipment manufacturers producing CAV switchers and other hardware to facilitate the creation of graphics rooms and other facilities where it was desired to work with unencoded RGB video. Much interest was expressed in CAV technology at the 1983 SMPTE conference, and at the 1985 conference, it was predicted that CAV would endure for some 10 years before eventually being replaced with digital video technology. Mirroring efforts to improve production of TV content via CAV, transmission systems were also developed for delivering unencoded RGB to the home. Multiplexed analog component (MAC) technology promised much better end-to-end TV images, and by 1985, the U.S. Advanced Television Systems Committee's (ATSC's) Enhanced 525-Line Technology Group was evaluating two such systems for transmission: CBS's B-TMC and Scientific Atlanta's (S-A) B-MAC.[1] The following year, the ATSC's Technology Group formally recommended the S-A B-MAC system for use in satellite transmission of video.[2] Both NTSC and PAL B-MAC systems were developed, but their use was limited to direct-to-home satellite transmissions, as signals were not backwardly compatible with existing terrestrial transmission systems.

From TV's inception onward, audio was referred to as "video's poor stepsister." This also began to change, beginning in the late 1970s with U.S. Public Broadcasting Service's (PBS's) delivery of stereo audio to member stations through its "DATE" (digital audio transmission equipment) technology. TV stations were not able to transmit two channels of audio, though; thus, one of the channels had to be transmitted by an associated public radio outlet. This changed in the 1980s, with the Federal Communications Commission's (FCC's) approval of stereo transmissions by TV broadcasters.

The Move to Digital TV

Even while such improvements for improving television quality were being made, the realization existed that digital technology would eventually eclipse analog. More and more digital technology had been integrated into broadcast products such as time base correctors, cameras, audio and video signal processors, and standards converters, and a complete movement of video and audio into the world of digital seemed inevitable. The Society had recognized this as early as 1974 with the establishment of a study group on Digital Television, and a working group on Digital Television Standards three years later. Additional early SMPTE digital involvement included the creation of a study group on Digital Tape Recording in 1979. SMPTE was not alone in its investigation of digital TV (DTV) technology, and during the 1970s, SMPTE had been engaged in informal interaction with organizations such as the European Broadcasters Union (EBU). Such collaborative efforts were formalized in 1980 by the creation of a task force on Component-Coded Television.[3]

By 1981, sufficient technology was in place to allow a full "digital TV station" laboratory to be created at San Francisco's KPIX-TV broadcasting facility (**Fig. 9**).[4] Assisted by Ampex, the SMPTE working group on Digital Video Standards assembled this temporary facility by using both state-of-the-art and developmental equipment, which included a live camera, a film scanner, test signal generators, digital encoding and decoding devices, and a digital VTR. (RGB signals were delivered from the camera in analog format but were transformed into component digital sources for the demonstration.) The event

FIGURE 9. This DTV demonstration was set up at San Francisco's KPIX TV facility to allow attendees at the 1981 SMPTE Television Conference to have a first-hand look at TV's future.

was timed to allow attendees at the 15th annual TV conference held in San Francisco to view the setup for themselves, and attracted a great deal of attention.

Events, such as this experimental DTV facility, helped drive home to policy makers, broadcasters, equipment manufacturers, standards organizations, and others that the shift to DTV technology was underway and that serious study needed to be done to map out the best plan for a digital future.

In the U.S., this need to move away from the NTSC color standard that had served the country (and a number of others) beginning in the early 1950s was underscored by remarks made by the CBS Broadcast Group's vice president of engineering and development, Joseph Flaherty, during an interview at the 1983 NAB Show. He opined that "the NTSC composite signal [had] moved from seriously ill to critically ill," and by 1984, it would likely be "dead" in terms of signal processing capability. He concluded, however, that it would still exist as a transmission standard for a long time.[5]

The 1980s saw increasing interest and activity in digital broadcast and production technology (**Fig. 10**), with some 45 papers on digital technology being published in the *SMPTE Journal* between 1981 and 1985 alone.

This period also saw the development and refinement of technologies for data compression, without which broadcast transmission of DTV would have been impossible. These compression technologies began to arrive in usable form in the early 1990s and set the stage for DTV broadcasts, allowing 270 Mbit/sec standard-definition and 1.5 Gbit/sec HD video to be transmitted within existing U.S. 6 MHz broadcast channels with a digital throughput of less than 20 Mbits/sec. (Similar reductions were necessary to accommodate DTV signals in existing 7 or 8 MHz TV broadcast channels used in other parts of the world.)

Moving into the HD World

The BBC's launch of the world's first regularly scheduled TV service in 1936 was also billed as "the world's first HD television service," and, indeed, it was at 405 lines. The U.S. was still experimenting with 343-line video at the time, and no one else was close to 405 operations either. Ever since, there has been a push for higher and higher line counts, with the French launching an 819-line service in the late 1940s. However, throughout the three decades, the world seemed generally content with either 525- or 625-line video. That began to change in the 1980s, concurrent with the drive for DTV systems.

Japan's NHK was an early advocate of HDTV, beginning work on what became known as "MUSE" (multiple sub-Nyquist-sampling encoding) in the early 1980s, and launched an experimental 1 hr satellite-delivered daily broadcast beginning in 1989).[6] It provided 1125/60 interlaced video with a 5:3 aspect ratio but could not be accommodated in a standard 6 or 7 MHz TV broadcast channel.

By the mid-1980s, interest in HDTV was running quite high, as evidenced by the presentation of a large number of papers on the topic at the fall SMPTE conference. There was also strong interest in establishing a global HDTV standard based on the Japanese system. In 1985, the Advanced Television Systems Committee (ATSC) prepared a document for presentation at the CCIR (now International Telecommunication Union Radiocommunication Sector [ITU-R]) recommending 1125/60 as an international standard, with the CCIR's study group later voting to endorse the standard. However, France, The Netherlands, and West Germany

FIGURE 10. 1982 test of Sony HD camera by CBS Sports; HD video was beginning to make news.

expressed reservations about moving away from the long-established European 50 Hz field rate. (In 1986, Philips, Thomson, Bosch, and Thorn/EMI began work on a 50 Hz HD system in a project dubbed "Eureka.")

The 1986 NAB Show featured what was termed "the world's largest exhibit of HD gear," with some two dozen firms showing HD cameras, monitors, recorders, and large-screen projectors. In early 1987, HDTV came to the U.S. capital, with the NHK MUSE system employed for month-long showings sponsored by the NAB and the Association of Maximum Service Telecasters (MSTV).[7]

Excitement about HDTV showed no sign of waning as the 1980s ended and the 90s began, with the NAB's Science and Technology department planning a special 30,000-foot high-definition exhibition area at the 1990 NAB Show. The Soviet Union also began HDTV testing the same year.

However, as is often the case with a change to a new technology or way of doing things, several schools of thought usually exist as to the best way for making the change. This was especially true in the United States. Early proposals addressed the requirement for backwards compatibility with the existing NTSC system so as not to disenfranchise those electing not to immediately move to a higher resolution service. Consequentially, initial proposals involved analog, or a mix of analog and digital, broadcasting technologies. Other variables also clouded the HD issue, such as a requirement for square pixels, line and field rates to be used, progressive or interlaced scanning, aspect ratios and more. The FCC took notice of this situation, establishing in 1987 a special committee—the Advisory Committee on Advanced Television Service or "ACATS"—comprised of television industry leaders to evaluate developments and methodologies in this area and make recommendations as to the best path to follow.[9]

A testing facility, the Advanced Television Testing Center (ATTC), which was sponsored by the NAB, ABC, NBC, CBS and PBS television, as well as the Association of Independent Television Stations and the MSTV, was created and began operations in late 1987. The facility was designed to serve as a test bed for both advanced and high-definition systems for the ATSC and the FCC's ACATS.

An initial move was to solicit proposals for an improved TV system, with more than 20 entities responding. This number was eventually winnowed down to six systems. As testing proceeded during the next several years, several decisions were made that shaped the direction of HD service in the U.S. These included a complete move away from analog transmission systems with no requirement for backward compatibility, and also an FCC decision to grant each TV broadcaster an additional 6 MHz channel for transmitting a DTV service. This grant was temporary in nature, with the spectrum eventually to be returned once a predetermined analog-to-digital transition period had ended. By early 1993, the initial ATTC evaluations had ended with no clear "winner." To stave off further delay and expense (each entrant had been charged $200,000 to participate in the initial testing), on May 24, five of the contenders reached an agreement to partner in developing a system that would combine the best features of each of the contenders' technologies. This coalition became known as "The Grand Alliance." With this development, ACATS was able to finally complete its tasking by delivering an advanced (digital) TV standard to the FCC on 28 November 1995.[10] Within a few months, the standard had been accepted, and the FCC began issuing licenses for several experimental HDTV stations.

The first of these to place an HD signal on the air was the privately owned WRAL-HD in Raleigh, North Carolina,

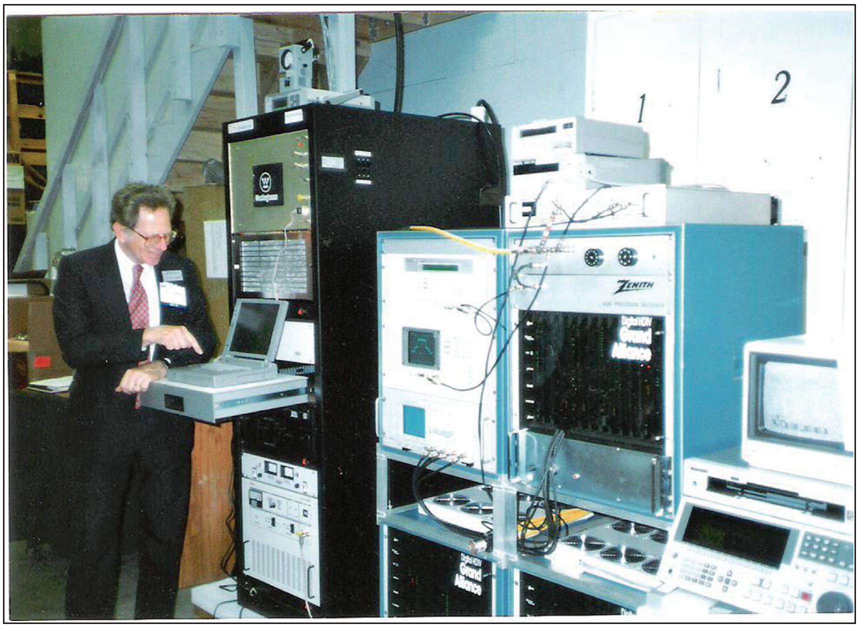

FIGURE 11. Ed Williams examines some of the equipment used in the WHD-TV test facility in Washington, District of Columbia.

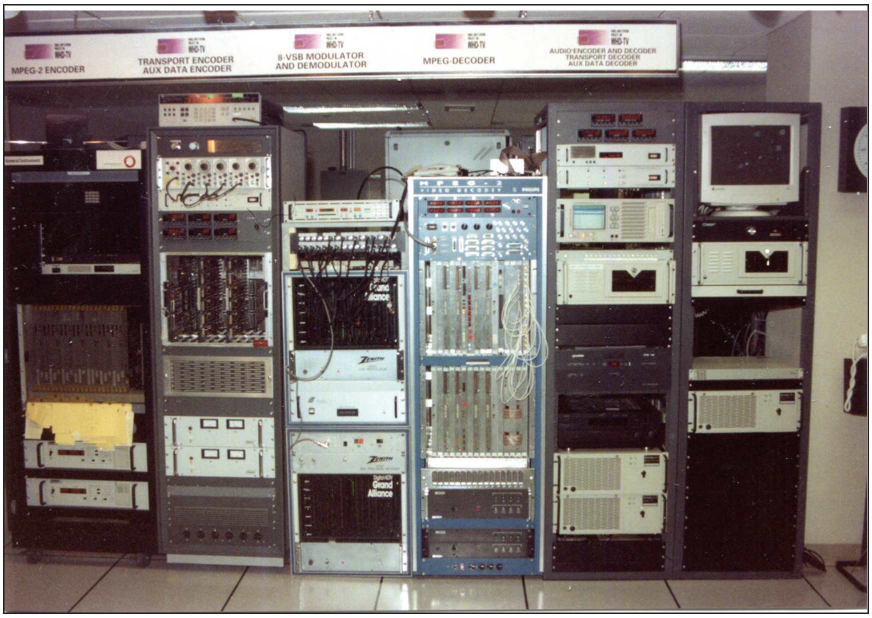

FIGURE 12. Additional WHD-TV HD equipment.

with an initial test broadcast taking place on 23 July 1996.[11] Other operations included WHD-TV in Washington, District of Columbia, which was created by a consortium of companies and organizations with broadcasting interests, including the NAB (**Fig. 11**). WHD-TV was colocated with the city's NBC owned-and-operated WRC-TV, and served as a test bed for testing developmental HD equipment in over-the-air broadcasts (**Fig. 12**).[12] (Another experimental field test facility developed during this was located in Charlotte, North Carolina (WWHD-TV), and was operated under the auspices of the ACATS (**Fig. 13**). It transmitted on both very high (VHF) and ultra high (UHF) frequencies.)[13]

FIGURE 13. Vehicle used for measurements in connection with HDTV field test operations in Charlotte, North Carolina.

In an effort to create awareness of the DTV transition, broadcast equipment manufacturer Harris Corp. and the U.S. PBS teamed to launch the "DTV/Express," a 66 ft long, 18-wheel vehicle that contained a complete low-power DTV station, a classroom, and a "Living Room of Tomorrow" where visitors could get a glimpse of what digital television would look like when it entered the home (**Fig. 14**). The tour began, in March 1998, in Capitol Hill, Washington, District of Columbia, and ran until August 1999, with week-long stops in 49 U.S. cities. It was billed as the "first fully-functional DTV station," including, in addition to the transmitter, an HD camera, MPEG encoder, and other elements necessary for generating and transmitting DTV signals. (In several cities on the tour, FCC "Special Temporary Authorization" (STA) had been secured, and the vehicle was able to couple into a transmitting antenna and radiate a DTV signal over the air. Classes offered to broadcasters included the basics of digital video and audio, RF transmission of digital signals, and business aspects (such as transmission of multiple program streams) associated with the shift to digital broadcasting.

The U.S. DTV standard (ATSC 1.0) allowed broadcasters to transmit multiple program streams in their choice of several line standards (480 interlaced or progressive, 720 progressive, or 1080 interlaced). It also allowed transmission for the first time of multichannel "surround sound" audio (5.1 channels) in addition to stereo. However, ATSC 1.0 lacked the capability for satisfactory transmission to moving receivers (mobile and portable). This deficiency was addressed with the creation of ATSC 2.0 in 2014 as an enhancement to the original 1.0. A government-subsidized program was created to allow owners of analog receivers to receive the

FIGURE 14. The Harris/PBS "DV Express" toured the U.S. in 1998 and 1999, providing a first look at digital video and HD for many. It contained a complete HDTV station, a classroom, and an HDTV viewing room. (Photo Credit: Kelly Cmielewski)

digital broadcasts. A timetable was established by the FCC for moving to a completely digital broadcasting environment; however, the analog shutoff date slipped several times before all high-power TV stations finally went to fully digital operations on 12 June 2009, thus ending some 70 years of analog TV transmissions.

Several European nations made digital transitions prior to the U.S., and others have made DTV transitions have made DTV transitions since then; however, today there are still a number of countries and regions with analog service. While a complete transition to digital broadcasting is not expected for almost another decade, in 2016, HDTV imagery is the norm rather than the exception in most countries. It is difficult to imagine a major sporting event or concert being telecast in standard definition at this point in time.

Along with this global shift to digital broadcasting and HD, it is interesting to examine some of the other evolutionary changes in TV technology during the past four decades.

FIGURE 15. The 1956 2 in. "quad" videotape format was still in use in the mid-1970s, but this would eventually be replaced by smaller and more economical to operate 1 in. "type C" VTRs. The machines shown here are from RCA.

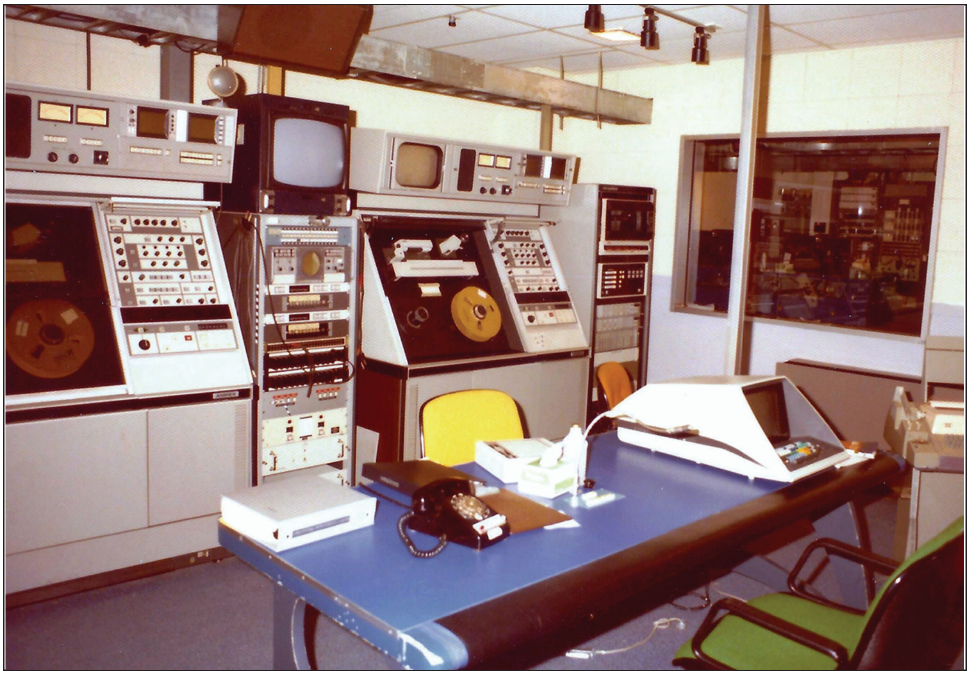

FIGURE 16. A 1970s computerized videotape editing suite. The VTRs are Ampex AVR-1 2 inch "quad" machines. The CMX-300 edit system was driven by the DEC PDP-11 computer in the rack on the right. Also on the right and just partially visible is an ASR-33 Teletype machine used to print the edit decision list (EDL).

Video Recording/Playback Technology

As described previously, the 2 in. quadruplex videotape format (inaugurated in 1956) was still considered to be the industry standard in 1976 (**Figs. 15** and **16**). However, due to the need for portability, Sony's 0.75 in. "U-matic" cassette format, which had been intended for institutional and educational applications, had been pressed into service for ENG applications. In addition, with the partnering of Ampex and Sony in creating a common high-performance 1 in. videotape standard ("type C") in 1976, and Ampex's development of "automatic scan tracking" technology for optimizing playback of this format, the popularity of "quad" began to slip by the end of the decade.

Not long after the introduction of the "type C" helical format, others began to appear: 0.5 in. Betacam and "M," along with a succession of digital formats that included D1, D2, D3, D5, D9, Digital Betacam, DCT, D5HD, DVCAM, DVCPRO, DVCPROHD, HDCAM, and others. However, some new technologies for video recording were also being developed, including the laserdisk. Heralding the start of a move to a "tapeless" environment was the showing of a solid-state recording device from NEC at the 1987 NAB Show. It could store more than 2 min of video. Other "tapeless" recording devices and technologies followed, leading up to a widespread introduction of video file servers at the 1994 NAB Show

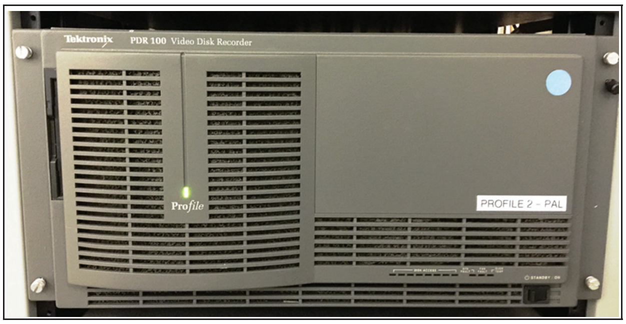

FIGURE 17. Video file servers began showing up at trade shows in large numbers beginning in the mid-1990s. This Tektronix Profile premiered at the 1994 Las Vegas NAB Show.

FIGURE 18. The Ikegami "Editcam" (an Ikegami and Avid joint venture) featured a dockable disk drive for speeding up editing operations. The 1995 camcorder was an early entrant in the "tapeless" TV production workflow.

FIGURE 19. This 2004 Panasonic camcorder marked the beginning of video capture in the field in solid-state storage media (P2 card) and also helped to define TV's tapeless production workflow.

(**Fig. 17**). At least nine manufacturers offered server devices for video applications, leading NAB's manager of TV engineering Kelly Williams to comment that the industry appeared to be on the "cusp" of a real revolution.[14] Video compression technology, which had also paved the way for DTV transmission, helped make such storage technology possible.

Subsequent NAB Shows saw other implementations of "tapeless" technologies, beginning in 1995 with Ikegami's "Editcam" which featured a ruggedized dockable hard drive that eliminated the time-consuming requirement to copy tape recordings to a hard drive before initiating a nonlinear edit session (**Fig. 18**). Ikegami had partnered with Avid in developing the product. Sony followed suit in 2003 with the introduction of its XDCAM camcorder, which recorded on an optical disc. The following year, Panasonic showed the first camcorder that captured on the company's P2 solid-state memory cards (**Figs. 19** and **20**). Use of videotape as a storage medium has continued to decline, with many longtime producers of tape ending production in the early 21st century.

FIGURE 20. Panasonic's first-generation P2 solid-state digital video storage card has a 2-Gbyte capacity.

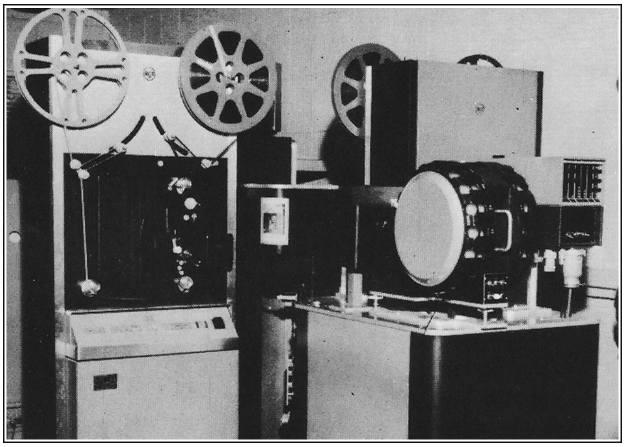

FIGURE 21. Film played a large role in broadcast TV from the 1930s well into the early 1980s. This is a typical telecine operation (also known as a "film island") from the 1970s. A remotely-controlled 35 mm slide projector is visible to the right of the photograph. It is flanked by the 16 mm motion picture projectors. The object in the center is an optical multiplexer, which was used to direct images from either projector into the telecine camera unit.

Lenses

A key part of the TV imaging system is the camera lens, and technology did not stand still in this area either. In 1976, the process of lens design differed little from that employed for nearly 100 years. A formula for the desired lens properties was established, and numerous trigonometric calculations were performed to help model the propagation of light rays through a medium with differing refractive indices. This very laborious process was speeded up to some degree by the use of mainframe computers to assist in performing calculations. The process was further enhanced when more powerful computers were developed in the 1980s and software written to generate optical designs. By the 1990s, virtually all lenses were being designed by computer software. This led to more and more sophisticated units (some employing as many as 40 separate lenses) with the greatly improved optical properties that would be needed for the move by TV first into the realm of HD and somewhat later into UHD. It is now relatively easy to create variable focal length lenses with up to 10 times the zoom ratio available in the 1970s. Color rendering characteristics of lenses have been also greatly improved during the past four decades by the development and application of multiple coatings to various elements. Ease of use and imaging acuity have been aided also by the use of servo system technology for canceling the effects of vibration or movement (image stabilization) and also to make it easier for a camera operator to achieve consistently sharp pictures (autofocus).

Film Technology

Although the ENG movement, which began in the mid-1970s, eventually spelled the death knell of TV news film operations, many stations continued to maintain film cameras and film processing and editing operations for a number of years after ENG and EFP were firmly entrenched in the broadcast industry. Similarly, 16 mm telecine equipment remained in operation for airing such locally produced footage (**Fig. 21**). Film distribution of syndicated programming and feature movies for airing on TV continued well into the 1980s before being replaced by videotape media. New telecine developments also continued into the 1980s, with Rank Cintel presenting a paper on a new CCD line array HD telecine at the 1983 SMPTE conference, and also displaying a working unit on the exhibit floor. However, by the turn of the century, film had almost completely disappeared from the TV landscape, save for digital restoration of classic movie projects and the conversion of such classic movies to digital format for airing and direct distribution to consumers in DVD and Blu-ray formats.

Distribution and Connectivity

Viewership of over-the-air TV broadcasts has shrunk considerably since 1976, with estimates today varying between 10% and 15% of the U.S. population obtaining programming in this fashion. Similar trends are reported in a number of other nations as well. The TV broadcast spectrum has diminished also in the last four decades. In the U.S. , this began with the FCC's reallocation of TV channels 70-83 for land mobile use. Another U.S. TV broadcast spectrum shrinkage occurred in 2009 after the mandatory shutoff of analog transmissions by full-power broadcasters, with the auctioning of spectrum formerly occupied by channels 60-69 to wireless broadband companies. As of this writing, another U.S. plan ("the incentive auction") is underway as part of an effort to encourage TV broadcasters to voluntarily relinquish spectrum for other purposes. Similar reallocation of TV broadcasting spectrum in other parts of the world has occurred, and this trend shows little sign of abating. In parallel with the auction, U.S. broadcasters have petitioned the FCC to permit use of a new broadcast format (ATSC 3.0) using coded orthogonal frequency division multiplexing (COFDM) techniques allowing satisfactory operation with both fixed and mobile viewing devices.

This movement paralleled the adoption of satellite technology by the cable TV industry and eventually led to the rise of the direct-to-home delivery of content via satellite (direct broadcast satellite or "DBS"), an industry that has become global in scope by 2016.

Terrestrial Broadcasting Technologies

Despite the loss of TV broadcast spectrum to wireless broadband providers in the U.S. and other countries, terrestrial broadcasting is expected to continue for quite some time, with transmitter technologies undergoing change also. In recognition of the global "green movement" for reducing release of carbon dioxide and other pollutants associated with the burning of fossil fuels in generating electrical power, transmitter manufacturers have been designing increasingly more energy-efficient models for several decades. Where tetrode vacuum tubes were once the only choice available for generating VHF TV signals, they have been almost completely replaced by solid-state devices. Making more energy-efficient UHF transmitters has also been underway since the 1970s. The demand for higher power levels associated with operation in the UHF spectrum made the multiple-cavity klystron the transmitting tube of choice practically at the birth of TV broadcasting in the upper channels. Despite the advantages of using the klystron in broadcast service, it suffered from low efficiency, and a number of technologies have been developed during the past several decades to improve operating efficiency. In the mid-1980s, a new device was introduced for UHF amplification that combined the best features of tetrodes and klystrons, the "Klystrode" or "IOT" (inductive output tube). The IOT offered greater efficiency, higher reliability and, more important, concurrent with the shift to DTV, is its ability to be operated in a common amplification mode in analog or digital service, something not possible with a klystron. This advantage ultimately moved the IOT transmitter to a position of "industry standard" as broadcasters transitioned from analog to digital service. Beginning in the early 2000s, the efficiency of the device has been increasing, resulting in operating efficiencies of greater than 50%. However, the ascendency of the IOT will likely not continue as solid-state RF-producing technology continues to develop, with models available now from several manufacturers capable of producing several tens of kilowatts in the UHF TV broadcast spectrum, and at least one manufacturer offering an 80 kW tubeless solid-state UHF transmitter. It is expected that the vast majority of new transmitter installations resulting from the U.S. post-auction channel-shifting repack operation will feature solid-state models.

A 2016 TV transmitter facility with its small-footprint modular solid-state amplifiers and their associated low operating voltages and greatly simplified cooling systems might appear quite strange to a 1976 transmitter technician.

The Internet

One of the biggest "sea changes" in the industry involved the "World Wide Web," or the internet. Once commercial service providers began to emerge and create public awareness of this far-reaching digital communication system in the late 1980s, both curious experimenters and profit-minded entrepreneurs began to probe the capabilities of the rapidly expanding network. One such usage involved the transport or "streaming" of video. While early demonstrations were less than satisfying in terms of quality, research continued, and by 1997, several computer-related entities (Intel, Microsoft, and Compaq) appeared at the 1997 NAB Show to tout internet-delivered video to what was largely a community of traditional broadcasters. As might have been expected, the reception was less than warm, and a year later, the companies were still smarting.[15] In just a few years, however, broadcasters had warmed up to the idea of using the internet to increase their reach and were beginning to accept the new communications modality. Following the 2000 NAB Show, one industry publication summed up the strengthening broadcaster/internet relationship with the headline "NAB: A New Door Opens."[16] As video compression and streaming technologies continued to improve, more and more broadcasters embraced the internet, offering a wide range of viewer services and realizing significant revenue streams from this enterprise. In 2016, internet access to video content via personal devices, such as "smart phones" and "tablets," is ubiquitous and rivals other viewing modalities.

Satellite Technology

The U.S. PBS network broke away from traditional AT&T Long Lines connectivity with its member stations (affiliates) in 1978 by shifting program feeds to satellite (Westar). Seven years later, in 1985, NBC TV followed PBSs' lead, with the distribution of content to affiliates via Ku-band transponders on Comsat spacecraft.[17] The other "classic" networks (ABC and CBS) also moved to satellite distribution, with AT&T Long Lines discontinuing both TV and radio network relay services in the 1980s.

Linkage of broadcast networks with their affiliates was not the only area into which communication satellites were seeing use. In late 1975, the fledgling cable pay-TV service, HBO (Home Box Office), seeking a way to increase its reach beyond New York City, began transmitting specialty programming to other U.S. cable systems. In just a few years, cable systems all across the country were receiving satellite-delivered premium content. This connectivity also led to the rise of U.S. TV "super stations," including Atlanta's WTCG (later WTBS), Chicago's WGN-TV, and New York's WOR-TV (now WWOR), with their regular broadcasts appearing on cable systems in every state of the union. (Importation of distant TV signals by cable systems had been achieved earlier on a limited basis by microwave radio linkage, but the advent of satellite connectivity soon obsoleted terrestrial linkage due to its near-universal reach.)

During the mid-1970s, interest in satellite-delivered video began to develop in another group, the home experimenters, with England's Steve Birkhill being credited as the first individual to privately access video being transmitted from a communications satellite (a U.S. spacecraft "on loan" to India as part of an initiative to transmit educational programming to that country's population on a widespread basis).[18] Reports of Birkhill's successful downlinking with rather primitive home-built equipment set off a groundswell of activity by similar-minded experimenters (and some entrepreneurs) in the U.S. and other parts of the world in unraveling the technological "secrets" for relaying video employed by commercial satellite carriers. This movement paralleled the adoption of satellite technology by the cable TV industry and eventually led to the rise of the direct-to-home delivery of content via satellite (direct broadcast satellite or "DBS"), an industry that has become global in scope by 2016. High-power downlink transmitters on satellites have made possible the use of very small aperture receiving antennas or "dishes" that can be installed virtually anywhere, thus providing a wide choice of viewing for consumers and allowing broadcasters and content creators to reach vast audiences.

Another giant leap in improving TV image quality began in the early 2000s, with emphasis on increasing resolutions beyond 1000 lines, boosting image contrast or "dynamic range," and a wider gamut of colors.

Other Video Linkage Modalities

Alternatives to microwave radio and coaxial cable for linkage of TV facilities developed in the 1970s, with the emergence of both point-to-point optical relay systems and fiber-optic connectivity in the late 1970s.

Another connectivity revolution of sorts took place in the latter half of the first decade of the new century, with wireless broadband company-funded replacement of existing TV station BAS (broadcast auxiliary service) analog microwave systems with digital gear as part of an effort by the carrier to obtain additional spectrum. Known as "the Sprint Nextel initiative," the conversion affected all broadcast operations using 2 GHz spectrum and netted Sprint Nextel some 35 MHz of spectrum in that region.

"Bonded cellular" or "backpack ENG connectivity" emerged in 2009[19] and has steadily increased in popularity for transmitting live video feeds from the scene of breaking news events back to studio and network operations. The technology involves "inverse muxing" of digital video across multiple cellular connections to obtain necessary transmission bandwidth. Although there are some drawbacks (occasional overloading of the cellular telephone network due to too many simultaneous users), bonded cellular has sidelined the use of ENG microwave and satellite vehicles in many situations due to ease of mobility and deployment, as well as substantial savings in operational costs.

Displays

TV display devices began to change too as technology moved closer to the 21st century. While the venerable CRT (with a great number of enhancements and embellishments) remained the display device of choice through the 1990s in both consumer receiver and broadcast monitor applications, the liquid crystal display (LCD) was beginning to attract attention as it delivered the capability for achieving the fabled concept of "hanging one's TV on the wall."

In addition to LCD, several other video display technologies also emerged during the 1990s and early 21st century. These included organic light-emitting diode (OLED) and plasma; however, with continued improvements in LCD technology, interest in plasma displays began to decline, with manufacturers eventually discontinuing production during the 2010s. (CRT production ceased some 10 years earlier, leaving LCD and OLEDs as the dominant display technologies today. It is imagined that even more display modalities and systems will emerge in the coming years (a 360° TV display "sphere" with touchscreen control was shown at the 2015 IBC Show).

One of the more interesting TV display developments during the shift away from CRTs arrived in 1987 in the form of the DLP or dynamic light processor integrated circuit developed by Texas Instruments. It was considered revolutionary, but actually harkened back to the era of mechanical TV and field sequential color. The chip consisted of a very large number of tiny reflective surfaces (micromirrors) with each independently addressable and able to be manipulated at a video rate, thus acting as a "light valve" for controlling an external light source. With the DLP, color displays can be achieved through the use of a white light source and a rotating color wheel, or by using three chips with RGB light sources. The technology has been used in consumer devices and also forms the basis for some HDTV projectors.)

FIGURE 23. Over-the-air UHD TV demonstration at the 2016 Las Vegas CES.

FIGURE 22. NHK's 8K Super Hi-Vision camera.

Further TV Progress

Another giant leap in improving TV image quality began in the early 2000s, with emphasis on increasing resolutions beyond 1000 lines, boosting image contrast or "dynamic range," and a wider gamut of colors. The arrival of the 21st century also saw serious study being given to further improving audio, enabling interactivity between viewer and broadcaster, transmission of targeted or "hyperlocal" information (i.e., notification of impending violent weather activity for viewers in the immediate path of a storm), and other enhancements to basic TV broadcast service.

The initial results of such research and development efforts were first revealed in 2005, when NHK began publicly showing its "Super Hi-Vision" 4000-line (8K) TV system in Japan (**Fig. 22**), and at the NAB Show in Las Vegas the following year. This NHK system also provides 22.2 channels of audio to provide "immersive" sound for viewers. NHK's pioneering work in advanced TV led to SMPTE standardization of the 8K video format in 2007 and the 22.2-channel audio in 2008.

Work continues in enhancing this NHK system; however, during the past four years, a somewhat lower resolution TV system has attracted a great deal of interest. This is UHD or "4K" with 2000-line capability. Public showings were staged in connection with the 2012 London Summer Olympic Games, and several TV receiver manufacturers have been marketing 4K sets since that time. Sources of UHD content are at present limited basically to direct-to-home satellite and internet streaming sources. In 2012, Sony marketed a 4K receiver with UHD content preloaded on an accompanying drive, and at the 2016 Consumer Electrics Show (CES) at least two manufacturers UHD Bluray players); however, this is due to change with the introduction of the ATSC 3.0 TV standard in another year or so. Demonstrations of over-the-air transmission of 4K content were performed at the 2016 CES event in Las Vegas (**Fig. 23**), and South Korea has announced that the 2018 Winter Olympic Games being held in that country will be broadcast in 4K.

As noted earlier, the U.S. is preparing for another digital broadcasting transition which should begin soon after completion of the full embodiment of the ATSC 3.0 standard. (As of this writing, development work on most of the standard's layers has been completed, but there are some that are still being finalized.) The standard was designed to be very flexible and extensible, allowing the transmission of 2000-line and higher resolutions, high-dynamic-range imagery, extended color gamuts, higher frame rates, highly satisfactory mobile and portable reception, and immersive multichannel audio. It also incorporates IP-based technology, allowing hybrid over-the-air and internet delivery of content, thus opening the way for consumer interactivity and targeted delivery of information. As ATSC 3.0 is being developed by an international team, many nations have expressed interest in adopting the standard; however, it is much too soon to speculate that there could eventually be one global standard for TV. It would appear that we are considerably closer to this than in 1976!

Conclusion

In summing up their 1976 paper, authors O'Brien and Monroe noted that it was regrettable that space did not permit their listing of all the individuals and their achievements that had led to the TV system being enjoyed then. The same situation exists in 2016, with a single journal article woefully inadequate to list more than just a few of the players and accomplishments that have, in just 40 short years, resulted in a TV system with image quality, flexibility, accessibility, and immediacy in terms of being able to cover breaking news events that was undreamed of in 1976. A multivolume encyclopedia would scarcely be adequate for fully reporting all of the progress in the science of TV occurring since publication of the O'Brien and Monroe paper. Indeed, TV's progress in the past 40 years has closely mirrored "Moore's law."

It is interesting to note and reflect on the five "confrontations" among technologies noted by O'Brien and Monroe at the conclusion of their "progress" article. These include the "contests" between the following: use of film and videotape for program production, 2 in. quadruplex videotape and emerging helical scan formats, replacement of the "surviving" videotape recording methodologies with the "concept" of digital recording, over-the-air terrestrial broadcasting versus other modalities for distributing TV content, analog versus digital technology, and the replacement of the (then) remaining vacuum devices employed in television (camera pickup tubes, CRTs, and high-power transmitter tubes) with "some form of solid-state technology," noting that this last shift would be "the only part [that is] difficult to predict," but when it does, "…Fleming's, De Forest's, and Zworykin's great contributions will have served their time."

Of course, in 2016, we have almost arrived at the point envisioned by O'Brien and Monroe, and are operating in a world completely devoid of camera tubes and CRTs, and increasingly broadcasters are moving to solid-state transmitter platforms.

It is extremely difficult to envision a point in time when some new technology will replace the inventions based on the work of Shockley, Bardeen, Brattain, Noyce and Kilby; however, it would be foolish in the extreme to "never say never." That point may well come; television technology is moving ahead at a great rate. We are already experiencing innovations as ultra-thin and flexible LCDs that can be "rolled up," undoubtedly leading to "wearable" TV screens; and it is being conjectured that it may be possible to eventually incorporate video displays in skin art, leading to the ultimate "personal portable" TV set.

As noted earlier, the world's first scheduled TV service began 90 years ago. It will be very interesting to see where the medium goes in the next 90 years, or even the next 40!

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The Last 100 Years of Motion Imaging

By John Belton

The history of moving image technology is, in fact, a history of moving image technologies (i.e., a history not of one but of many technologies). The *Journal* has broken this history down into a series of film and video timelines, on pgs. 138-160, each of which, in acknowledgement of this, is broken down into categories of technological development that have informed the growth of moving image technology as a whole. Motion picture film, for example, evolved slowly within a horizon of other industrial technologies, ranging from photochemistry, optics, photography and cinematography, phonography, radiotelegraphy, telephony, and audio electronics to various digital technologies. At each moment in its history, film is an ever-changing entity—not a fixed object but a site where multiple technologies meet.

The history of video imaging is similarly multitechnological. The average consumer undoubtedly thinks that television and video were simple extensions of film technology. After all, television came after film, didn't it? However, video imaging has its own complex technological lineage, which has nothing to do with photochemistry, but looks directly back to sound (e.g., the phonograph industry and radio) and the transmission of electrical signals from one point in space to another to another (e.g., the telegraph, telephone, and Marconi's wireless telegraph). Does the general public know that videotape has its origins in the magnetic tape developed by the Germans for sound recording in the 1930s or that one of the major breakthroughs in the development of the Ampex videotape recorder in 1956 involved the conversion of video signals to a broadcasting format—to FM signals—before recording them?

These timelines then tell the story of various related strands of technological development that informed the development of the motion picture industry, television, and digital imaging. It is the story—or, rather, stories—of the coordination of research and development programs across a broad spectrum of different media and teams of engineers from a variety of disciplines who drew upon one another's work to develop and improve moving image technologies.

Readers might want to note that there is no clearly marked boundary in either chronology between analog and digital technologies. The trajectory from rotoscoping (1914) to motion capture (2002) can be seen as early and late features of a larger continuity that characterizes the development of motion imaging technologies. Similarly, images sent by telegraph in 1904 share the same conceptual DNA of video transport over IP networks, referenced in the video timeline in the form of SMPTE 2036-x and 2022-x standards for IP transport (2007). From our vantage point in the present, the so-called digital revolution looks more and more like a linear *evolution* from one stage of technological development to the next. Digital emerges as a crucial tool that facilitates this evolution—an evolution that could not have occurred without it—and although digital has transformed the way we create, process, and distribute the moving image, what we consume at the other end is in analog form.

These timelines then tell the story of various related strands of technological development that informed the development of the motion picture industry, television, and digital imaging.

These timelines provide a portrait of technological development that enables us not only to see new connections between the past and the present but also to reconceptualize the nature of moving image technology itself. For example, one of the most striking features of the "film" timeline is the importance (in terms of its placement and length) that the category of Visual Effects (VFX) and Animation plays. This category comes first and is longer than other sections in the timeline. How can we explain that? From the vantage point of the digital present, the moving image can be seen as a visual effect, as the by-product of external manipulation. This is inarguably the case with computer-generated imagery (CGI), but is it not also a productive way to understand the illusion of movement itself, whether it be at 24 (film), 30 (television), 48 (Peter Jackson), 60 (Showscan), or 120 frames/sec (high-frame-rate video). As matte artist and cofounder of digital effects company Matte World Digital, Craig Barron, has argued,

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the cinema, as the by-product of various optical toys, originated as a visual effect, and its status as VFX remains part of its identity.

Animation provides an even more compelling way of rethinking the moving image. Barron suggests that the illusion of movement is a special effect that results from the animation of still photographs at 24 frames/sec. In his answer to the question "What is Digital Cinema?" (1995, http://manovich.net/index.php/projects/what-is-digital-cinema), Lev Manovich uses digital cinema as a way of rethinking the history of cinema itself. Manovich argues that "the manual construction of images in digital cinema represents a return to nineteenth century pre-cinematic practices, when images were hand-painted and hand-animated. At the turn of the 20th century, cinema was to delegate these manual techniques to animation and define itself as a recording medium. As cinema enters the digital age, these techniques are again becoming the commonplace in the filmmaking process. Consequently, cinema can no longer be clearly distinguished from animation. It is no longer an indexical media technology but, rather, a sub-genre of painting."

Consequently, cinema can no longer be clearly distinguished from animation. It is no longer an indexical media technology but, rather, a sub-genre of painting.

-Lev Manovich

Barron and Manovich are clearly making arguments that are designed to provoke further thought and debate about the nature of moving image technologies. It is possible to see traces of their arguments in these timelines, but the timelines themselves are not argumentative. They are composed of historical events that the individuals and institutions that authored them consider significant, if we are to grasp the outlines of technological development in moving image technology over the past 100 years. Readers should be cautioned that any technological development's presence in or absence from these timelines reflects the necessary constraints that inform a project such as this, most importantly, including the constraints of space. Any items omitted here have not been left out in order to further an argument, but only because the *Journal* lacks the space to recognize the importance of all of the work that our industries have accomplished over the past 100 years.

About the Author

John Belton teaches film at Rutgers University and is the author of five books, including *Widescreen Cinema*, winner of the 1993 Kraszna-Krausz prize for books on the moving image, and *American Cinema/American Culture*. He edits a series of books on film and culture for Columbia Univ. Press (1989 to present) and is a former member of the National Film Preservation Board (1989 to 1996) and a former Chair of the Archival Papers and Historical Committee of the Society of Motion Picture and Television Engineers (1985 to 1996). He is an Associate Editor of the *SMPTE Motion Imaging Journal*.

The success of the Next Century Fund will contribute to SMPTE's legacy of service to the industry for the next 100 years!

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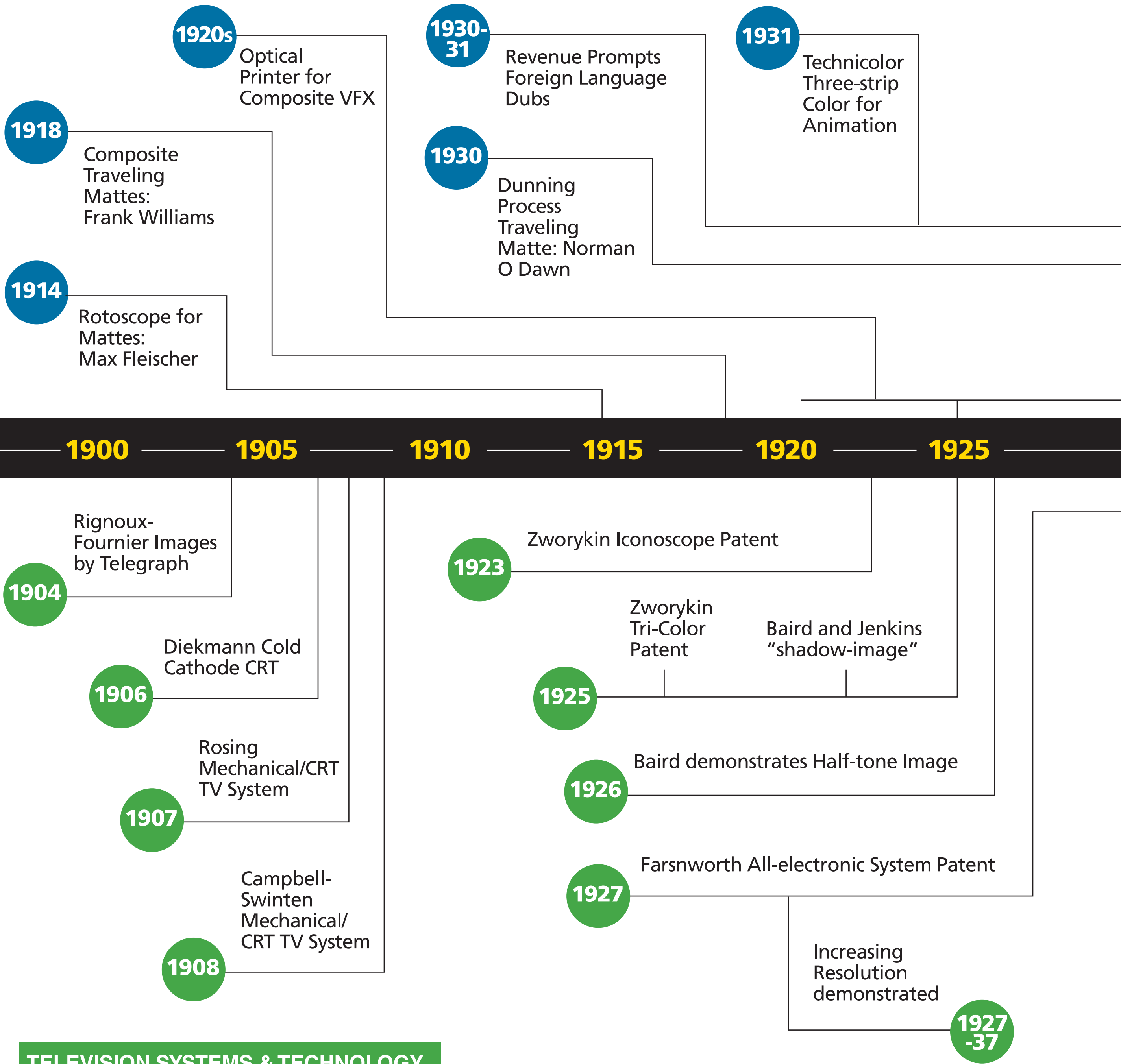
1916 – 2016

VISUAL EFFECTS - ANIMATION

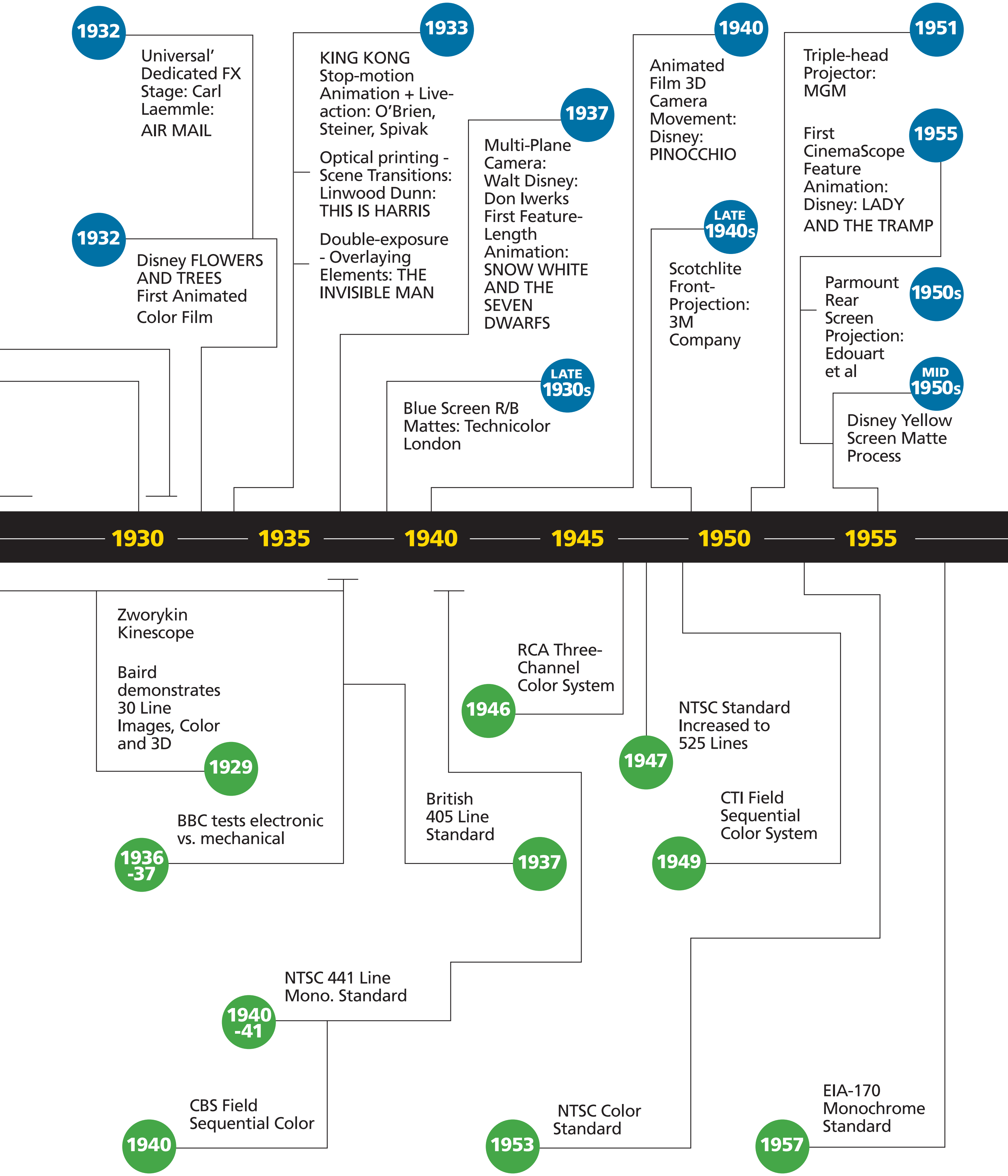
MOTION IMAGING – **FILM** – THE LAST 100 YEARS



TELEVISION SYSTEMS & TECHNOLOGY

MOTION IMAGING – **VIDEO** – THE LAST 100 YEARS

Digital Object Identifier 10.1109/SMPTE.2016.2599105
Date of publication: 30 August 2016


1932
Universal' Dedicated FX Stage: Carl Laemmle: AIR MAIL
1932
Disney FLOWERS AND TREES First Animated Color Film
1933
KING KONG Stop-motion Animation + Live-action: O'Brien, Steiner, Spivak
Optical printing - Scene Transitions: Linwood Dunn: THIS IS HARRIS
Double-exposure - Overlaying Elements: THE INVISIBLE MAN
1937
Multi-Plane Camera: Walt Disney: Don Iwerks First Feature-Length Animation: SNOW WHITE AND THE SEVEN DWARFS
LATE 1930s
Blue Screen R/B Mattes: Technicolor London
1940
Animated Film 3D Camera Movement: Disney: PINOCCHIO
LATE 1940s
Scotchlite Front-Projection: 3M Company
1951
Triple-head Projector: MGM
1955
First CinemaScope Feature Animation: Disney: LADY AND THE TRAMP
1950s
Parmount Rear Screen Projection: Edouart et al
MID 1950s
Disney Yellow Screen Matte Process
1930
1935
1940
1945
1950
1955
Zworykin Kinescope
Baird demonstrates 30 Line Images, Color and 3D
1929
BBC tests electronic vs. mechanical
1936 -37
RCA Three-Channel Color System
1946
British 405 Line Standard
1937
NTSC Standard Increased to 525 Lines
1947
CTI Field Sequential Color System
1949
NTSC 441 Line Mono. Standard
1940 -41
CBS Field Sequential Color
1940
NTSC Color Standard
1953
EIA-170 Monochrome Standard
1957

VISUAL EFFECTS - ANIMATION, CONT.

1916 – 2016

MOTION IMAGING – **FILM** – THE LAST 100 YEARS

1962 Sketchpad Computer Graphics: Evan Sutherland

1964 Traveling Mattes: Technicolor

1968 Slit-scan Photography: Douglass Trumbull
Front Projection: MGM, 3M

1972 Catmull Scripting Language - Animates Smooth-shaded Hand
Fred Parke, computer Facial Animation

1973 First CGI: WESTWORLD

1975 Industrial Light & Magic Founded

1976 First 3D CGI: FUTUREWORLD

1977 "Dykstraflex," Motion-Control: John Dykstra, ILM
3D Computer graphics: STAR WARS

1978 Zoptics Front Projection: Zoran Perisic

c.1980 Empire Camera System: ILM

1981 Introvision Front Projection
First film with Virtual Actor: LOOKER
Quantel Paintbox Digital Paint system
Go-Motion Computer Stop-motion: ILM

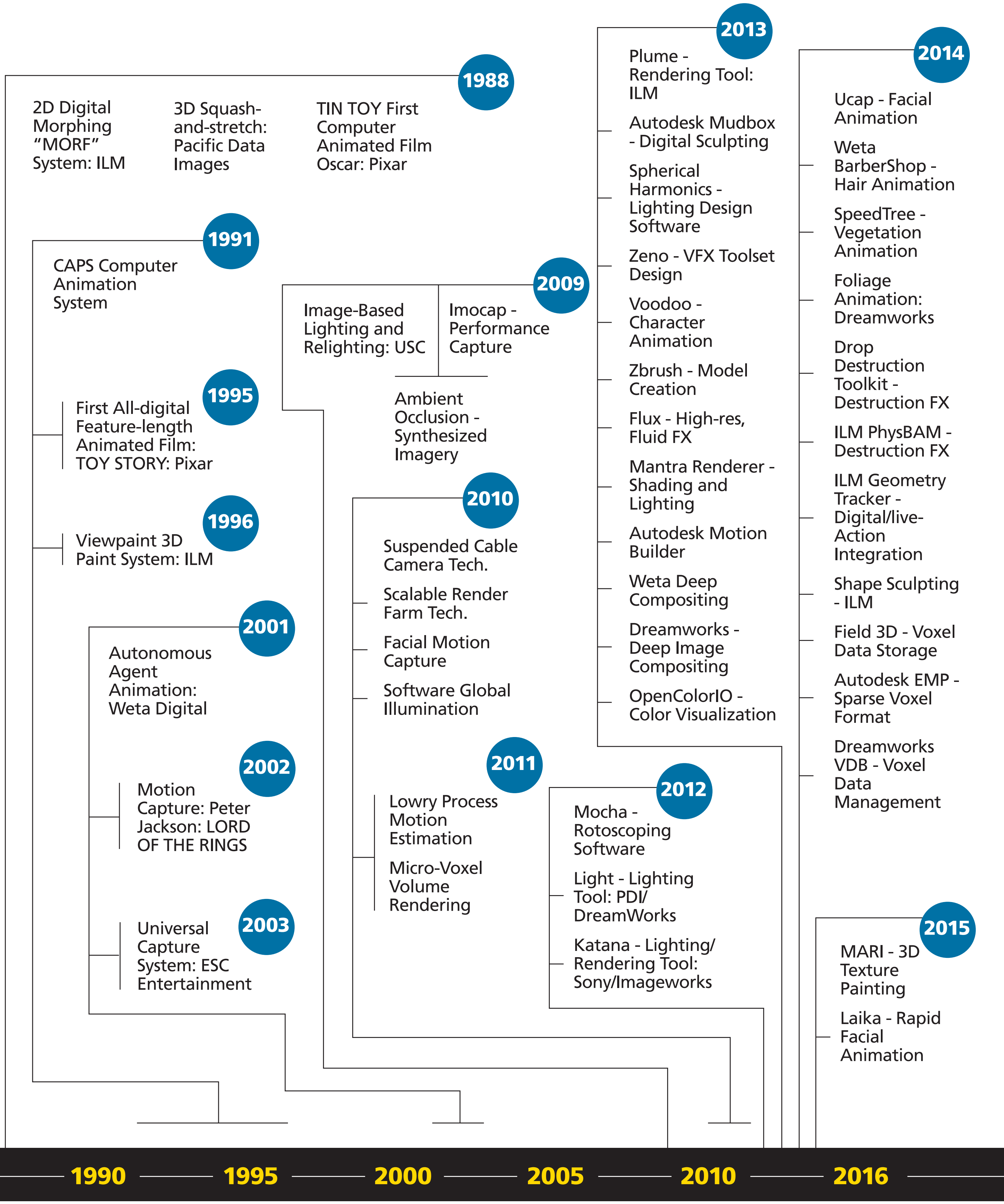
1982 First fully realized Computer-Animated Sequences: Disney
First use of Puppetry, Stop Motion and Animatronics: Jim Henson
First All-Computer-Animated VFX shot: Genesis Effect: ILM

1984 First Photorealistic CG for Live-Action Feature: Digital Productions
RenderMan Shading Language: Pixar Catmull, Carpenter

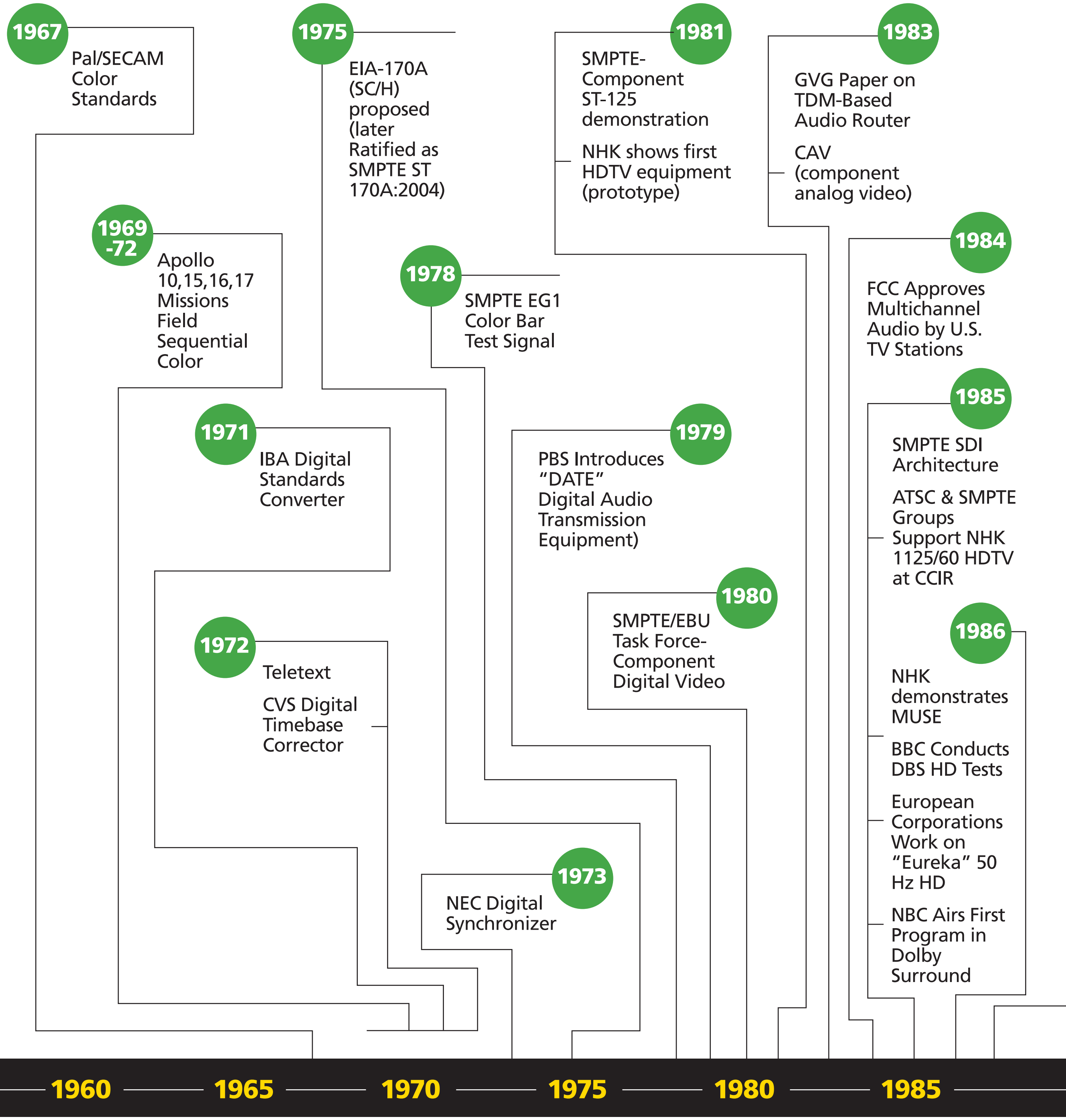
1986 3D Scanning: Cyberware 3030 3D Digitizer

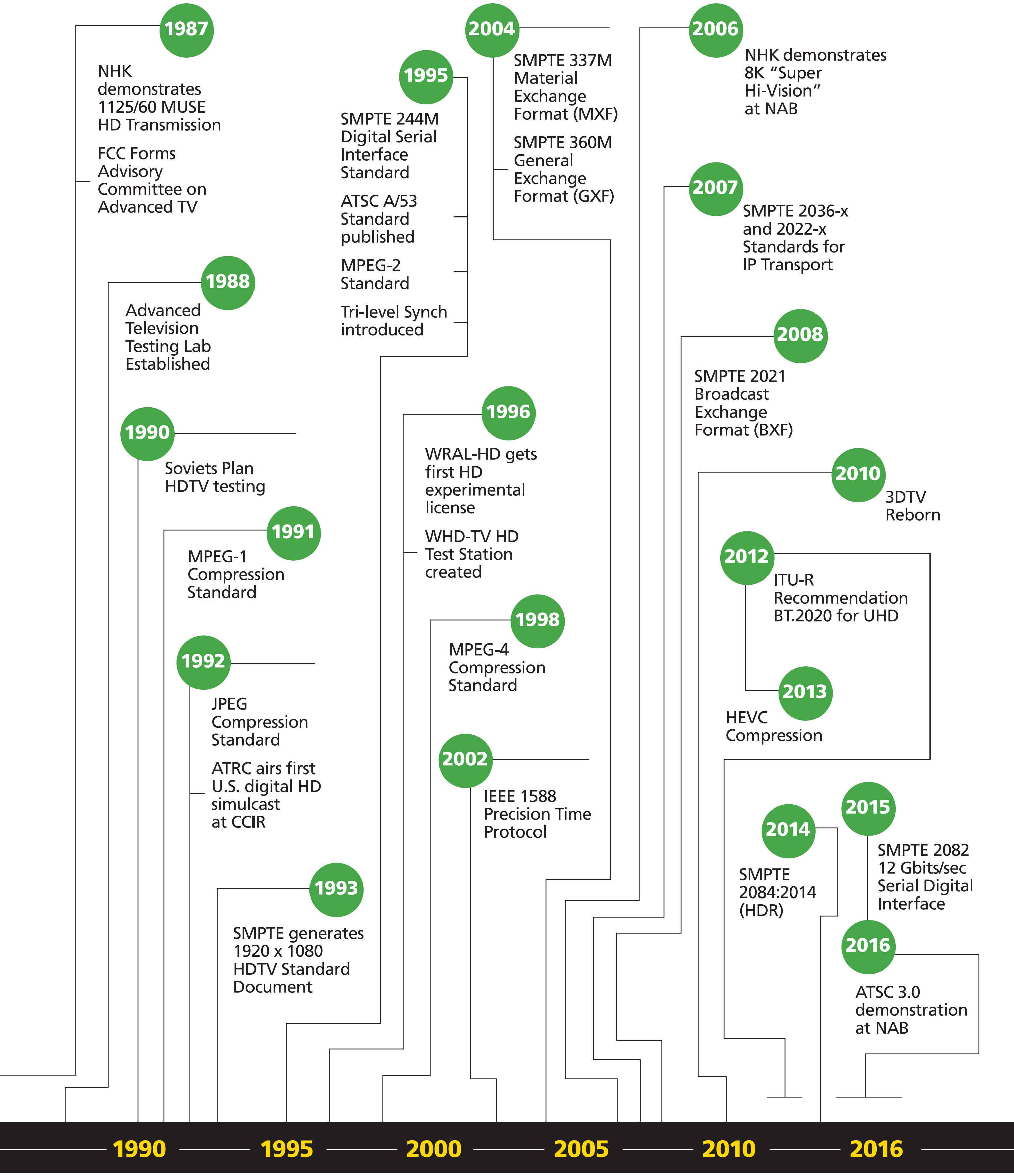
1960 — 1965 — 1970 — 1975 — 1980 — 1985

c. = approximately


1988
2D Digital Morphing "MORF" System: ILM
3D Squash-and-stretch: Pacific Data Images
TIN TOY First Computer Animated Film Oscar: Pixar
1991
CAPS Computer Animation System
1995
First All-digital Feature-length Animated Film: TOY STORY: Pixar
1996
Viewpaint 3D Paint System: ILM
2001
Autonomous Agent Animation: Weta Digital
2002
Motion Capture: Peter Jackson: LORD OF THE RINGS
2003
Universal Capture System: ESC Entertainment
2009
Image-Based Lighting and Relighting: USC
Imocap - Performance Capture
Ambient Occlusion - Synthesized Imagery
2010
Suspended Cable Camera Tech.
Scalable Render Farm Tech.
Facial Motion Capture
Software Global Illumination
2011
Lowry Process Motion Estimation
Micro-Voxel Volume Rendering
2012
Mocha - Rotoscoping Software
Light - Lighting Tool: PDI/ DreamWorks
Katana - Lighting/ Rendering Tool: Sony/Imageworks
2013
Plume - Rendering Tool: ILM
Autodesk Mudbox - Digital Sculpting
Spherical Harmonics - Lighting Design Software
Zeno - VFX Toolset Design
Voodoo - Character Animation
Zbrush - Model Creation
Flux - High-res, Fluid FX
Mantra Renderer - Shading and Lighting
Autodesk Motion Builder
Weta Deep Compositing
Dreamworks - Deep Image Compositing
OpenColorIO - Color Visualization
2014
Ucap - Facial Animation
Weta BarberShop - Hair Animation
SpeedTree - Vegetation Animation
Foliage Animation: Dreamworks
Drop Destruction Toolkit - Destruction FX
ILM PhysBAM - Destruction FX
ILM Geometry Tracker - Digital/live-Action Integration
Shape Sculpting - ILM
Field 3D - Voxel Data Storage
Autodesk EMP - Sparse Voxel Format
Dreamworks VDB - Voxel Data Management
2015
MARI - 3D Texture Painting
Laika - Rapid Facial Animation
1990
1995
2000
2005
2010
2016

MOTION IMAGING – **VIDEO** – THE LAST 100 YEARS

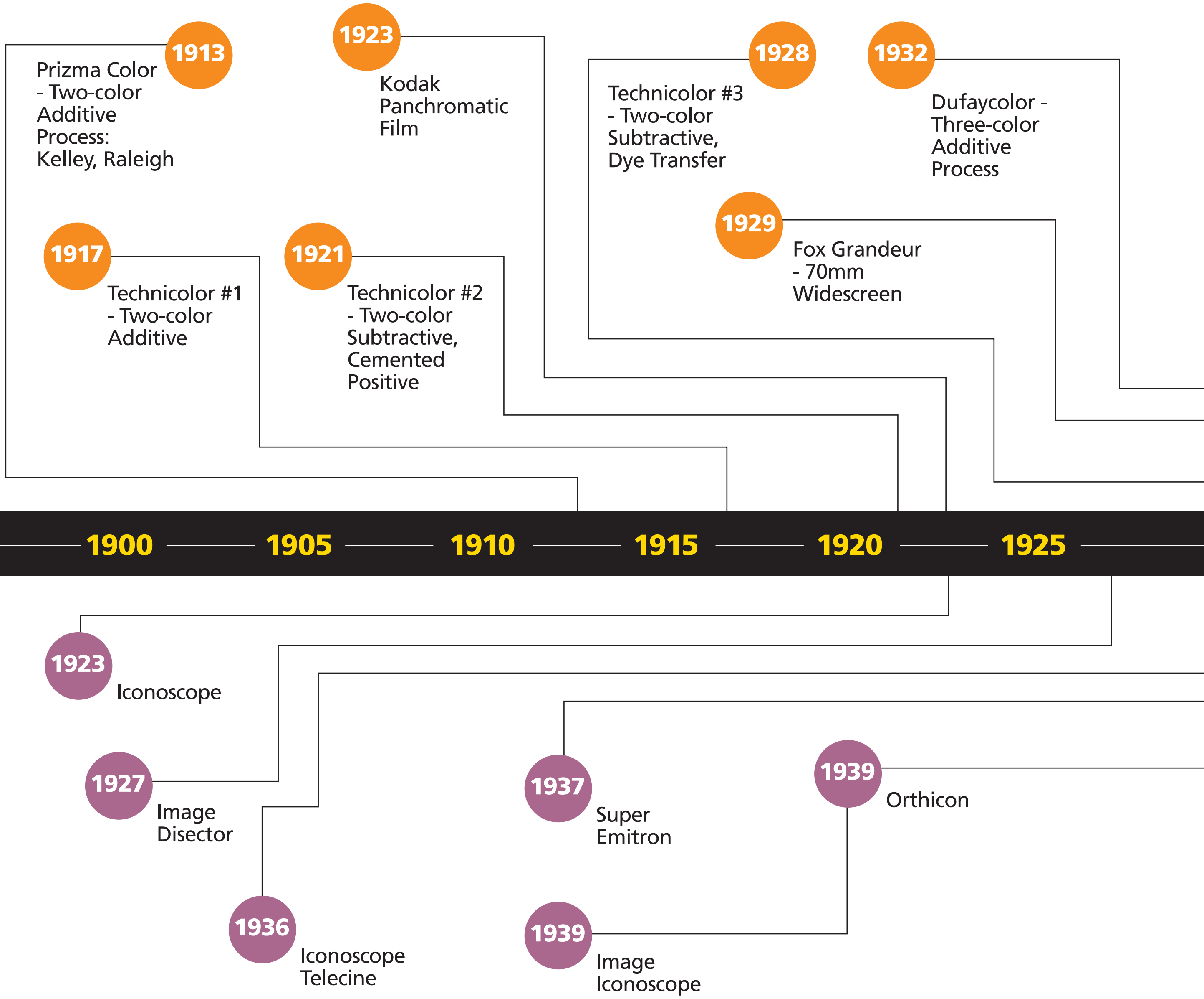



1987
NHK demonstrates 1125/60 MUSE HD Transmission
FCC Forms Advisory Committee on Advanced TV
1988
Advanced Television Testing Lab Established
1990
Soviets Plan HDTV testing
1991
MPEG-1 Compression Standard
1992
JPEG Compression Standard
ATRC airs first U.S. digital HD simulcast at CCIR
1993
SMPTE generates 1920 x 1080 HDTV Standard Document
1995
SMPTE 244M Digital Serial Interface Standard
ATSC A/53 Standard published
MPEG-2 Standard
Tri-level Synch introduced
1996
WRAL-HD gets first HD experimental license
WHD-TV HD Test Station created
1998
MPEG-4 Compression Standard
2002
IEEE 1588 Precision Time Protocol
2004
SMPTE 337M Material Exchange Format (MXF)
SMPTE 360M General Exchange Format (GXF)
2006
NHK demonstrates 8K “Super Hi-Vision” at NAB
2007
SMPTE 2036-x and 2022-x Standards for IP Transport
2008
SMPTE 2021 Broadcast Exchange Format (BXF)
2010
3DTV Reborn
2012
ITU-R Recommendation BT.2020 for UHD
2013
HEVC Compression
2014
SMPTE 2084:2014 (HDR)
2015
SMPTE 2082 12 Gbits/sec Serial Digital Interface
2016
ATSC 3.0 demonstration at NAB
1990
1995
2000
2005
2010
2016

FILM FORMATS

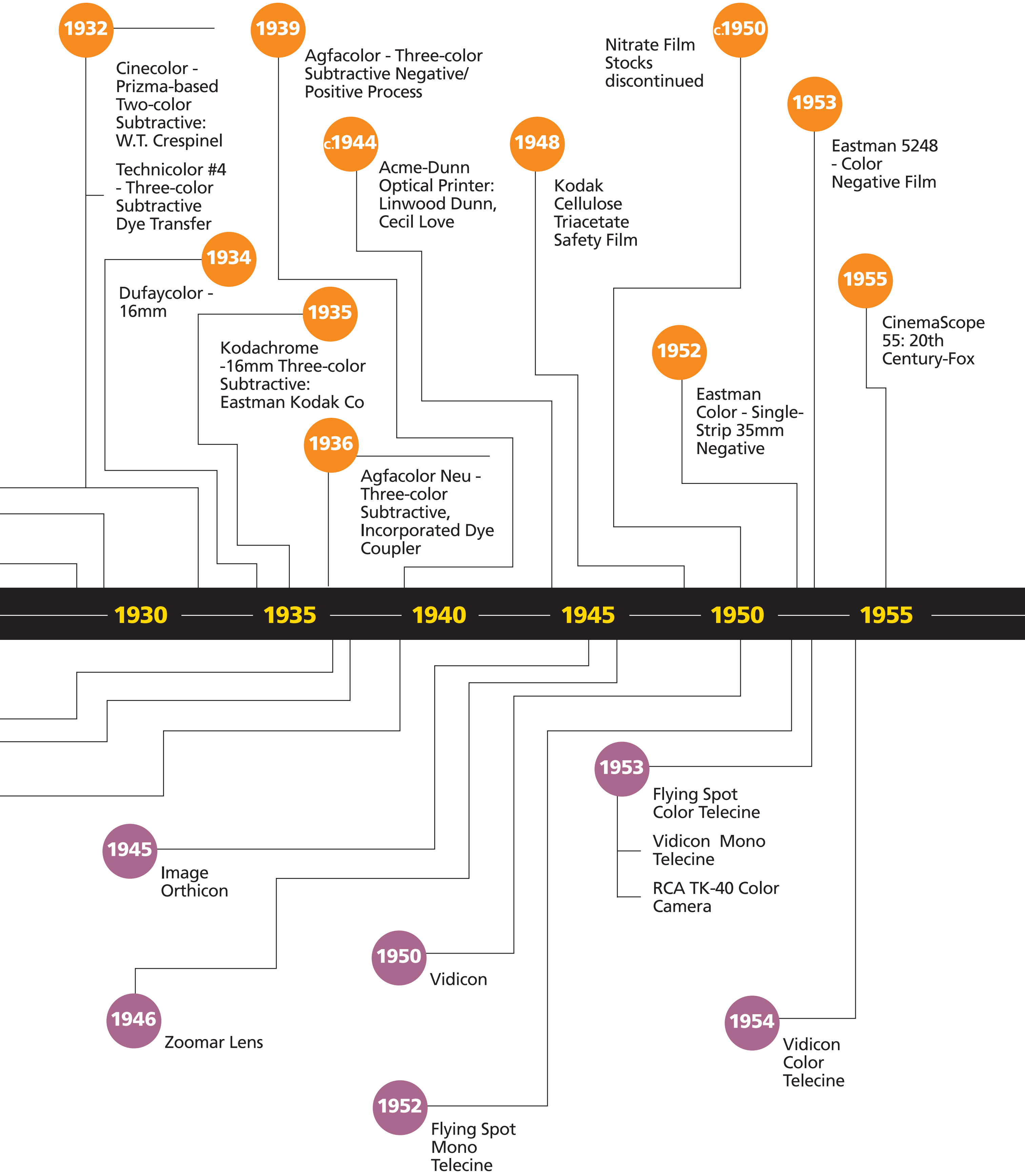
1916–2016

MOTION IMAGING – **FILM** – THE LAST 100 YEARS



CAMERAS/IMAGING DEVICES AND TECHNOLOGIES

MOTION IMAGING – **VIDEO** – THE LAST 100 YEARS



c. = approximately

FILM FORMATS, CONT.

1916–2016

MOTION IMAGING – **FILM** – THE LAST 100 YEARS

1955
- Technicolor #5 - Single-Negative, Dye Transfer Process
- Polyester Film

1960
- Kodak Ektachrome 7386 - Reversal Film Stock
- Techniscope 2-perf 35mm Camera

1960s
- Technicolor ENR Process: Technicolor Rome

1965
- Super 8 mm Film Stock

1968
- Eastman Color Reversal Intermediate Film

1955 — 1960 — 1965 — 1970 — 1975 — 1980 — 1985

1959
- 4-1/2-inch Image Orthicon

1968
- 1-inch Plumbicon

1973
- Cassette Telecine Projector

1974
- 2/3-inch Plumbicon

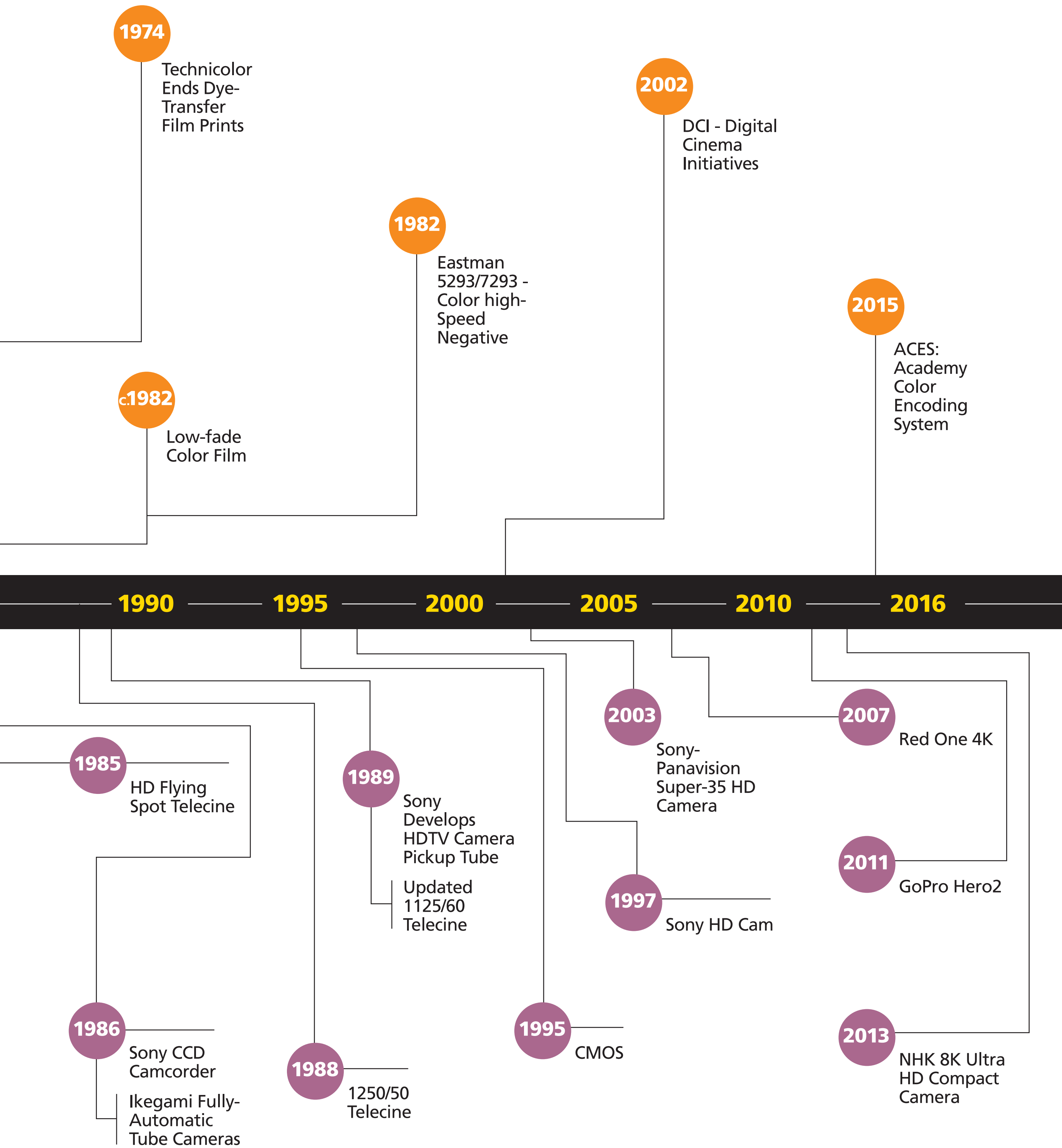
1975
- 2/3-inch Saticon
- Kodak CCD Still Camera

1983
- RCA and NEC CCD Live Cameras
- Rank Cintel HD CCD Telecine

1984
- Sony HDTV Camera
- RCA CCD ENG Cameras

CAMERAS/IMAGING DEVICES AND TECHNOLOGIES, CONT.

MOTION IMAGING – **VIDEO** – THE LAST 100 YEARS



c. = approximately

SOUND

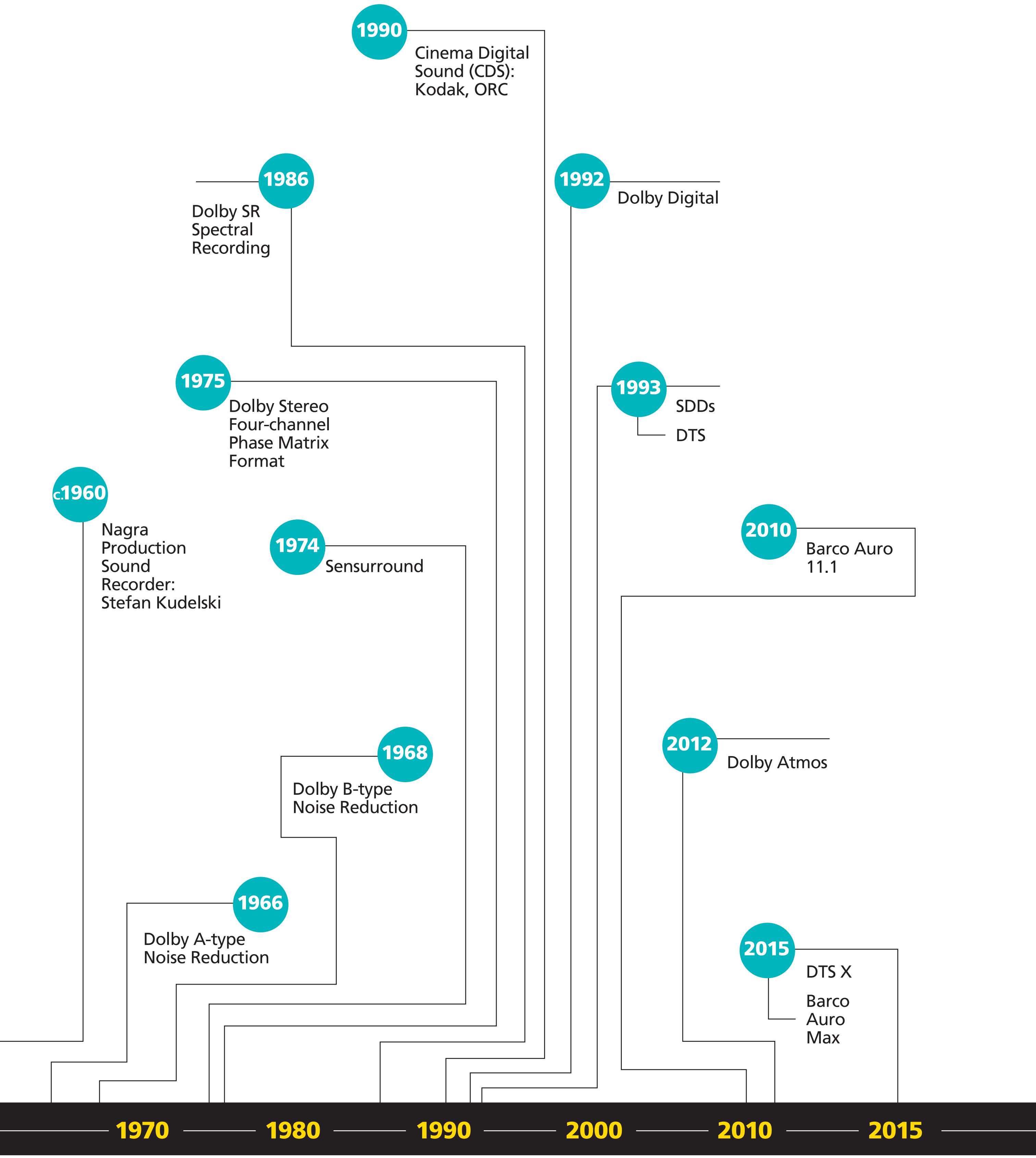
1916–2016

MOTION IMAGING – **FILM** – THE LAST 100 YEARS

- **1919** Phonofilm - Variable Density SOF: Case/De Forest
- **1926** Vitaphone - Disc Sync Sound: DON JUAN
- **1927** GE/RCA Kinegraphone - Variable-area SOF: WINGS
- **1928** Microphones concealed in lamps, vases, flowerpots...
  - "Ice box" soundproofed booth to eliminate camera noise
  - Moviola Sound Reader: Iwan Serrurier
- **1930** Ribbon Microphone
  - AMPAS Academy Leader
  - 180-degree Bi-directional Microphones
- **1933** KING KONG Innovative Sound: O'Brien, Steiner, Spivak
- **1934** Automatic Sound and Picture Printer: Bell & Howell
- **1935** Perspective Sonore - Monophonic Surround: NAPOLÉON re-edit
- **1938** AMPAS Academy Curve
- **1940** Fantasound - Multichannel: Disney: FANTASIA
- **1941** Uni-directional Microphones
- **c.1945** Magnetic Recording Coated Sprocketed Film
- **1950** Paramount Magnetic Recording System
  - Wireless Microphones
- **c.1952** Automated Dialogue Replacement and Foley Sound FX: Jack Donovan Foley
- **1954** Perspecta Sound, pseudo-Stereo System: C. Robert Fine

1910 — 1920 — 1930 — 1940 — 1950 — 1960

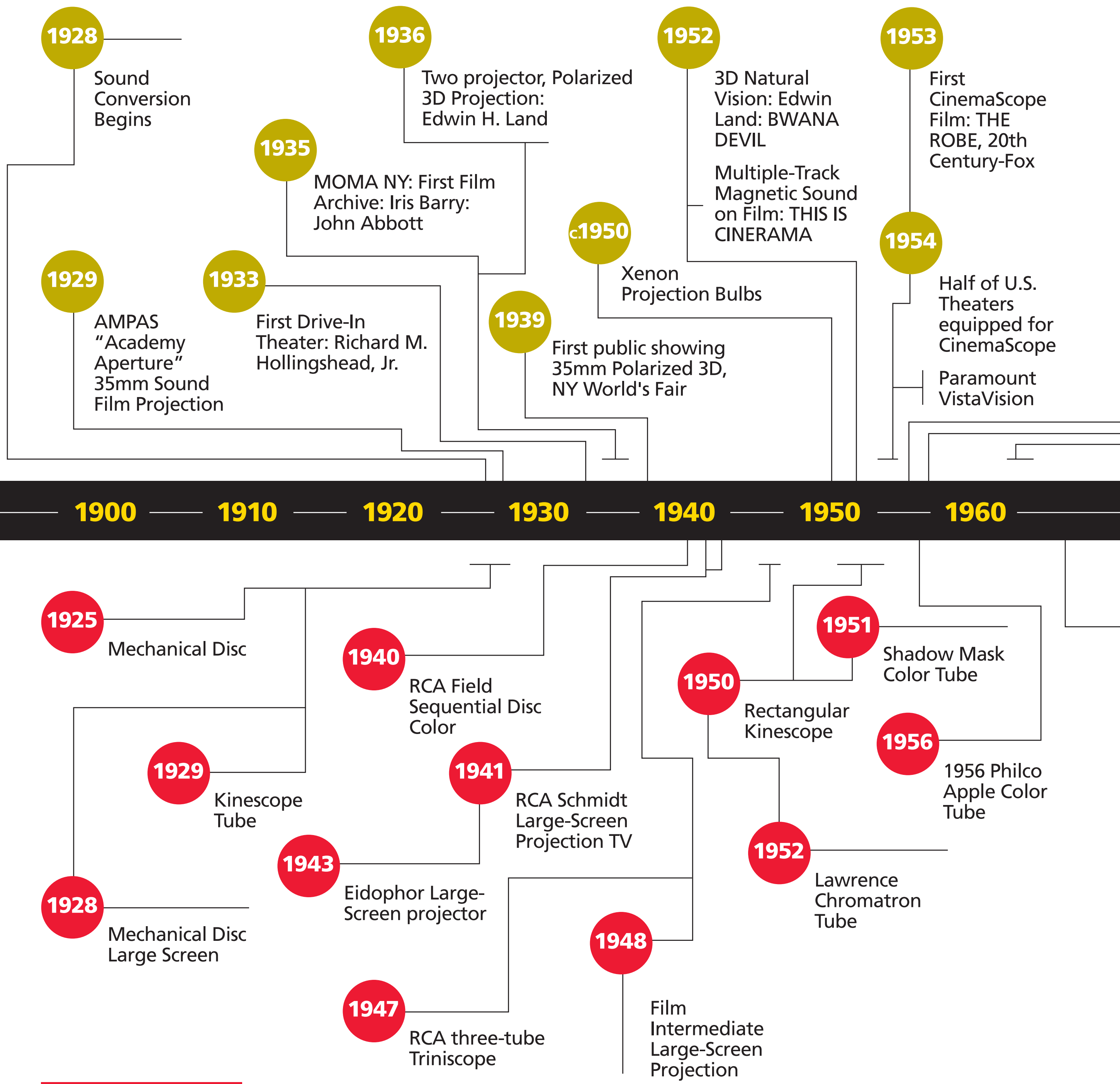
c. = approximately


1990
Cinema Digital Sound (CDS): Kodak, ORC
1986
Dolby SR Spectral Recording
1992
Dolby Digital
1975
Dolby Stereo Four-channel Phase Matrix Format
1993
SDDs
DTS
c.1960
Nagra Production Sound Recorder: Stefan Kudelski
1974
Sensurround
2010
Barco Auro 11.1
1968
Dolby B-type Noise Reduction
2012
Dolby Atmos
1966
Dolby A-type Noise Reduction
2015
DTS X
Barco Auro Max
1970
1980
1990
2000
2010
2015

EXHIBITION

100 SMPTE 1916–2016

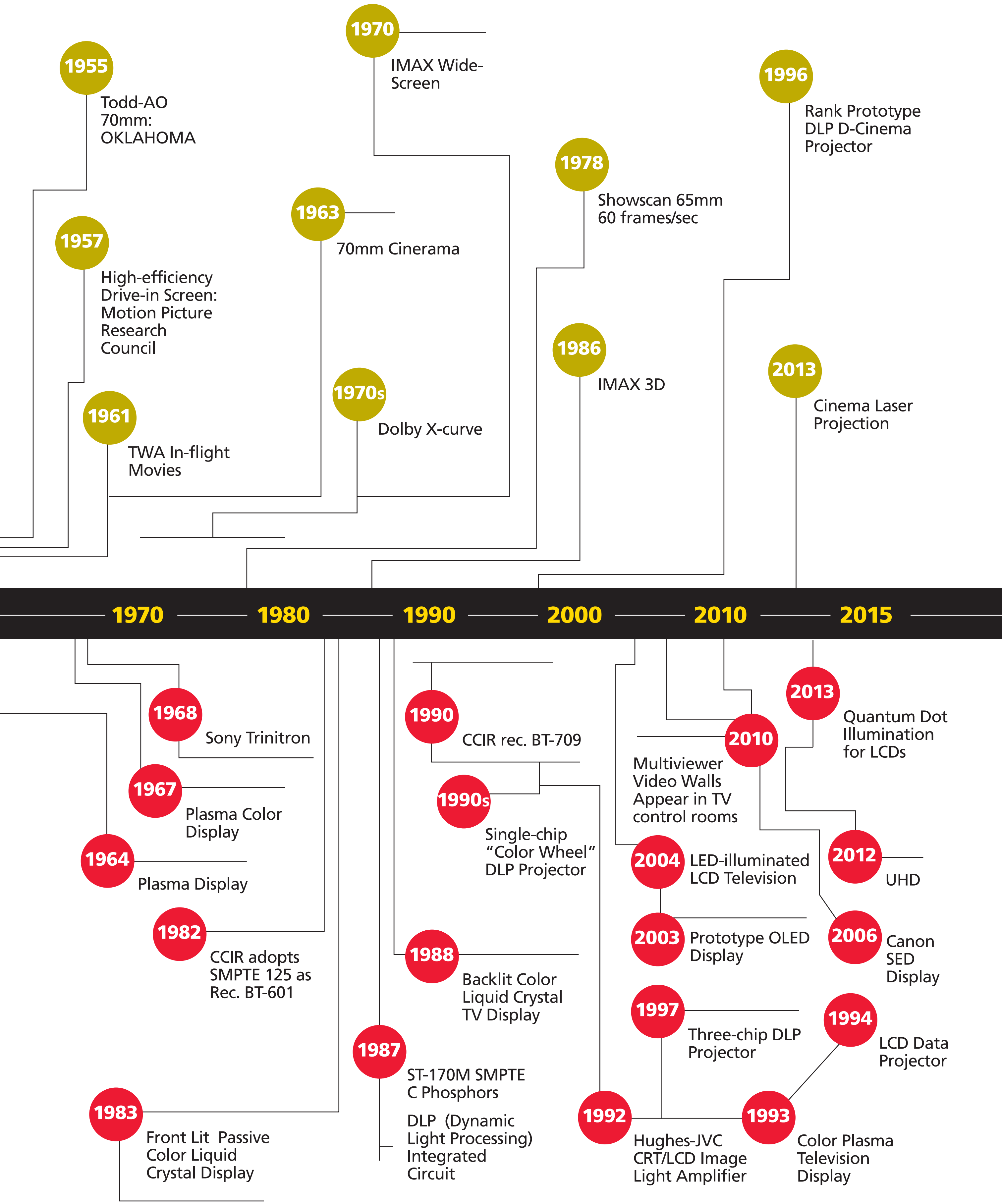
MOTION IMAGING – **FILM** – THE LAST 100 YEARS



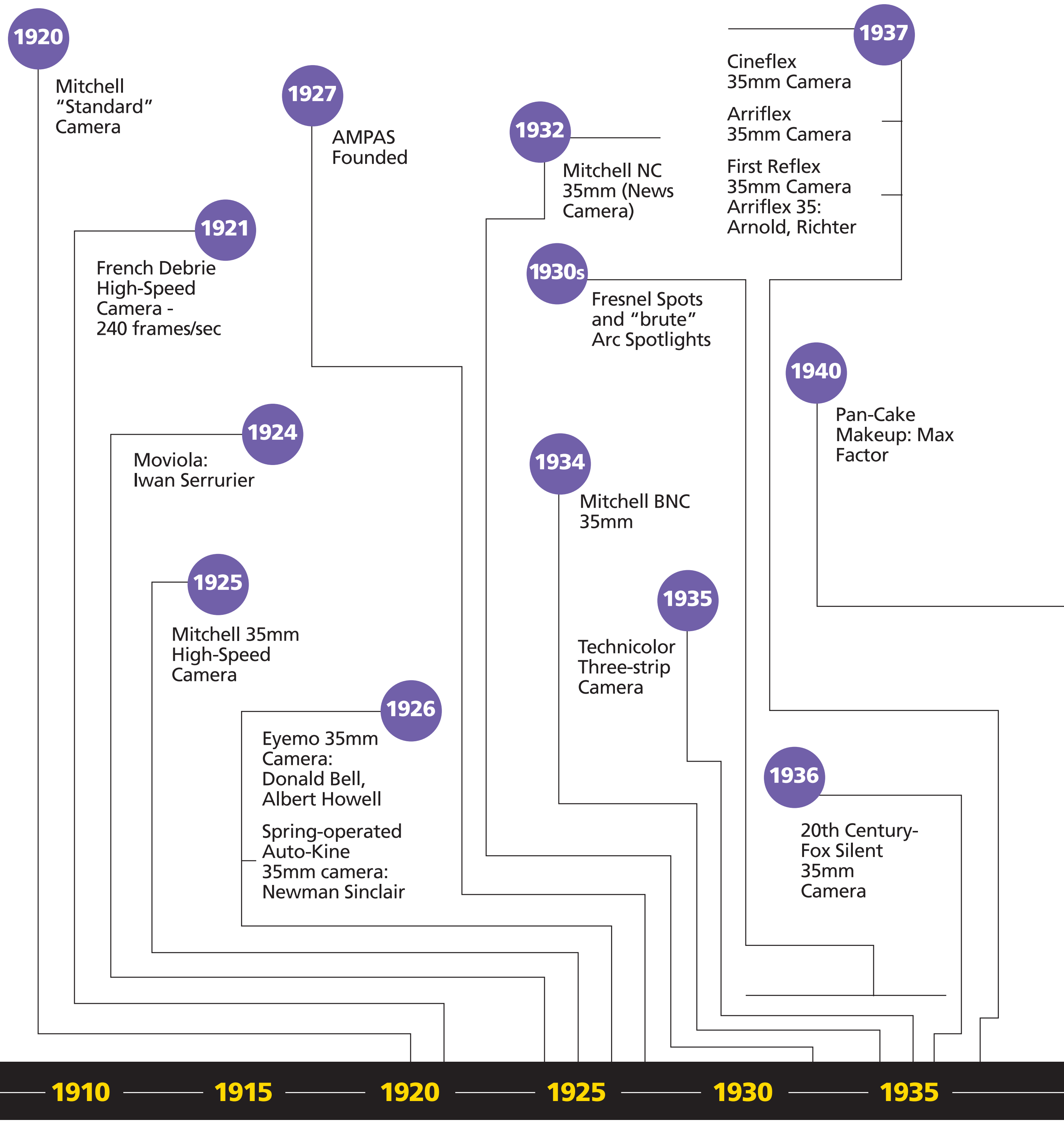
DISPLAY DEVICES

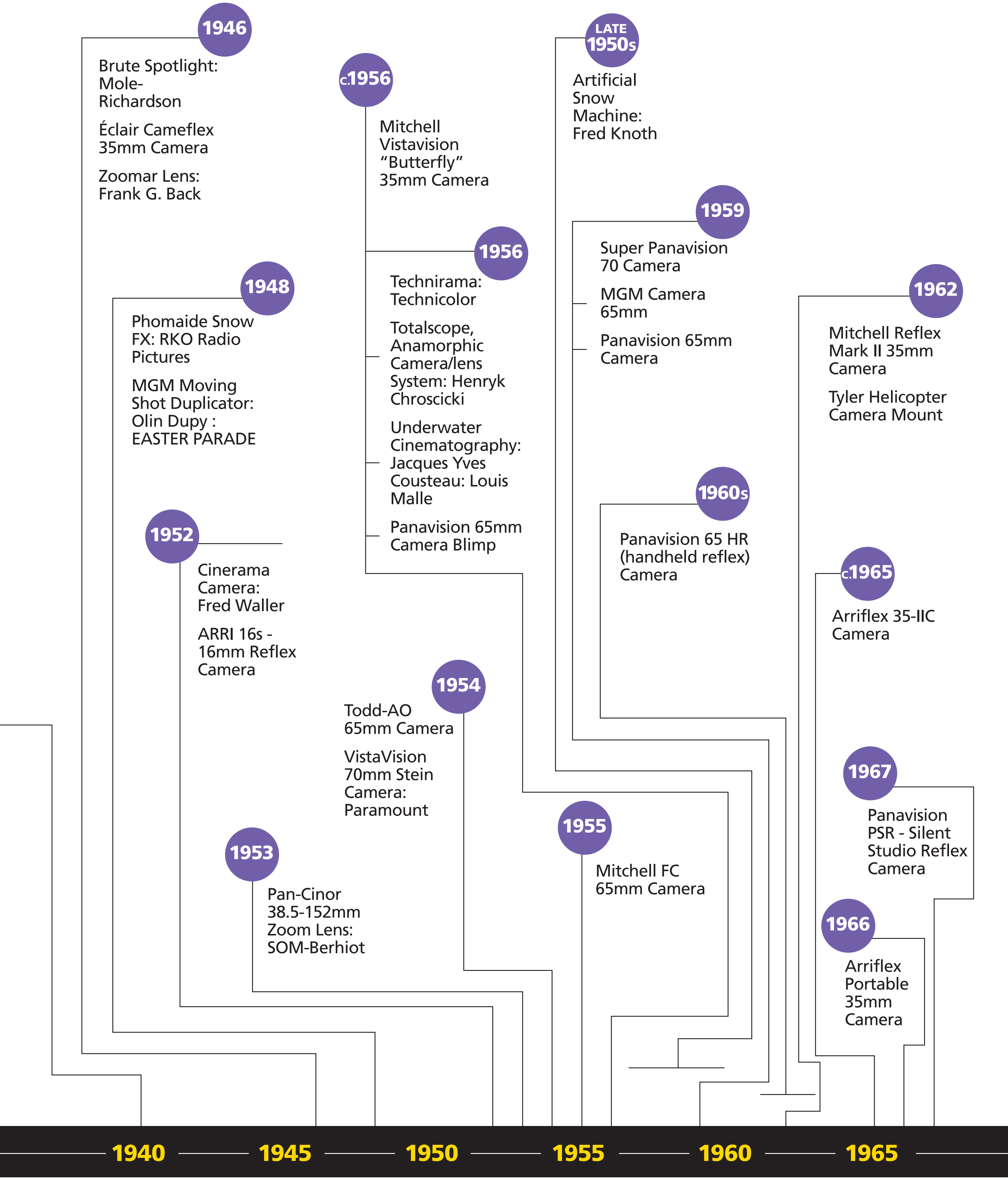
MOTION IMAGING – **VIDEO** – THE LAST 100 YEARS

c. = approximately


1955
Todd-AO 70mm: OKLAHOMA
1957
High-efficiency Drive-in Screen: Motion Picture Research Council
1961
TWA In-flight Movies
1963
70mm Cinerama
1970
IMAX Wide-Screen
1970s
Dolby X-curve
1978
Showscan 65mm 60 frames/sec
1986
IMAX 3D
1996
Rank Prototype DLP D-Cinema Projector
2013
Cinema Laser Projection
1970
1980
1990
2000
2010
2015
1968
Sony Trinitron
1967
Plasma Color Display
1964
Plasma Display
1982
CCIR adopts SMPTE 125 as Rec. BT-601
1983
Front Lit Passive Color Liquid Crystal Display
1990
CCIR rec. BT-709
1990s
Single-chip "Color Wheel" DLP Projector
1988
Backlit Color Liquid Crystal TV Display
1987
ST-170M SMPTE C Phosphors
DLP (Dynamic Light Processing) Integrated Circuit
2010
Multiviewer Video Walls Appear in TV control rooms
2004
LED-illuminated LCD Television
2003
Prototype OLED Display
1997
Three-chip DLP Projector
1992
Hughes-JVC CRT/LCD Image Light Amplifier
2013
Quantum Dot Illumination for LCDs
2012
UHD
2006
Canon SED Display
1994
LCD Data Projector
1993
Color Plasma Television Display

MOTION IMAGING – **FILM** – THE LAST 100 YEARS





c. = approximately

1916 – 2016

MOTION IMAGING – **FILM** – THE LAST 100 YEARS

1970
Angénieux 16mm 20:1 Zoom Modified for 35mm: Pierre Angénieux: Ed Digiulio

1970s
1990s Flatbeds Common in U.S.: Arriflex, Kem, Moviola, and Steenbeck

1971
Louma Crane
CMX-600 Non-Linear Editing System

1976
Video Recording On-Set Shot Review
Steadicam - Camera Stabilizier: Brown
Panavision Panaflex Gold 35mm Camera

c.1980
Arriflex 35mm BIII Camera

1986
Single-ended Discharge Lamp Fresnel Spots
Digital Wire Removal: ILM

1987
Montage Picture Processer - Nonlinear Editing

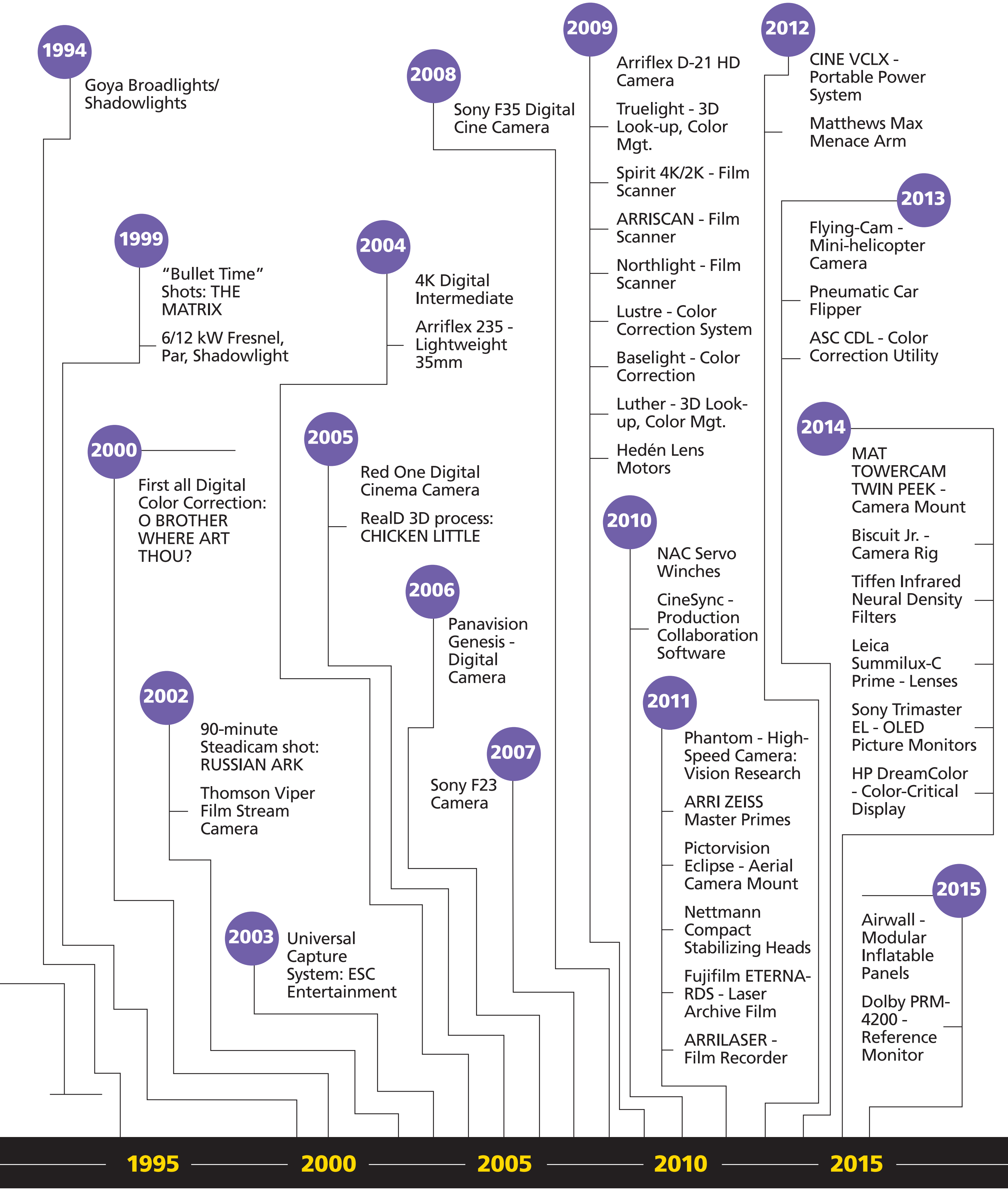
1990
Arriflex 535 - 35mm Silent Production Camera

1992
Green Screen Use instead of Blue: THE MUPPET CHRISTMAS CAROL

MID 1990s
Computer-Based Editing: Avid, Lightworks

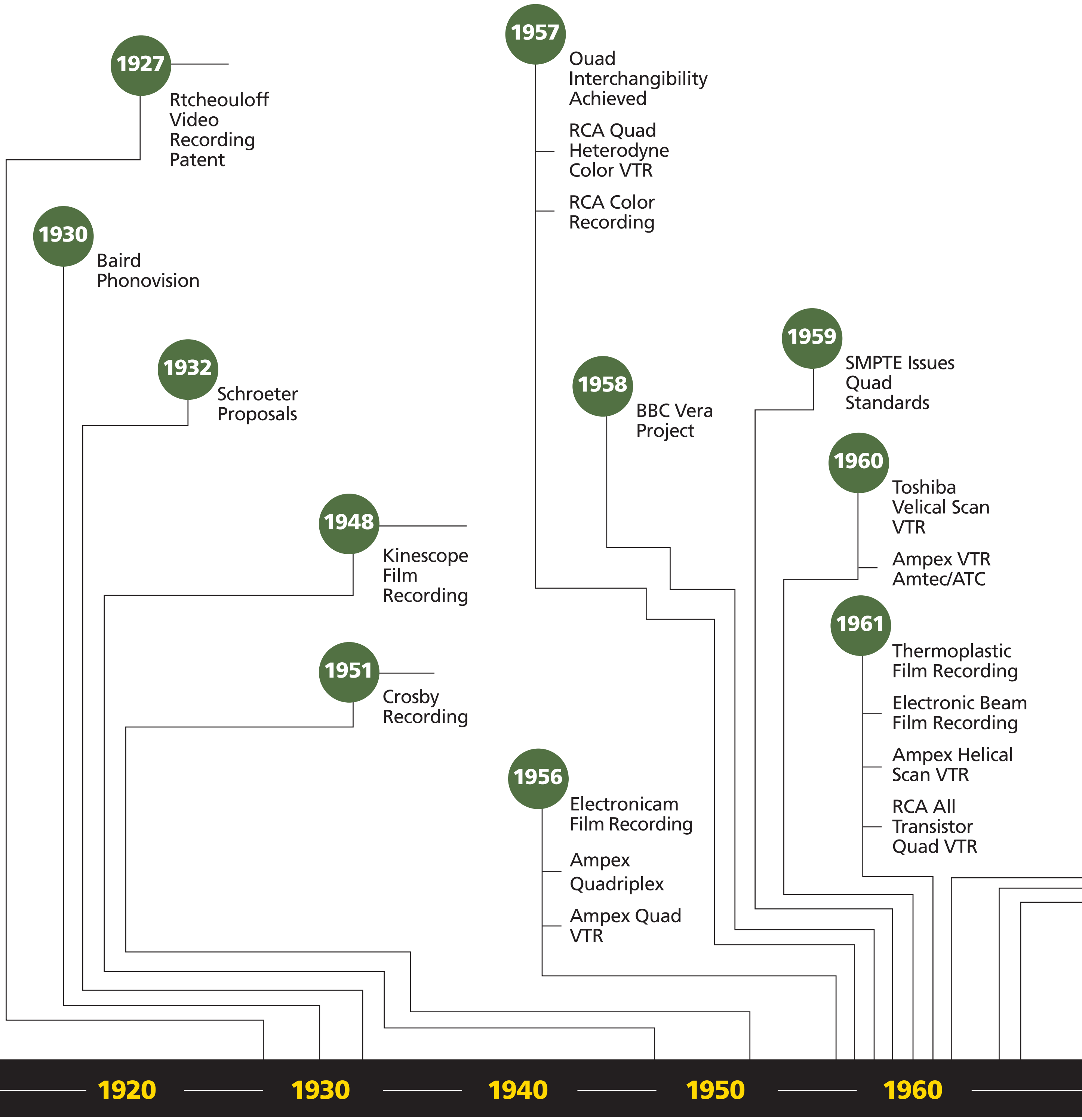
1970 — 1975 — 1980 — 1985 — 1990

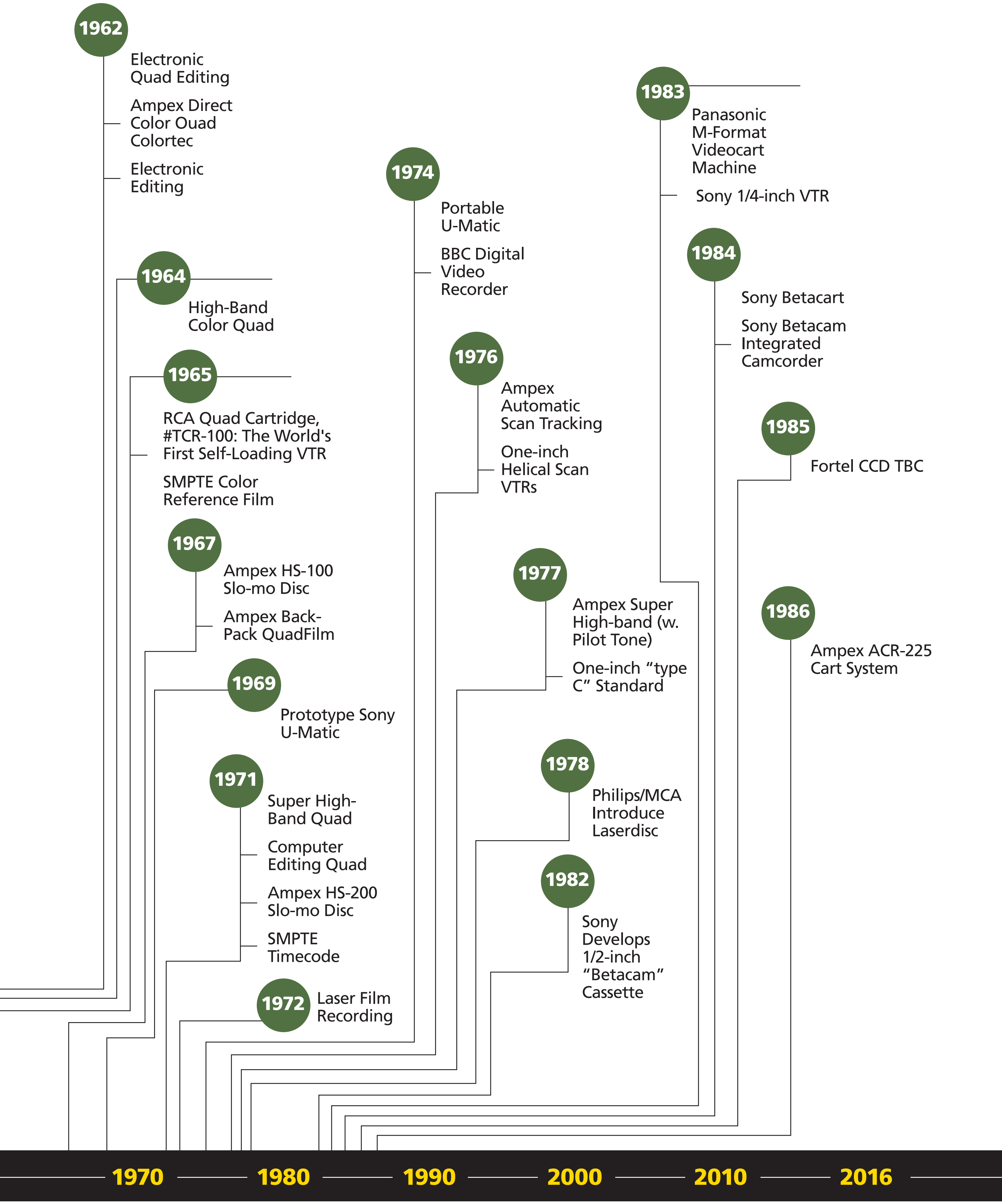
c. = approximately


1994
Goya Broadlights/ Shadowlights
1999
"Bullet Time" Shots: THE MATRIX
6/12 kW Fresnel, Par, Shadowlight
2000
First all Digital Color Correction: O BROTHER WHERE ART THOU?
2002
90-minute Steadicam shot: RUSSIAN ARK
Thomson Viper Film Stream Camera
2003
Universal Capture System: ESC Entertainment
2004
4K Digital Intermediate
Arriflex 235 - Lightweight 35mm
2005
Red One Digital Cinema Camera
RealD 3D process: CHICKEN LITTLE
2006
Panavision Genesis - Digital Camera
2007
Sony F23 Camera
2008
Sony F35 Digital Cine Camera
2009
Arriflex D-21 HD Camera
Truelight - 3D Look-up, Color Mgt.
Spirit 4K/2K - Film Scanner
ARRISCAN - Film Scanner
Northlight - Film Scanner
Lustre - Color Correction System
Baselight - Color Correction
Luther - 3D Look-up, Color Mgt.
Hedén Lens Motors
2010
NAC Servo Winches
CineSync - Production Collaboration Software
2011
Phantom - High-Speed Camera: Vision Research
ARRI ZEISS Master Primes
Pictorvision Eclipse - Aerial Camera Mount
Nettmann Compact Stabilizing Heads
Fujifilm ETERNA-RDS - Laser Archive Film
ARRILASER - Film Recorder
2012
CINE VCLX - Portable Power System
Matthews Max Menace Arm
2013
Flying-Cam - Mini-helicopter Camera
Pneumatic Car Flipper
ASC CDL - Color Correction Utility
2014
MAT TOWERCAM TWIN PEEK - Camera Mount
Biscuit Jr. - Camera Rig
Tiffen Infrared Neural Density Filters
Leica Summilux-C Prime - Lenses
Sony Trimaster EL - OLED Picture Monitors
HP DreamColor - Color-Critical Display
2015
Airwall - Modular Inflatable Panels
Dolby PRM-4200 - Reference Monitor
1995
2000
2005
2010
2015

VIDEO RECORDING/PLAYBACK TECHNOLOGIES

MOTION IMAGING – **VIDEO** – THE LAST 100 YEARS




1962
Electronic Quad Editing
Ampex Direct Color Quad Colortec
Electronic Editing
1964
High-Band Color Quad
1965
RCA Quad Cartridge, #TCR-100: The World's First Self-Loading VTR
SMPTE Color Reference Film
1967
Ampex HS-100 Slo-mo Disc
Ampex Back-Pack QuadFilm
1969
Prototype Sony U-Matic
1971
Super High-Band Quad
Computer Editing Quad
Ampex HS-200 Slo-mo Disc
SMPTE Timecode
1972
Laser Film Recording
1974
Portable U-Matic
BBC Digital Video Recorder
1976
Ampex Automatic Scan Tracking
One-inch Helical Scan VTRs
1977
Ampex Super High-band (w. Pilot Tone)
One-inch "type C" Standard
1978
Philips/MCA Introduce Laserdisc
1982
Sony Develops 1/2-inch "Betacam" Cassette
1983
Panasonic M-Format Videocart Machine
Sony 1/4-inch VTR
1984
Sony Betacart
Sony Betacam Integrated Camcorder
1985
Fortel CCD TBC
1986
Ampex ACR-225 Cart System
1970
1980
1990
2000
2010
2016

1916 – 2016

MOTION IMAGING – **VIDEO** – THE LAST 100 YEARS

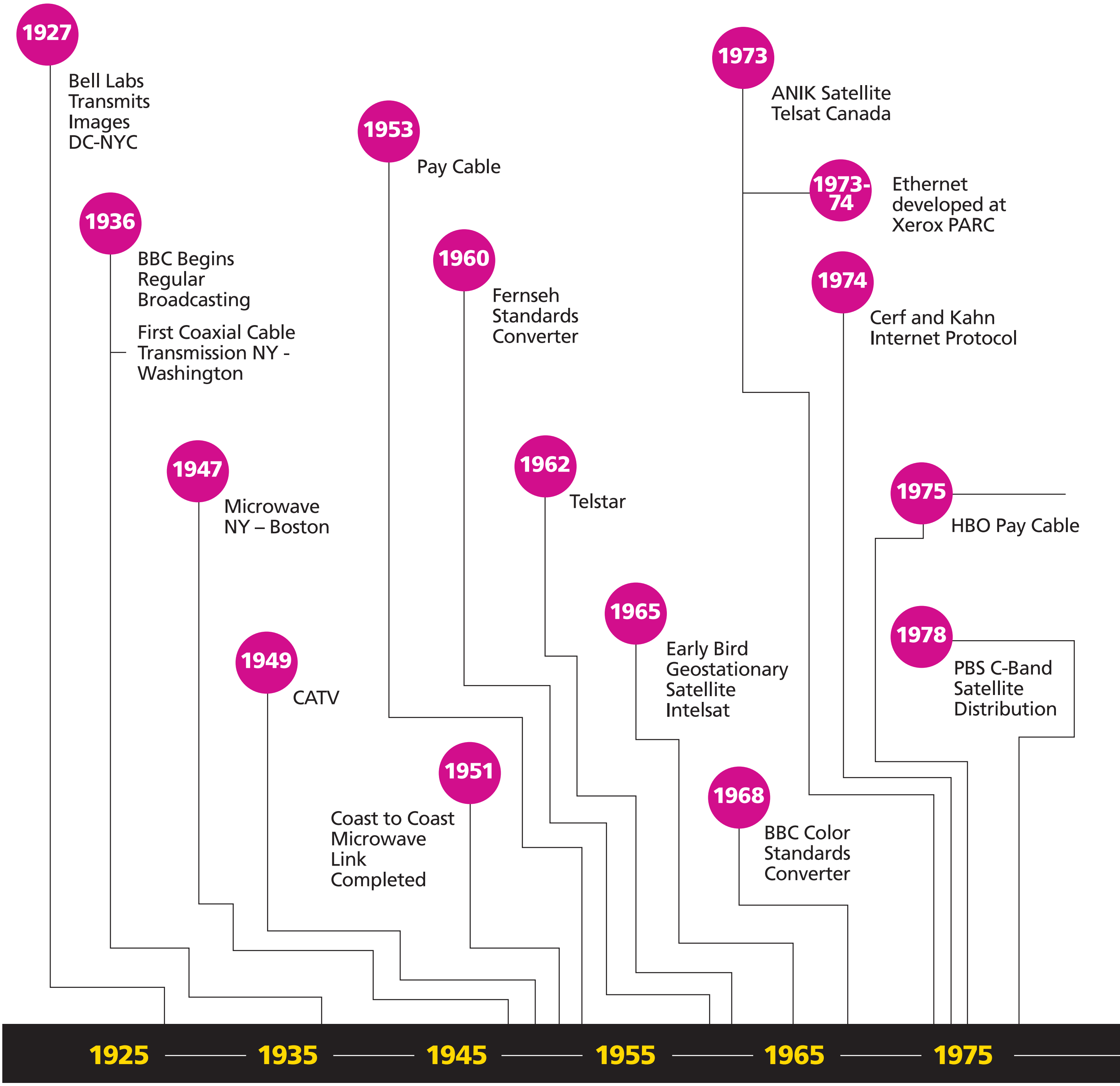
- **1987**
  - NEC Solid-State Video Recorder
  - Ampex and Fuji Metal Particle Tapes
- **1988**
  - Panasonic D3 Digital Recorder
  - Seven-Second Solid-State Video Delay Unit
- **1993**
  - SMPTE D2 Digital VTR (D2) Standards
- **1994**
  - Video File Servers Appear at NAB
  - Video Server, JPEG, Tektronix PDR 100
  - Video Server, MPEG, Hewlett Packard Broadcast Server
- **1995**
  - Ikegami Hard Drive Editcam Tapeless Workflow
  - DVD Introduced
- **2001**
  - Hitachi DVDCAM Camcorder
- **2003**
  - Sony XDCAM Camcorder
- **2004**
  - Panasonic's Digital P2 Card
- **2005**
  - SMPTE 409M Last Videotape Standard
- **2006**
  - Blu-ray Disc
- **2012**
  - Sony Optical Disc Archiving System

1985 — 1990 — 1995 — 2000 — 2005 — 2010 —

TRANSMISSION & DISTRIBUTION

1916 – 2016

MOTION IMAGING – **BROADCASTING** – THE LAST 100 YEARS



1916 – 2016

MOTION IMAGING – **BROADCASTING** – THE LAST 100 YEARS

1982
FCC approves DBS Satellites

1983
FCC reduces Satellite Spacing to 2 degrees

1984
FCC's OST proposes Land Mobile/UHF TV Spectrum Sharing

1985
CCIR proposes TMAC Video Transmission

NBC begins Ku-band Satellite Distribution

1986
"Dynabus" High-speed Broadcast Operations Data Net

1987
NEC 1 to 30 kW Solid-state UHF Transmitters

1989
SES Launches Astra 1

1994
ATSC 1.0 Approved

1996
Compaq Cloud Computing Concept

U.S. Telecommunications Act Decrees End of Analog TV

2000
Large Showing of Video Streaming Systems at NAB

FCC Rejects COFDM Backs 8-VSB for HD Transmission

2004
FOX deploys MPEG Splicing System for HDTV

2009
U.S. High-power Analog TV Broadcasting Ends

1985 — 1990 — 1995 — 2000 — 2005 — 2010

MOTION IMAGING – THE LAST 100 YEARS

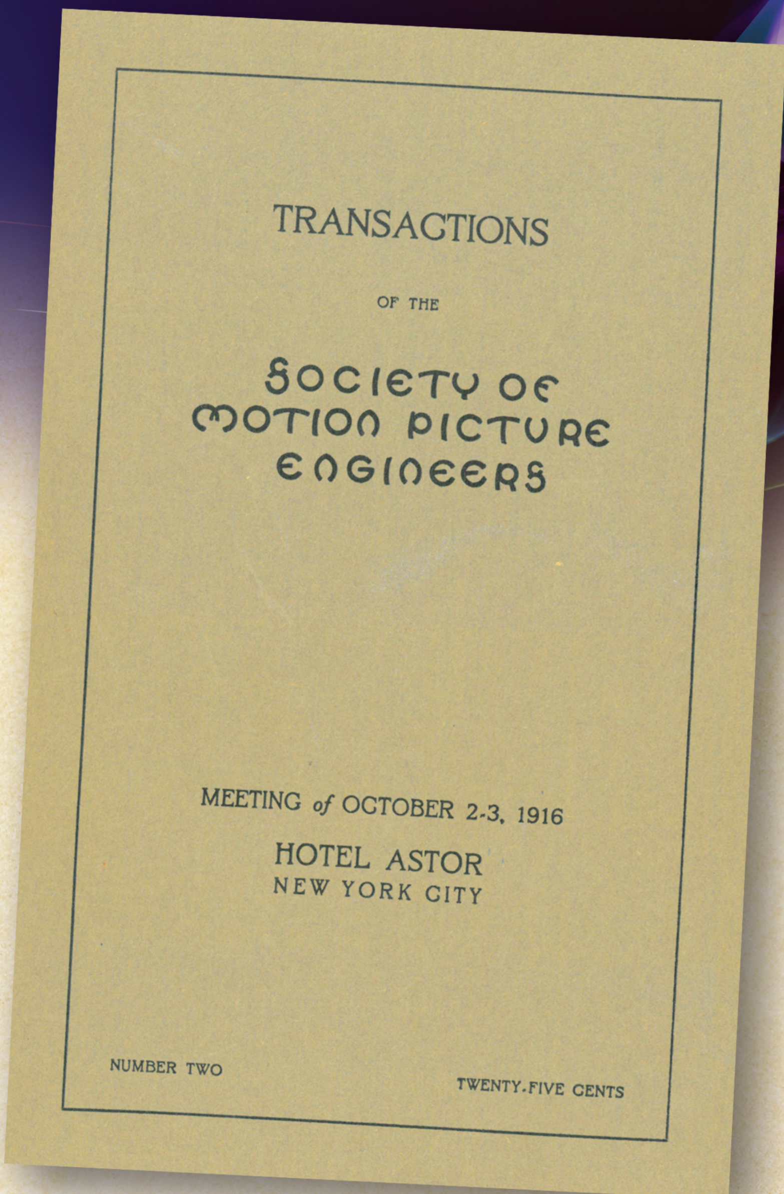
1916–2016

The Living Timeline Project

The Journal is exploring the possibility of a curated "Motion Imaging Living Timeline" on the SMPTE website. During the preparation of the timeline in this issue, it became apparent that the time and space constraints inherent in a one-time print effort necessarily limit the amount of information that can be included for individual entries and increase the potential for errors and omissions. We envision a timeline with broader input from the Motion Imaging community, more room for description, and stock web features such as word search.

Since this issue's timeline would be our starting point, we would appreciate any updates, corrections or additions our readers could provide to the current version.
We would also like to know what features would be most useful in a web-based timeline which would be periodically updated as motion imaging and knowledge of its past history evolve.

A Look Back at SMPTE's History Archives



TRANSACTIONS

OF THE

SOCIETY OF
MOTION PICTURE
ENGINEERS

MEETING *of* OCTOBER 2-3, 1916

HOTEL ASTOR
NEW YORK CITY

NUMBER TWO

TWENTY-FIVE CENTS

This Section of the Journal highlights some significant historical articles and advertisements that have been published by SMPTE in the past century. It provides further insight into our journey in Motion Imaging as we look back at the earlier years.

Readers may have noticed the first issue is marked as #2. Where is #1 you might ask? The 1930 article index has a citation to just one article for issue #1 (July 1916). However, that one article actually appears in what is believed to be the inaugural issue (#2, October 1916). Neither SMPTE's archives in White Plains, NY nor the UCLA library (both of which seem to have an otherwise complete set of Journals) has a copy of a #1 issue.

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THE PHONOFILM

By Dr. Lee DeForest

CONTRARY to the popular idea, the history of attempts to record sound vibration photographically is not new. It dates back almost as far as the birth of the telephone itself. In 1879, Prof. Alexander Graham Bell and his associate, Tainter, succeeded in telephoning a short distance over a beam of light, using as a transmitter a very small mirror attached to a diaphragm. Less than a year after these experiments were published a man by the name of Fritts filed a patent application disclosing exactly the transmitting methods employed by Bell and Tainter, and in addition a moving photographic plate upon which the vibrating beam of light was to be photographed through a narrow slit transverse to the motion of the photographic surface. Fritts did nothing in the way of working out a practical method. The Fritts patent application was two generations ahead of the art and remained merely a "paper" patent.

The first successful attempts to photograph sound were those of the German, Ernst Ruhmer. As transmitter Ruhmer employed the speaking arc, shortly before invented by another German, Simon. Strong telephonic currents from a powerful microphone were superimposed on the direct current across the arc, producing sufficient fluctuations in the arc light to permit a crude photographic record upon a cinematograph film which was driven at a very high speed, several meters per second. Ruhmer's work was carried on in 1906 and '07.

Following this a number of other experimenters entered the field, mostly of very recent years, chief among whom are to be mentioned Professor Rankine, of England, Berglund of Sweden, Vogt of Germany, and in our own country, C. A. Hoxie of Schenectady, who by going back directly to the methods originally shown by Fritts, nearly forty years before, has recently succeeded in photographing very clearly the sound waves impinging on a diaphragm to the center of which is attached an extremely small mirror. To this device has been applied the interesting name "Pallophotophone"—a new addition to the lengthening list of Greco-Schenectady words. In this respect Mr. Hoxie's work is somewhat similar to that of Matthews and Rankine in England, although the latter employs, in addition to the vibrating mirror, two fixed grids or shutters which make of his light beam a comb or lattice. More or less of the light coming through the spaces of the first comb is thus permitted to pass through those of the second grid, and thus, after having been condensed by a lens, to fall through a narrow slit upon the moving photographic film.

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In most of the methods above described the sound record occupies so much space on the film that it is impractical to photograph pictures of the speaking object upon the same, *standard width* film. In fact most of those who have attempted to photograph the voice and the object simultaneously have used separate films for the two records.

It hardly seems necessary for me to mention at this time the more or less successful attempts which have been made, chiefly in this country by Edison, Webb, and Kellum to achieve talking motion pictures by means of synchronizing the *phonograph* with the moving picture camera and projector. The fundamental difficulties involved in this method were so basic that it should have been evident from their inception that commercial success could hardly be achieved in that direction. Subsequent developments have certainly justified the correctness of that opinion.

My attention was focused on the field of talking motion pictures, wholly by photographic recording in 1918. Perhaps the one consideration which, more than any other, prompted me to enter this field was my desire to personally develop a new and useful application of the audion amplifier. One which I could expect to develop largely by my own efforts, as distinguished from its application to long distance telephony, where obviously the intensive efforts of large corps of engineers, backed by a gigantic business organization, were indispensable. Another motive was my desire to possess a phonographic device which would be free of many of the inherent shortcomings of the disc machine, notably the short length of record, the necessity for frequent changing of needles, and the belief that by means of a pencil of light instead of a steel needle it might be possible to completely escape from the surface scratch which has always been inseparable from the existing types of phonograph.

But at the beginning of my work I laid down several principles, based wholly on commercial considerations, limitations which I considered the talking motion picture must, in order to be commercially successful, fall within. These considerations were—

First, nothing but a single standard cinematograph film could be employed.

Second, the speed must be that of the standard motion picture film.

Third, the recording and reproducing devices must be absolutely inertialess, excepting possibly the diaphragm for receiving and the diaphragm for reproducing the sound.

Fourth, the receiving device must be sufficiently sensitive to permit its being successfully concealed at a reasonable distance from the speaker or source of music to be photographed.

Fifth, the reproduction must be as good, or better, than the existing phonograph, and loud enough to fill any theatre where the talking pictures should be exhibited.

Sixth, the photographic sound record must be so narrow as not to materially cut down the size of the normal picture projected on the screen.

Seventh, the photographic record, therefore, must be one in

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which the *width* or *amplitude* on the film was constant throughout, and the sound variations must therefore be photographed as variations in density in the photographic image. In other words, the light record should be in the form of exceedingly fine lines or parallel bands of varying densities all of the same length, and lying always transverse to the direction of the motion of the film.

To photograph the highest harmonics of any music which it might be desired to record upon a film travelling at normal speed, i.e., 12 to 16 inches per second, necessitated a slit not more than two thousandths of an inch in width. And in order not to appreciably cut into the size of the picture the length of this slit must not exceed at most three thirty-seconds of an inch. This in turn necessitated the employment of an intense light source, small enough to go inside the moving picture camera, and yet one whose intensity could instantly and proportionately be varied by the slightest and fastest sound vibrations which it might be desired to record. Some of the above conditions, it will now be admitted, were by no means easy of realization.

Early in the spring of 1919 I filed patent applications on the methods which I believed would accomplish the above laid-down conditions, and began actual research on the various means which might be successfully employed. At that time I figured that the work involved should require about two years—a period one half as long as that which has actually been demanded to accomplish what you are actually witnessing this evening. The work has been almost uninterrupted, and of the most exacting and discouraging nature. Literally hundreds of experiments have been made, and many thousands of feet of films have been photographed, only to be thrown away.

I well remember the grim satisfaction I felt when, for the first time in reproducing a photographic record of my voice, I was able clearly to determine whether or not it was being run backwards!

At the start I undertook to photograph the light fluctuations from three different sources. First, that of the speaking flame; second, that from a tiny incandescent lamp filament. To determine whether or not the radiation from these sources were faithfully following the voice I first exposed the photo-electric cell to their light and listened to the reproduction after it had been many times amplified by the audion in a telephone receiver. I found that both these sources were capable of reproducing voice and music with astonishing fidelity. This was after many refinements in learning how best to apply the voice to fluctuate the flame, and to secure sufficiently rapid cooling of the extremely short incandescent filament to permit the light from the latter to follow the voice frequencies up to three thousand per second. But to my disappointment I then found that to photograph these light variations which were producing such perfect reproduction in the photo-electric cells was an entirely different proposition. A photo-electric cell is far more sensitive than the most rapid photographic emulsion, requiring for translation far less percentage of the variation of the normal light of the source to produce a sufficient change in the electric conductivity of the cell, than is

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necessary to produce for recording corresponding changes in density in the photographic image.

The other of the three methods which I originally set out to develop, although far less simple and more difficult of attainment proved in the end the practical method for producing by electrical means light fluctuations of sufficient amplitude to be photographed in every *necessary* degree of intensity.

The light that I employed for this purpose was that of a gas-filled tube excited by high frequency current. It was not difficult to construct a gas-filled tube giving such a light when excited by a high frequency current from a small radio telephone transmitter. But it was no easy task to design such a tube which could, when connected to a small 5 or 10 watt high-frequency apparatus, generate a sufficient light to photograph all necessary variations of intensity upon a narrow strip of standard emulsion film, moving at the rate of 12 to 16 inches per second in front of a slit, one and one half, or two thousandths, of an inch wide.

Having now briefly outlined the general principles emp'oyed in develop ng the Phonofilm, a clearer understanding will be obtained if I outline briefly step by step the various instrumentalities employed from

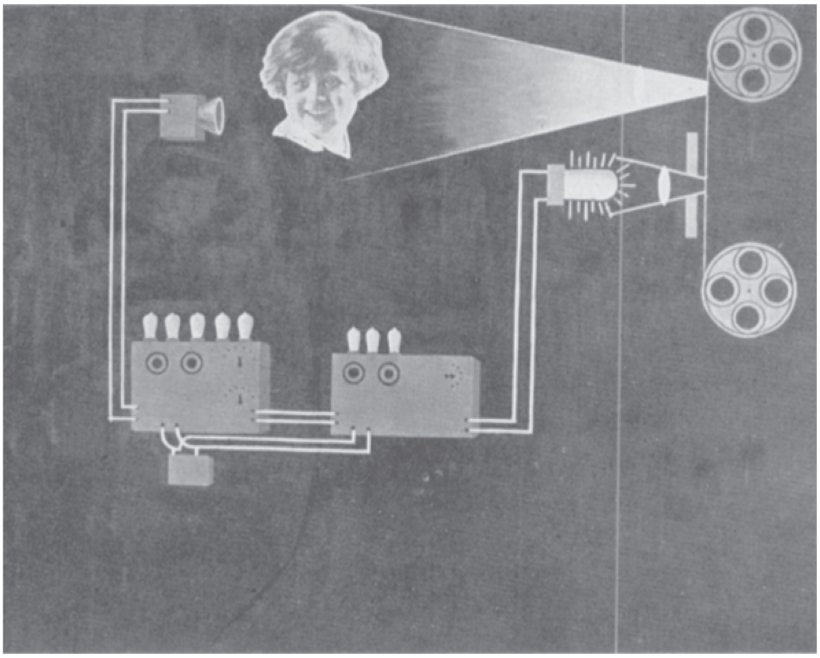

FIG. 1. THE RECORDING PROCESS

Chart showing the method of photographing a moving picture and sound waves (music or voice) on the same strip of film. The sound waves are recorded by fine lines on a narrow path along one side of the regular motion picture film. Sound waves are picked up by telephone transmitters, then amplified to radio frequency, thereby controlling the amount of light in the photion lamp, from which the photographic record is made of the original sound vibrations.

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the original source of sound to its reproduction alongside of the picture upon the silver screen. The photographic charts illustrate quite clearly the various steps involved. First, Fig. 1 is the voice transmitter, designed to transform into electric currents the lightest and the strongest sound waves which may be spoken or played within five to twenty feet from the device. Telephonic currents thus generated are naturally exceedingly weak, and must be amplified through a series of audions to the order of several hundred thousand times their original magnitude in order to effectively modulate the high frequency currents which are being generated in the small oscillator shown on the right. This oscillator is a form of the radio telephone with which you are all more or less familiar. Connected to this high frequency output circuit is a gas filled tube which I have called the "Photion." This tube glows at all times with a violet light which is highly actinic in quality. The intensity of this light increases and decreases around its normal brilliance in exact correspondence with the modulated high frequency energy of the oscillator. The light from the end of this tube is focused by means of a lens upon the very fine slit directly upon the emulsion side of the film. This Photion lamp is placed inside the moving picture camera at a point where the film is moving continuously some ten inches away from the window of the camera, at which point the motion of the film is, as you all know, intermittent for the purpose of photographing the picture. The combined picture and sound record thus made are, of course, in absolute fixed relation to each other and there is consequently no problem of synchronization to be solved. It is only necessary that in the projecting apparatus in a moving picture theatre the sound reproducing device shall be the same distance from the picture aperture, measured in inches along the film, as was the case in the moving picture camera where the voice and the picture were originally photographed.

The next chart, Fig. 2, shows in the same manner the arrangement used in the projector. Between the upper film magazine and the intermittent, step-by-step, mechanism of the standard moving picture projector machine are located in two small co-axial metal tubes, the sound projector lamp and the photo-electric cell. The light from this small lamp is focused through a fine slit having the same dimensions as that in the camera, upon the photo-electric cell, which is a few inches in front of the slit. Across the slit and in close contact therewith passes the film on which the original photographic image of the sound has been photographed and printed. The fine lines of light and dark, which represent the sound record, passing across this tiny slit produce corresponding variations in the light beam which transverses the slit and falls upon the photo-electric cell. Now in series with this photo-electric cell are connected a dry battery and the grid and filament of the first audion of a specially designed five-step audio-frequency amplifier. This amplifier, which has been designed with the utmost care to avoid any form of distortion, magnifies the minute telephonic currents thus generated in the photo-electric cell, by the order of a hundred thousand times. The output circuit of this amplifier is then connected by means of electric wires to the loud

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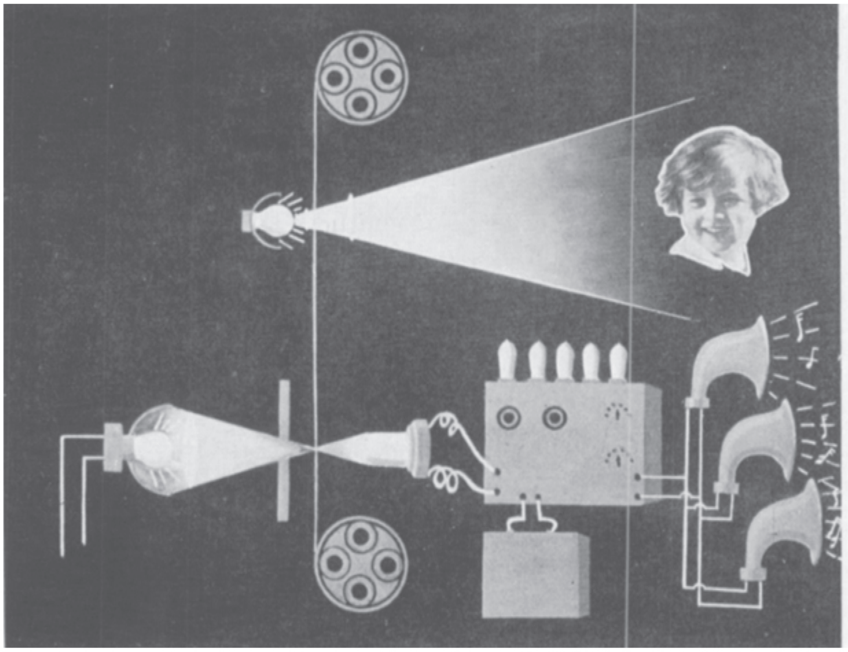

FIG. 2. THE REPRODUCING PROCESS

Chart illustrating the method of reproducing the moving picture and sound waves (music or voice) registered on the same moving picture film. Two different parts of the same film aroused simultaneously in the reproducing process of the Phono-film projector, which is an ordinary moving picture projector with a special attachment for the sound record. The keynote of the reproducing process is the use of a photo-electric cell. The fine photographic markings on the edge of the moving picture film where the sound record is recorded control the amount of light thrown upon the photo-electric cell which thus translates light waves back into electric vibrations, afterward amplified by means of audion lamps and loud speakers.

speakers which are concealed behind, or directly around the screen, on which at the same time the original picture is being projected.

Note now the all-important part which the audion plays in the talking motion picture, or as I prefer to call it the Phonofilm. First, we have an amplification of the order of five thousand to one hundred thousand times of the original telephonic currents, then an oscillating audion generating the high-frequency energy for lighting the Photion tube, and another audion, acting as modulator to control the high frequency output of this oscillator. Then at the reproducer we have again a multi-stage audion amplifier, thus giving in all an amplification, from the original transmitter near the camera to the final loud speaker at the projection screen, of the order of several million times. I do not mean by this to state that the reproduced voice you are hearing is several million times as loud as the voice that made the record! There is between the photographing of the voice on the film and its reproduction in the photo-electric cell, a very great diminution in intensity, which diminution must be made good, and in addition

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amplified thousands of times in order to permit the loud sound which is required to fill the auditorium.

I have employed two types of photo-electric cells with my reproducer. The so-called Kuntze, potassium-mirror, photo-electric cell, and the less known but more sensitive and reliable "Thallafide" cell of Theodore W. Case. This latter cell has been perfected after many months of most painstaking, scientific research by Mr. Case, until it is unquestionably the complete answer to the problem of how to obtain electri al from light variations, at least where one has a choice of light wave-lengths in which to work. The Thallafide cell is most sensitive to the infra-red and red radiations. It was used to excellent purpose in the Case system of secret signalling during the latter part of the great war. (The lack of sensitiveness and well known lag in response, or fatigue, of selenium, is such that no *well-informed* designer of photo-electric apparatus for rapid signalling would to-day consider the employment of selenium.)

I wish here to acknowledge my indebtedness to Mr. T. W. Case, not only for his contribution of the beautifully suitable Thallafide cell, but for many very valuable suggestions, as well as practical laboratory assistance, in the latter course of my experimental work.

It has for a long time been realized by telephone and acoustic engineers that the necessity for a diaphragm at the transmitter introduces at the very outset of the sound translation problem a source of distortion and imperfection. It is the diaphragm more than any other element which introduces the deformities in recording and in reproducing voice and music on the phonograph as well as in telephone transmission. Therefore for many years efforts of telephone and phonograph engineers have been devoted to reducing as far as possible distortions thus introduced by the natural period of vibration of the diaphragm, or membrane, against which the sound waves impinge. But these engineers it would appear have not looked elsewhere in the realm of physics with sufficient scrutiny. Otherwise we should long ago have been free of the necessity for using any diaphragm whatsoever at the transmitter element of apparatus, the object of which is to translate sound into electric currents with the minimum possible distortion, regardless of the expense or the elaborateness of the apparatus thereby involved. (I do not here refer to the ordinary microphone transmitter, millions of which are in use thruout the world, and which must necessarily be as simple and cheap as possible. For such telephone apparatus the carbon microphone with diaphragm may possibly always be used.)

But where exact and accurate translation of sound waves into electric currents is desired it is quite unnecessary to use a vibrating diaphragm. It has long been the dream of telephone engineers to translate the sound waves in the air directly into electric currents. There are, I have found, a variety of ways of doing this. You are perhaps familiar with the story of the discovery of the audion; how the first suggestion came to me as a result of observation of a sensitive gas flame. From this rudimentary idea, which originated in 1900, was developed, during the ensuing five years, the three-electrode vacuum tube which was destined to become the telephone repeater or amplifier for which telephone engineers had been searching for twenty years. For these were working always along the well beaten path of a telephone receiver siameesed by some more or less ingenious method to a carbon microphone transmitter controlling a local source of electric energy.

And now in exactly the same way, starting from exactly the same point of investigation, the sensitive gas flame, has been evolved a new form of microphone device, which does directly what the telephone engineers have so long dreamed of accomplishing, that is, turning sound waves in the air directly into electric currents. Take the ordinary bat-wing gas burner, or a certain form of Welsbach mantel gas light, or special forms of oxy-acytelene gas flame; insert two heat-resisting electrodes therein, in proper relation to the flame and to each other; connect these electrodes to an appropriate electromotive force. You will then have an extremely sensitive sound converter which gives an electric reproduction of the sound waves in the air enveloping the flame which is of an entirely different order of fidelity from that ever obtained from any form of microphonic device using a diaphragm, whether this be of the carbon, electro-magnetic, or electro-static variety. Here again history repeats itself. After I had first used the gas flame as a detector of wireless signals I next tried the intensely heated gases in an electric arc and found the same phenomena, although very imperfect on account of the overwhelmingly loud disturbances due to the arc itself. So again it has been found that a long electric arc in the air possesses the property of modulating to some extent the electric current passing between the electrodes in response to the changes of air pressure produced by the impinging sound waves.

In Germany an investigator by the name of Vogt has found a similar action in the ionic currents passing through the air between a Nernst glower and a cold anode placed nearby. All of these electric reproductions of sound waves are naturally extremely weak, and must be amplified, by means of a series of audion amplifiers, several thousand times before they can be applied to any useful purpose.

More recently, Dr. Philip Thomas, of Pittsburgh, has demonstrated that a high-potential low current discharge between two electrodes in air may be "modulated" by sound waves. This is a return to the method which I showed in a patent taken out in 1906 for controlling very simply by the voice the high-frequency high-potential currents in a radio-telephone transmitter.

But I have found still another method of translating sound waves direct into electric currents without the imposition of any diaphragm. This arrangement, independently suggested by Mr. T. W. Case, is the reversal of the well known "Thermophone," a device wherein an extremely fine platinum wire, thru which is passed a telephonic current, reproduces these in the form of sound waves due to the alternate heating and cooling of the air immediately surrounding the extremely fine wire.

We have found in the same way that when a series of very fine and very short platinum wires are heated to a dull red from a local source of current, the resistance of these wires changes, alternately

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increasing and decreasing in conformity with the sound waves impinging thereon; so that from a telephone transformer connected in series with the battery and this thermo-microphone, a remarkably faithful representation of the sound waves is obtained, even though the frequency of these be as high as 3000 per second. The sensitiveness of this device is greatly enhanced by a gentle stream of air, by fluid evaporation in the neighborhood, and by other auxiliary means. In a word, therefore there now exist several ways of obtaining extraordinarily faithful reproductions of sound waves in the form of electric currents, entirely unlike the diaphragm method on which telephone engineers have been working from the beginning of the telephone art.

Of all the diaphragm types of transmitters unquestionably the electro-static type, as perfected by engineers of the Western Electric Company, comes nearest to approximating perfection. While this is extremely insensitive compared with the best carbon microphone type, there is small comparison between the fidelity of reproduction by the two means. But one listening in a telephone to the reproduction by means of the flame microphone, and then by means of the electro-static microphone, will at once exclaim that the fidelity of reproductions in the first case is of quite a different order from that obtained even from the highly perfected diaphragm of the best electro-static microphone.

Passing now to the loud speaker, or reproducer, the last step in the many translations which I have been describing, I regret to say that we are here still limited to the use of a diaphragm and horn. Although the loud speaker has been developed to a high state of perfection, notably again by engineers of the Western Electric Company, there is still room for improvement, and much is left to be desired. And I am convinced that final perfection will come not thru any refinements of the telephone and diaphragm, but by the application of entirely different principles. For example the talking arc has been known for many years as a fairly faithful converter of telephonic currents into sound waves; and recently I have done some development work along the lines of the "loud-speaker thermophone"; but thus far with no very promising results. Some entirely novel method of agitating the air waves, as distinguished from the thus far single useful method of beating them by means of a solid diaphragm, must be discovered. For the present, however, the form of telephone loud speaker with properly designed horn, to which you are listening, answers the actual requirements well, if not perfectly.

The question is often asked, "What happens when the film becomes torn? Is not synchronism lost in a film that has been patched together?" Where pictures are taken, as here, at the rate of 20 to 22 per second, one or even two "frames" may be cut out of both voice and picture records without the flaw in exact synchronism being observable. This holds true even though the picture is some ten inches ahead of the corresponding voice record. However the sharpest ear will not notice the omission from a voice or music record of a portion occupying not more than one twentieth part of a second.

Of course should a film become badly torn, or worn out, it must be replaced by a fresh print, as in any motion-picture film.

A comparison of the photographic records of various sounds, as of the five vowels, is interesting. Some of the patterns here are very pretty and symmetrical—that of the letter E particularly.

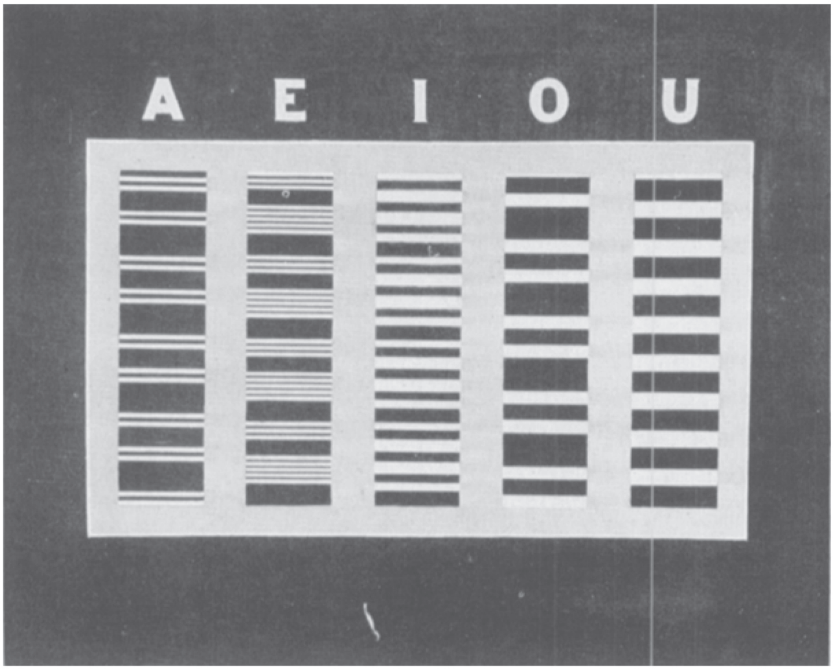

FIG. 3. The Vowels

We have often heard comparisons of light with sounds. Here, on the Phonofilm, we have them both truly interlinked—Sound registered and interrupted by Light—Light waves have become the carriers of sound waves, and we have here caused Sound to write its autograph in Light.

These symmetrically beautiful, but ever-varying lines of light are indeed "sound shadows"—long sought by the poets—"photographic echoes" which can resound and reverberate, and re-echo, again and again, with all true color of tone and fidelity of phrasing, whenever it pleases one to again pass light athwart these shadows!

In studio practise with Phonofilm recording new methods must be introduced in contrast to those heretofore employed in the ordinary motion picture. For example, everyone must work in absolute silence, except the actors or musicians who are being actually recorded. This involves, of course, studios particularly designed for this work with every precaution taken against extraneous noises and interior echoes. The usual hammering, pounding and general bedlam which has heretofore distinguished the moving picture studio must be completely eliminated during a "take."

A new type of moving picture director must be evolved, or if the old type is continued he must be thoroly gagged, and learn to direct by signal and gesture only. Special means must be taken to shield the highly sensitive transmitters and amplifiers from electric induction from the various types of lamps which must be employed and the cables leading thereto. However these difficulties are not insurmountable nor really serious. We have made great progress along this line, and our productions are each week coming nearer to the ideals we have set ourselves to work towards.

There is no reason why the Phonofilm process cannot be used with one or two of the better colored-picture methods. Already steps have been taken to combine the Phonofilm with color, and we expect to be able to release films combining this doubly charming novelty within a few months.

We believe this will mark a great advance towards that perfect realism on the silver screen of which we have all dreamed, but which in its perfection can never be attained.

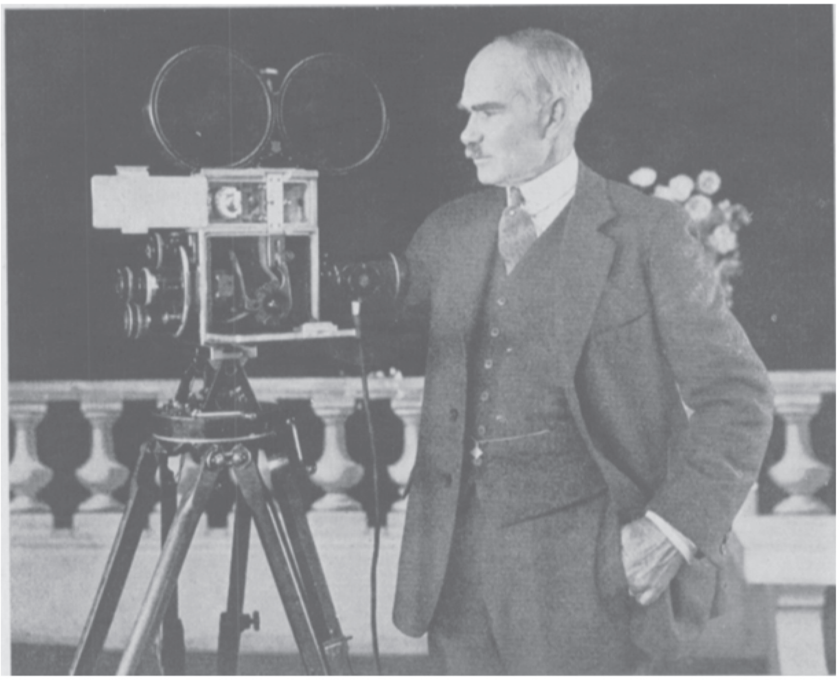

FIG. 4. Camera

I have now equipped a Bell-Howell camera with the Photion attachment which, combined with a specially built portable transmitter and amplifier unit, will permit of the Phonofilming of outdoor subjects. For example open air band concerts, pictures of waterfalls, ocean surf, singing birds, and similar subjects where nature has combined the beauties of sound and form.

Having now run over briefly the evolution of the methods of

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recording and reproducing sound photographically on the moving picture film it is appropriate to direct your consideration to some of the useful commercial and educational applications of this principle, and also of the many inventions which the development of this principle have entailed. These questions have doubtless been passing thru your minds since the topic of talking motion pictures was first called to your attention:—"Does the public want the talking picture? Is there room in the field of the silent drama for screen versions which are not all merely pantomime?" "Can the picture and the sound which go together so naturally in actual life, and which have been so completely divorced from each other since the beginning of the cinema art, be again brought together in a manner which shall be, if not entirely natural, at least artistic and pleasing?"

If you ask whether the ordinary silent drama to which we are all so familiarized can in general be improved by the addition of the voice, the answer is unquestionably "No." Many, and in fact most of the moving picture artists are not trained on the legitimate stage; they have no adequate speaking voices—many in fact are incapable of speaking good English. The situation is exactly like that existing when the moving picture was first evolved. It was then the common idea that the moving picture drama would be nothing more than an attempt to photograph the ordinary drama of the stage, limited to the same confined situations, the same small scenes, the same few characters, etc. It did not take long to demonstrate the total failure of the new motion picture art to enter into successful competition with the drama along these lines. An entirely novel type of dramatic scheme and presentation was necessary before screen versions were artistically possible. But Edison, and the other moving picture pioneers, had supplied a new medium, and it did not take the more enterprising, energetic, and progressive producers long to see the entirely new possibilities which thus lay open to them, and to evolve an entirely new form of entertainment. How well they have succeeded in evolving a new art is attested by the immense financial success of the moving picture industry of today.

The situation therefore, as regards the future of the Phonofilm, is today very similar to that which faced the new art of the silent picture when it was first realized that in order to fulfill its mission as a means of entertainment and education, it must not seek to follow blindly in the path of the legitimate drama. That it must take full advantage of the immensely wider ranges which were inherently its own property, and enter entirely new fields which were, by the very nature of things, completely closed to the older form of stage pictures and stage entertainment. Thus I claim that an entirely new form of screen drama can be worked out, taking advantage of the possibilities of introducing music and voice, and appropriate acoustic effects, not necessarily thruout the entire action, but here and there where the effects can be made much more startling, or theatrical if you will, or significant, than is possible by pantomime alone, no matter how cleverly such may be worked out. It is incumbent on the scenario writers to see these possibilities, and to work up their situations and scenes around such acoustic effects as can be successfully brought out, rather than to follow the reverse principle of merely attempting to introduce acoustic effects into scenes and situations which were primarily better adapted to the pantomime art.

To reproduce in an artistic and pleasing manner, both musically and pictorially, operettas, entire acts of opera, selections by symphony orchestras, popular bands, the songs of concert singers whom the public admires but are seldom privileged to actually hear—really popularize the playing of famous virtuosos, on piano or violin—there can be, I believe, no question as to the long felt vacant field which the Phonofilm is destined to fill. For here surely the silent drama is totally lacking; and the too brief phonograph record, blind to sight, and leaving much to be desired in naturalness of tone quality, can never be expected to qualify as a means of entertainment of public audiences.

There are, moreover, many instances where the silent drama, as it actually exists today, can be improved by the introduction of spoken matter. And numberless cases where incidental music, which can be played only by adequate orchestras available solely in a few of the largest theatres, can be successfully introduced into every medium-sized moving picture theatre in the land. Similar y where the action and sequence of so many silent dramas are today badly interrupted by the necessity of reading long and elaborate titles and explanations on the screen. The reading of lengthy letters, telegrams, etc., could frequently be far more effectively rendered by a clear resonant voice, spoken; it may be entirely off the scene, and not necessarily by one of the principals. I can in fact picture some very dramatic effects which may be obtained where, perhaps, only one or two words or sentences spoken throughout the entire run of an otherwise silent drama, will grip the attention, and startle the imagination, as does the occasional introduction of a hand-tinted object in an otherwise monotonous black and white picture.

I intend here only to point out that there lie dormant in the Phonofilm new possibilities for obtaining dramatic and genuinely artistic and beautiful effects, which lie entirely out of the range of the silent drama. It is rather for the progressive and imaginative producers and scenario writers to act on these hints to evolve something which the public has for a long time, in an inarticulate and half recognized manner, been expecting. To those who have the requisite daring and initiative will come the greatest meed of reward.

So much for the Phonofilm drama. But there are other fields for the useful combination of picture with voice and music which can admit of no serious dispute. Foremost in this category I would place the educational film. Unquestionably most of the educational films, especially for class room work, could be greatly improved in interest to the audience and in clarity of the lesson conveyed, if their presentation were accompanied by a lucid explanation, delivered in the first place by some authority on the subject who is far more competent to lecture thereon than are the majority of the instructors who are presenting the film to their classes. The proper matter, concise and to the point, will thus always accompany the picture, not too much and not too brief; and information be thus conveyed which the picture alone is quite inadequate to confer.

Similarly in the presentation of scenic films, travelogues, etc. Their interest and beauty can be immeasurably enhanced by virtue of verbal descriptions couched in impressive, and sometimes poetic terms. Consider moreover the appeal of fine pictures of the great Outdoors, the vision of wide horizons, views from some mighty mountain top,—the emotions awakened in the heart of the Artist who gazes out upon some noble forest landscape or over the magnificent vistas of far reaching valleys, the deep sentiments which are aroused when one stands beneath the trees of some lofty cathedral grove! These sentiments, these emotions, can only be adequately expressed by appropriate music, or perchance to the accompaniment of the poem of some great master. All such music and all such poetry can now be interwoven with the picture; and its beauty and its message thereby elevated to ennobling heights, to which the silent picture, however lovely, has never yet attained.

The weekly News Items which are now recognized as an appropriate part of every film program can be made vastly more interesting and informative to the audience if, in a few terse sentences, the scene depicted be also described, or the situation, which is frequently so inadequately told by the picture alone, be interpreted by the voice of some well informed, entirely invisible, speaker. Once this form of pictorial news service has been adequately introduced, I venture to say that the average audience will feel that without the spoken accompaniment, these pictures have lost their grip, their lively interest.

In the realm of the comedy immense possibilities for the Phonofilm unquestionably lie. The humor of many ludicrous situations can be screamingly increased if the right words, the right jest were spoken at the right time, in the proper dialect, or vernacular, or tone of voice. Similarly in animated cartoons, where the little animals or manikins can speak their funny thoughts as well as act in their funny ways, the humor of this new type of comedy can be readily doubled.

The filming of notable men, characters in the public eye, presidents and rulers, candidates for public office, etc., will be made many fold more interesting and genuine to the audience when their voices also are reproduced, instead of the present more or less inane mockery of their moving lips accompanied by silence. Picture for a moment what the Phonofilm will mean in the future in perpetuating our really great men for coming generations—How priceless now would be the film reproduction of Lincoln delivering his immortal Address at Gettysburg, or of Roosevelt as he stood before the Hippodrome audience at his last public appearance delivering a message to his countrymen, the inspiration of which has already been, how sadly, lost. Could we now see and hear Edwin Booth as Hamlet; Irving as Richelieu; Mary Anderson as Juliet—for real comparison, not based on treacherous and fading memories, with our present day "great" tragedians! None can deny the need to our present thoughtless generation of frequently seeing and hearing in their exalted moments our really great men reproduced from time to time for the benefit and uplift and inspiration of us all. That these great moments in the lives of great men shall not be forever lost to our descendants, is one of the debts which those who come after us shall owe to the film which records both the voice and the visage of the nation's leaders. And, thus, I ask you, judge not the future usefulness of the Phonofilm by its present accomplishment, as already displayed in a Broadway theatre, but rather by its promise of finer things soon to be achieved!

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January 1956 Journal of the SMPTE Volume 65

Published in JSMPTE, 65 (1), Jan. 1956

RADIO PHOTOGRAPHS, RADIO MOVIES, AND RADIO VISION

C. FRANCIS JENKINS

ATTEMPTS to send pictures electrically, and to see by wire, i.e., "television," are very old, dating back well-nigh a hundred years. And as radio differs from wire only as a means of carrying the picture characteristics over the intervening distance between stations, with the advantages in favor of radio, it is quite natural that the early workers should immediately begin the adaptation of their apparatus to radio as soon as radio was available.

There are two outstanding characteristics in these earlier efforts; (1) without exception every scheme which has attained any degree of success at all has depended upon the synchronous rotation of two cylinders, one at the sending station with the picture thereon which is to be sent; and the other at the receiving station where the picture is to be put; and (2) that the schemes employed were limited to the reproduction of the picture in black and white only.

Perhaps the very age of this scheme, and also that there are no patents thereon to prevent anyone from using it, explains the reason it has been employed so often by so many.

And there have been many workers; e.g., in England no less personages than Lord Northcliff, Sir Thompson, Mr. Evans, and Mr. Baker; in France are MM. Armengaud, Ruhmer, Rignoux, Fournier, and Belin; in Germany Paul Nipkow, Dr. Auchutz, and Dr. Korn; in Norway Mr. Petersen; and in Sweden Mr. Hansen.

In America Mr. Ballard, Mr. Brown, and Mr. N. S. Amstutz, the latter deserving particular mention for, from a distant picture, a swelled gelatine print, he engraved a printing plate which could be put directly into a printing press for reproduction.

All these workers have adopted the cylinder method of sending and receiving, and all have arrived at approximately the same stage of development, stopped by the physical limitations of the scheme itself. Quite obviously it is not with the cylinder and-dot-and-dash schemes that we will ever get television.

Development toward "television," or as I prefer to call it, Radio Vision, contemplates the sending from a flat surface and receiving on a flat surface, and a modulation which will give not only the high lights and shadows of photographs, but the half-tone values also. By flat surface is meant to include the depth of focus of the lens employed, that is, not only must the lens at the sending station send from a flat surface, but it must likewise send from a solid object, and also from an outdoor scene; while at the receiving station the

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picture must be caught on a flat surface like a photographic plate, a white wall, or a motion picture screen as employed in the theatres.

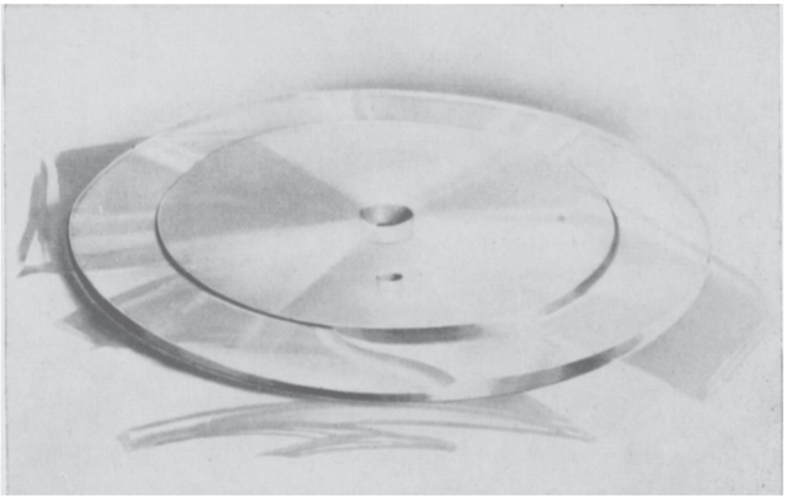
It was with these facts before me that I began my solution of the problem. My first published article on the subject appeared in the Electrical Engineer, July 25, 1894, which contemplated the use of wire connections from station to station. My first published article on the application of radio to the problem appeared in the Motion Picture News, October 4, 1913, under the heading "Motion Pictures by Wireless," and had editorial comment.

But no practical, workable scheme seemed possible when the combination was made up of parts selected from apparatus available, that is, already employed in science and industry, a missing part must be found to tie them together.

So I set about the discovery of this missing link, the something which would remove existing limitations. The result is the Prismatic Disc, a new optical shape in glass which gives to a beam of light passing therethrough a fixed axis on one side of the prism and a hinged or oscillating axis on the other side of the prism, described in the Transactions of the Society of Motion Picture Engineers, Montreal meeting, May, 1920.

By these means I am able to make a picture image move over a light sensitive cell in such a manner that every part of the picture eventually impinges on the cell so that the successive picture characteristics are impressed on the radio carrier wave; while at the receiving station these picture characteristics cause a fluctuating point of light, a tiny twinkling star, to travel in lines over a photographic plate, which when developed, becomes a negative of the picture, object or scene at the sending station.

Now to receive Pictures-by-Radio it is only necessary (1) to cover a photographic plate in parallel adjacent lines, and (2) to vary



Prismatic Ring Disc, the New Optical Shape in Glass the density of the lines, to build up the shadows, the half-tones, and the high lights of the picture.

The essential device which thus makes Pictures-by-Radio is this Prismatic Ring, perfect examples of which have been attained only since the perfection of automatic machinery for its making.

This Prismatic Ring is equivalent to a glass prism which changes the angle between its faces; that is, a small pencil of light coming from a fixed source and passing through the overlapping surfaces of two rotating Prismatic Rings, having their diameters at right angles where the diameters cross, and one of the plates rotating many times faster than the other, will cause this pencil of light to sweep across the picture in adjacent parallel lines, until the whole surface of the picture negative is covered.

At the same time, if the intensity of the light impinging on the negative is varied, that is, strong at the same place in adjacent lines, dense spots are built up; if the light is less intense elsewhere, half-tones will be obtained; while if the light is very faint, little or no exposure will result.

It is thus the lights and shadows which make the picture are built up, line by line, for when this negative is developed, and prints made therefrom, the dense areas produce high lights in the picture; the less dense areas the half-tones; and the thin areas the shadows.

And these high lights, half-tones, and shadows correspond in exact position and density to the high lights, the half-tones and the shadows of the picture broadcasted at the sending station.

At the broadcasting station a radio carrier wave is impressed with electrical current modulated by the picture characteristics of the photograph sent, as the high lights, half-tones, and shadows of the photograph fall in succession on a light sensitive cell in the amplifying circuit going to the radio set.

Further, it is immaterial whether the modulation is taken direct from a flat photograph, from a solid object, or from an outdoor scene at which the lens of the transmitter is pointed.

That is, by means of these Prismatic Rings and a light sensitive cell at the sending station, the light characteristics which make up the picture are converted into electric current characteristics, which in turn are impressed on radio waves employed as a carrier.

Now, when these modulated radio waves arrive at a receiving station, the electric characteristics are changed back into picture characteristics by means of another pair of Prismatic Rings and a light source fluctuating in intensity. The scene at the sending station is, therefore, reproduced with remarkable fidelity on a photographic negative at the receiving station.

Again, as the picture characteristics are taken up from the outer focal field of the transmitter lens at the sending station, an actual scene or object may be sent as readily as a drawing, handwriting, or a photograph, and at all the receiving stations is reproduced on photographic negatives from which duplicate prints on paper or lantern slides are made.

The whole apparatus is comparable to a camera with a lens in Washington and its photographic plate in Boston, for example;

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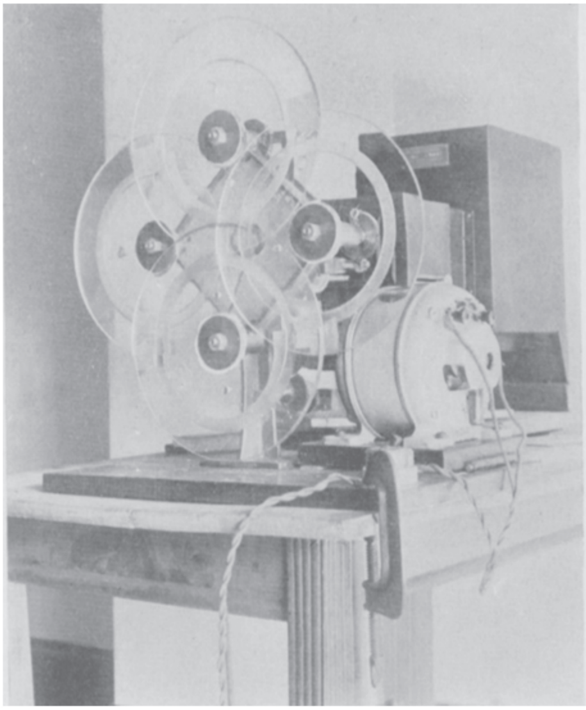


The Multiple Prismatic Disc Sending Machine

with this difference, that the one lens, in Washington, may put its picture on ten, one hundred, or one thousand photographic plates in as many different cities at the same time, and at distances limited only by the radio power of the broadcasting station.

With this new apparatus wireless distribution of news pictures for daily-paper illustration insures the distribution of picture news as promptly as telegraphic news; which means that pictures of news events get into the daily papers as early as telegraphic text, and simultaneously the whole country over. It means just exactly that, and it takes no particular imagination to visualize the value of such service to the newspapers.

It is even more than this, for these Radio News Pictures projected from magic lantern slides onto the screens of the best picture theatres in the cities, enable the theatre to put news events before the public sooner than the newspapers can print and distribute telegraphic news; that is, the daily paper is now threatened with second place as a means of news distribution, for no newspaper can possibly put a distant news event before the public as quickly as the theatre can with Radio Pictures.

It is possible, perhaps probable, that a news bulletin in pictures and type may be broadcasted and the photographic negative thereof (at all receiving stations) be used in the printing of the usual news bulletin sheet either by direct photographic process, photostatic prints, or by a photo-etching process, the etched plate for use in the printing press; this would eliminate the necessity of local typesetting plants.

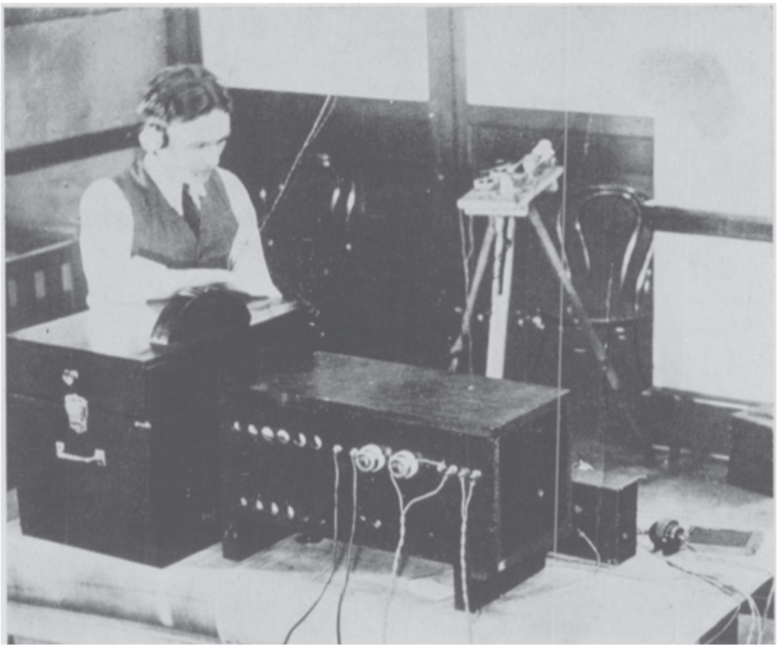
The Police Departments of the various cities of the country would also doubtless be customers for picture distribution service, as photographs of criminals, as well as their thumb prints, could thus be readily distributed.

Bankers and business executives could, in a few minutes, verify the signatures to checks, drafts, or documents; indeed contracts and other forms of credit could be exchanged across the continent within the hour.

Telegraph messages in fac-simile of handwriting, signature, and explanatory sketch can be sent in competition with the dot-and-dash wire telegraph.

These instruments should also have great tactical value, enabling the Navy and the Army to send messages, maps, etc., which cannot be deciphered by the unauthorized.

The remarkable flexibility of this system is further shown by the photographs successfully sent over an ordinary unaltered desk telephone to the radio set, and from there broadcasted, i.e., remote control. This has been repeatedly done, though central too often



Radio Camera and (in background) Control Fork for Synchronizing

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breaks in to ask "What number, please," or to tell us "Your party has hung up."

This feat is not strange if one but remembers that our sending set simply changes picture characteristics into electrical modulation, just as a carbon transmitter changes speech characteristics into electrical modulation. At the receiving set this radio-carried electrical modulation may be changed into sound by "head-phones," or into pictures by a radio camera.

In fact my young men judge of the quality of the picture they are getting by listening in, and are able to identify an unknown picture by sound, where they have been using the picture several times in their experiments.

In the official Navy demonstration of this past fall, two portraits, a map, a written message, and an outdoor scene were being sent. This the young man at the receiving station knew, but he did not know the order in which Commander Taylor would send them from N O F, the Navy broadcasting station.

Presently one of the admirals, standing by the receiving set, asked what picture was being sent. The radio-camera man listened a moment, and replied—"Secretary Denby," which was found to be correct when the negative was developed.

Thereupon the admiral asked to listen in. As he intently watched the fluctuating light which was exposing the photograph on the negative, someone asked:—"Admiral, what does the Secretary sound like?", to which he replied:—"He sounds like he looks."

As many of you doubtless noted from the daily papers, we sent photographs from Washington to Philadelphia the first of March.

When I reached Philadelphia, I found that the receiving apparatus was expected to be located in the Bulletin building down in a pocket surrounded by tall steel structures, and in the radio shadow of the City Hall tower, with Wanamaker's powerful station, W O O, only a square away, plus other broadcasting stations, the Navy Yard spark set, and then, for good measure, arc lamps, electric elevators, and the Associated Press telegraph room near by, a situation so bad that a firm of radio engineers, called in by the Bulletin a week previously, had refused to install a receiving set and guarantee satisfaction.

However, as we had come to Philadelphia to make the trial, we set up anyway and by careful tuning and trapping, and eternal vigilance, we got pictures through, with perfect photographic modulation and symmetry, although they were overwritten with code interference. The pictures were used for illustrations in the notice of the test which appeared in the afternoon papers.

The test was particularly valuable in that it confirmed our judgment that pictures could be sent by our apparatus over radio distances, still retaining the likeness in the photograph with absolute fidelity.

The test was also valuable in showing what could *not* be done satisfactorily. For example, the antennae and radio receiving apparatus should have been set up in the suburbs, or even out in the country, and the picture signals sent in from there over a wire to the radio-camera in the city, that is, remote control of the radio-camera.

It may be worth recording here that the apparatus of the sending station, N O F, at Washington, was wholly in charge of a Navy officer who had had only a few minutes' instruction before the radio photographic sending set was turned over to him for operation.

It may also be of passing interest to note that we were working so close to the Wanamaker broadcasting station that each of us listened to the beautiful pipe organ music simply by holding in our hands the brass part of the plug of the head phones as we walked about the room, with no connection whatever to the receiving instrument.

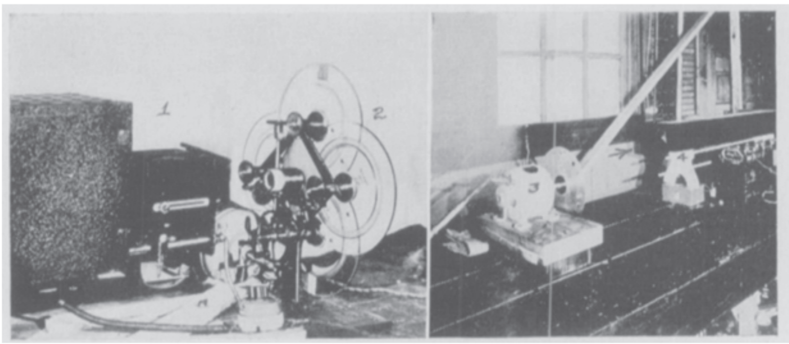
Perhaps a short detailed description of some parts of our apparatus might be interesting to you as engineers.

The sending apparatus is so simple as to need no explanation, perhaps. It is simply an illuminated photograph, some rotating Prismatic Rings, a lens and a light-sensitive cell. Which reminds me of the remark one of the G. E. engineers made:—"Sure, I could do it myself if I had Jenkins' glass butter plates."

Of all the schemes that have been tried by us as substitutes for the Prismatic Ring, none has been successful, whereas a number of different devices have been used as the source of light in the receiving set. Familiarity with the requirements has made the problem rather a simple one, the problem being that the point of light traveling over the photographic plate shall be properly modulated.

We have made photographs with a miniature vibrating mirror; we have made photographs with glow lamps; we have made photographs by employing the spark of an ordinary automobile engine spark plug, but of all these and other schemes tried, none has so far equalled the incandescent filament in a hydrogen atmosphere. This lamp has produced photographs which are absolutely photographic in character, being entirely free of any dot or line effect whatever.

The hook-up for the filament lamp consists of a battery to bring



Photographs by Radio. Sending set at Naval Radio Station N. O. F. Washington. Washington-Philadelphia Tests. 1. The Magic lantern for illuminating the photograph; 2. The Prismatic discs; 3. The "chopper"; 4. The light cell

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the filament to a red glow; and then the incoming radio signals are put right through the battery, and lamp to variably increase the glow of the lamp to photographic values corresponding to the light values of the different parts of the photograph at the sending station.

These lamp filaments are very delicate and fuses must be used to protect them against current surges. No such delicate fuses are available, so far as we know, so we cut them ourselves. I fastened two thin razor blades side by side, and cut through thin tin foil on a smooth lead block. We thus obtained a very minute lead fuse which was picked up and put in place with a wet match stick.

In working with the spark as a light source, the spark plug was put directly into the secondary of the transformer, the primary of which was in the plate circuit of the amplifying tube. We then added a condenser across the spark plug terminals. Naturally the number of sparks per second depended upon the break-down strength of the incoming signal, and because the density of exposure on the photographic plate depended upon the number of sparks per second, obviously exposure in different parts of the plate corresponded exactly, but in reverse order, to the densities of the various parts of the picture at the sending station. For blacks and whites and straight C.W. radio it is a most excellent scheme, and very rugged and dependable.

As for synchronism, that is no problem at all where current for all the stations can be taken from the same A.C. power plant, or in Radio Movies, where synchronism is maintained by hand. But over greater distances, synchronism of the sending and receiving stations is maintained by controlling the motor at each station with tuning forks, the fork at the receiving station being adjusted to the period of the sending station fork. Adjustment is easily done by stroboscopic observation of the rotation of the receiving station motor, the required intermittent illumination being timed by the incoming signals of the sending station fork.

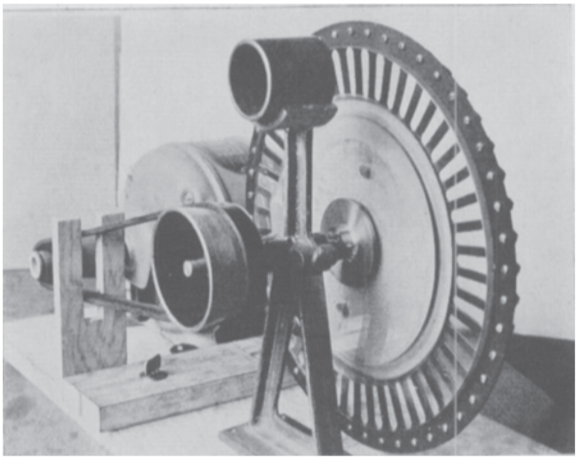
Both hydrogen filled tungsten lamps and neon filled glow lamps are successfully employed for the intermittent illumination. The tungsten hydrogen lamp has a period as high as 1000 per second; the neon lamp a period much higher, higher than any means at hand would measure, but believed to be equal to commercial radio frequencies.

During the Washington-Philadelphia tests a lack of dependability in the synchronism of the forks was noted. They would stay together for an hour perhaps, and then get out of step without apparent cause, necessitating readjustment. This was later overcome by making the incoming fork signals control the period of the receiving station fork, as well as furnish stroboscopic illumination. This was entirely successful, and without mechanical relays.

It might be noted in passing that a very rapid, very sensitive, and very simple relay was developed as a sort of by-product of these experiments, the essential element of which was a new form of armature, an X-shaped armature. For that matter there has been quite a residue of new information resulting from the year's work.

There will be no regular radio news picture service on a commercial scale for some months yet. Steps have been taken looking to the establishment of close co-operation with the newspapers, but this is not to be interpreted as forecasting the immediate institution of commercial service.

When photographs were sent from Washington to Philadelphia, it was to stir up interest and encourage assistance in the improvement of apparatus to insure its practical day after day employment in the broadcasting of photographic spot news.



Laboratory Test Set for Radio Motion Pictures and Radio Vision

Motion-Pictures-by-Radio

Photographs-by-Radio being now an accomplished fact, and Motion-Pictures-by-Radio differing therefrom only in speed, the Radio-Motion-Picture seems now only a matter of time.

When this is developed folks in California, in Nebraska, in Maine, will be able to see the inaugural ceremonies of their President, in Washington, the Army and Navy football games at Franklin Field, in Philadelphia, or both see and hear grand opera broadcasted from anywhere.

In weighing the reasonable probability of the successful solution of Motion-Pictures-by-Radio, it should be borne in mind that as light which makes up our picture and radio which carries it are both practically limitless and imponderable, the accomplishment seems well within reasonable expectation of early realization.

From the very nature of the invention, it would seem that in the homes Motion-Pictures-by-Radio would ultimately find its greatest usefulness, for not only would motion pictures for news and for entertainment be received, but music as well. An entire opera might thus be enjoyed through both ear and eye, as all the family, old and young, listens in and looks on amid the comforts of their own home.

Radio-Motion-Pictures might similarly be found useful in schools, churches, granges and clubs; perhaps even the theatre may ultimately be changed from celluloid to radio.

The progress of a great battle on land or sea could be watched from the offices of the chiefs of staff, in Washington, sent in by re-transmission from scout planes flying overhead.

It seems to me, therefore, that this attainment, which now seems so near realization, should develop an enormous business, for the mystery of Motion-Pictures-by-Radio will be even more attractive than music by radio, to the million and a half army of fans who play with their radio sets practically every evening, plus a much larger, new group of radio-movie fans.

Physical Property

The establishment of powerful broadcasting stations in the several centers of probable spot news should doubtless be the first activity undertaken, for there are abundant opportunities for useful and profitable service for Radio-Pictures for newspapers, theatres, daily bulletin sheets, police and governmental use.

For example, wire or wireless broadcasting stations should be established in North America at points of maximum news distribution. At these stations pictures for transmitting would be received by mail, or messenger, or by short range radio automobile set for relay on a long range wave, or sent in through the telephone nearest the scene of the news happening.

Assuming six broadcasting stations, between the Atlantic and the Pacific, then two hours A.M. and two hours P.M. might be assigned each station during which news would be initially broadcasted, the other five stations acting for these hours as relay or retransmitting stations, which latter for other allocated hours would act as initial stations.

In this manner the whole country would be covered with broadcasted picture news simultaneously, San Francisco getting its Boston news pictures at the same moment as New York, Washington, Chicago, and all other intervening cities.

In unusual news, like the tumbling down of the Capitol building, the collapse of the Brooklyn bridge, or the dynamiting of Faneuil Hall, for example, the traffic manager would stop the station broadcasting at the time and direct the station nearest the scene of this special spot news to broadcast pictures out of its turn, while all the other stations relayed them to every newspaper the country over.

Many hundreds of comparatively inexpensive radio cameras would be hooked up to receiving sets all over the country wherever the reception of news pictures might be desirable.

All receiving stations would pick up all the news transmitted by all the broadcasting stations, giving a very full and complete service at the minimum of cost.

It will not be the purpose of the broadcasting stations to gather pictorial news, but rather to act as a carrier agency for distributing pictures handed to it for transmission, a service comparable to the distribution of news text by the telephone and telegraph companies.

That is, news items in pictures handed in at the nearest sending station will be broadcasted; to be picked up by all subscribers to such Radio-Picture service.

Incidentally it might be mentioned that the same equipment will transmit titles and short descriptions for the Radio-Pictures, as well as additional news items.

From the very nature of the service to be undertaken, it not only seems eminently wise but almost obligatory that the parent corporation retain ownership of all apparatus and instruments employed in all picture broadcasting stations and all receiving stations, not only to avoid the confusion now prevailing in audio-radio broadcasting, but to encourage the investment necessary to the greatest public good of Radio-Pictures.

All manufacturing facilities necessary for equipping such stations should be under the control, or at least the friendly co-operation of the parent corporation in order that standardization of apparatus may result.

In the very beginning of the business of furnishing Radio-Picture-Service, it should be foreseen that there will be developed many varieties of auxiliary and related apparatus which should be controlled by the corporation to prevent limit in the development of equipment; and—

To insure the highest standard of service and equipment, the control of all important patents, present and future, should be in the hands of the parent corporation and for no less advantage to the public than that it insures standardized apparatus and uniformly dependable service. That is, adequate financial provision should be made not only for operating charges, but also for standardization of apparatus, as well as depreciation as apparatus becomes obsolete during the early period of operational development.

C. FRANCIS JENKINS

(*1867–1934*)

With the death of C. Francis Jenkins, June 6, 1934, our Society lost not only its founder, but also one of the inventors of the motion picture projector, around which the entire industry has been built up. Those of us who had the privilege of knowing Mr. Jenkins intimately knew him as a man of great imagination and boundless energy, evidenced by something over four hundred patents in his own name, both here and abroad.

On various occasions he had to leave his beloved laboratory and devote his attention to raising sufficient funds to carry on his prime work—research and invention. His indomitable will and faith can not be better indicated than by quoting a statement that he often made and evidently thoroughly believed, "If a thing is very difficult it is as good as accomplished; if it is impossible it will take a little time."

In his laboratory he surrounded himself with young men and young women because, as he put it, "If Jenkins tells them it can be done, they believe it." Once Mr. Jenkins hired a brilliant scientist from one of the great research laboratories of the country. The scientist did not last long because, as Jenkins said, "He spent too much time proving why it wouldn't work instead of figuring out how to do it."

Mr. Jenkins was a true and loyal friend; a hard fighter, loved by those who knew him well, and respected by even his business enemies, of whom he had a few—invariably the price of success.

In his home life I have never seen a more beautiful relationship between man and wife. Mrs. Jenkins was his sweetheart to the very end, and he treated her, both in private and in public, as a youthful lover. They had no children but were continually doing things for their nieces and nephews and the children of their friends. Jenkins was always trying to help young people to get a start finanically.

Just before the depression Jenkins sold his business. His manner of disposing of the tidy sum he received was very characteristic of the man. First he created a trust fund to take care of Mrs. Jenkins

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for the rest of her life. The remainder of the money he and Mrs. Jenkins gave away outright and unconditionally to poor relatives, friends, and servants whom they had had from time to time.

Like many inventors Jenkins was of a high-strung, nervous temperament. At times when he would get too fidgety and nervous to work, he would leave his laboratory and pilot his private plane up into the great blue reaches of the sky, where he found peace and quietness to rest his nerves. Often his wife, good sport that she was, would go with him on those flights.

About 1930 Mr. Jenkins' health began to fail. His heart made it necessary for him to drop most of his active work at his laboratory. The majority of his time thereafter was spent quietly, though restlessly, at his home in Washington.

Probably realizing that his years were numbered, he wrote his autobiography and published it in 1931 as a book entitled *The Boyhood of an Inventor* from which the following data are drawn largely.

A red-headed boy, C. Francis Jenkins, was born of Welsh-French parents—Quakers—near Dayton, Ohio, in 1867. When he was about two years of age his parents moved to a farm near Richmond, Indiana. His early boyhood was spent in the log cabin home on that farm. Like many other farm boys Jenkins learned various things by experience and hard knocks. He early began to show great interest in mechanical things. Hours were spent turning the hand-wheel of his mother's sewing machine and trying to puzzle out the mechanics of the sewing. Other lessons were learned from the spinning-wheel, the flax-break, the wool-carder, the butter-churn, the log-lever cheese press, the winnowing mill, and such early mechanical aids that have long since been superseded but that nevertheless utilized many of the principles of mechanics of modern machinery.

Probably his earliest invention was a bean-shelling machine which he made as a boy. Following that, he invented a jack to lift wagon wheels for greasing purposes. Some of them he painted bright colors, and in selling them he learned one important business principle, *i. e.*, that appearance goes a long way in selling an article.

Jenkins' early schooling was at the little country school to which he walked three miles from his house and three miles back again. This was followed by high school and Earlham College. Later in life his College gave him the honorary degree of Doctor of Science (1929). While at school the school board gave him a Leyden jar and a static machine, because nobody else knew how to work them. That was probably the start of his interest in electricity, which was to play so great a part in his success in later life.

Jenkins also learned that hydrogen gas made from sulphuric acid and zinc would fill paper bags and cause them to rise like balloons. Perhaps those experiments implanted in his mind the seed of a desire to fly. After he was fifty years old he bought his first aeroplane and received his pilot's license.

Parties in his youth usually furnished their own entertainment. The games played were those of mental skill, cleverness, quickness; tricks such as trying to blow a card from off a spool by blowing through the hole—involving a principle of aerodynamics; turning a tumbler of water upside-down on a card, and the like—far different from the hired entertainment furnished the present-day youth.

Jenkins' father was progressive, although not inventive nor particularly mechanical. He used machinery of the latest type on his farm, and it was Jenkins' particular job to keep all the mechanical gadgets operating and in repair. He proved so adept at the job that he built up quite a reputation in the neighborhood as a clever mechanic. The day he saw his first locomotive he ran off from his family, who were meeting friends at the rear of the train, and spent his time studying the engine. Later he found out enough about its operation so that he borrowed a locomotive and took his girl for a ride.

When he was a young man his desire to "go places and do things" took him to the Pacific Coast. There he worked in lumber camps, on a ranch, and down in Mexico in a mine. His first job in the lumber camp was riding logs. The first day was a series of spills into the water, but his persistence kept him at it all day long, even though soaking wet, and he soon learned the trick. His indomitable will and persistence were characteristics that contributed greatly toward his success.

As a result of a Civil Service examination he received an appointment as a clerk to Sumner I. Kimball, the founder of our life-saving service, which is now the U. S. Coast Guard. This position brought him to Washington, D. C., where a few years later he resigned to start on his real life work, inventing.

It was at Washington that he met and married Grace Love, of whom he writes in his book, "Perhaps the turning point came when he married that wonderful girl, 'Miss Grace,' who had endeared herself to everyone by her sympathetic understanding and unselfishness, winning the hearts and confidences of all who came in contact with her. It is to her kindly help and business widsom, rather than to any personal 'genius,' that this inventor attributes such success as has attended his efforts."

Jenkins built the first horseless carriage in Washington—a small steam car— and went broke trying to promote it. Later he developed the self-starter for automobiles, which proved to be a financial success.

Photography and the projection of motion pictures were really his life's great work. In addition to his work on the development of the motion picture projector, he made many contributions to the motion picture art. Notable among them are the first fire-proof projector—really the foundation of the home and school movies of today; a high-speed camera for showing in slow motion such things as the flight of a projectile, Bobby Jones' golf drive, *etc.* His Chronoteine camera takes 3200 separate exposures in one second; the film moves through it so rapidly that 400 feet of film can be shot up into the air before the first end falls to the ground.

Jenkins early recognized the need of standardization in the motion picture industry. The need was stimulated by the World War, and to meet the demand Jenkins founded the Society of Motion Picture Engineers in 1916 and became its first president. That organization is today international in scope. It is the outstanding organization in motion picture engineering, and its standards have attained world-wide recognition. Its *Transactions* and JOURNAL form the greatest technical library pertaining to motion pictures in existence.

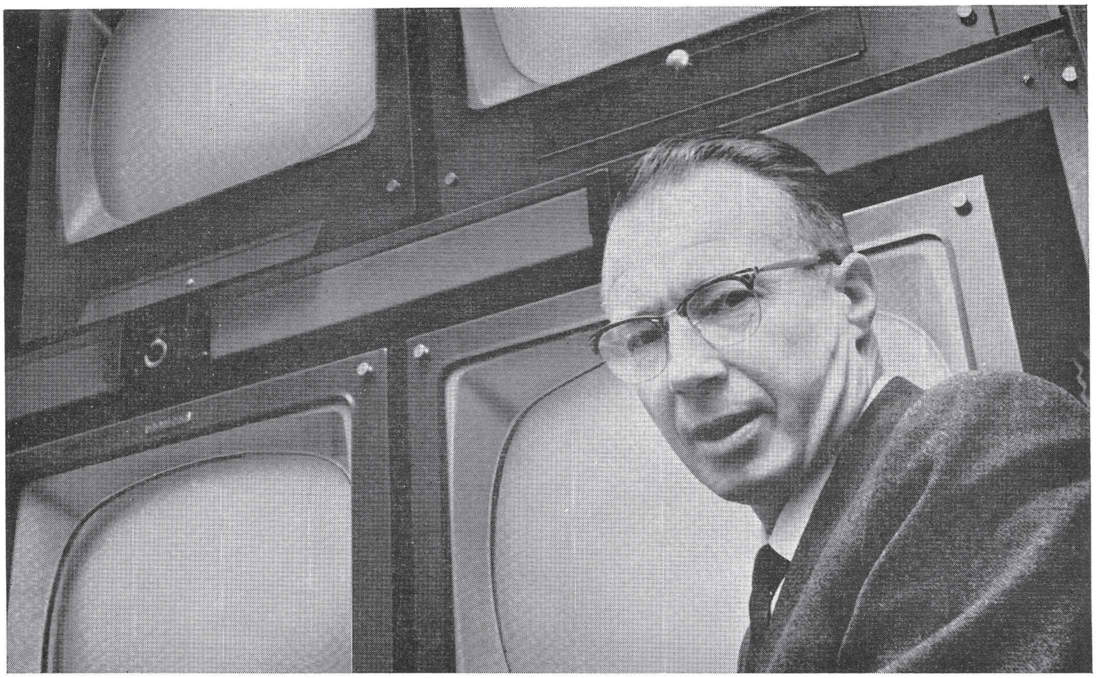
In 1921, Jenkins set up his own research laboratory at Washington, D. C. It was in this laboratory that Jenkins developed the prismatic ring, a device for producing a smoothly oscillating beam out of a continuous beam of light. As time went on, Jenkins became interested in radio. By conducting tests with his own aeroplane he discovered that a radio "shadow" was cast behind a metal plane and that an antenna flown in that area could be used for two-way telephone conversation without interference from engine ignition.

Sending photographs by radio, and later by television, interested Jenkins greatly. I shall never forget the thrill of standing in his laboratory and having a photograph of my daughter transmitted over the regular telephone line to the U. S. Naval broadcasting station at Anascostia, Md. There it was broadcast by radio, picked up in the Jenkins laboratory, and reproduced at the side of the sending device. Jenkins established his own station for broadcasting motion pictures by radio. Nightly entertainment of that sort was transmitted from his station, *W3XK*. Relatively simple and inexpensive receivers had been developed by Jenkins and sold practically at cost to thousands of radio fans all over the country.

A more complicated machine for receiving weather bureau maps by radio was developed and installed on many of the Government ships. Jenkins had the fullest coöperation of the U. S. Bureau of Standards, the Army, and particularly the Navy, in testing out his many inventions, some of which were purchased by the Government and put into regular service.

As often happens to a man who works so intensively, his health began to fail. As a result, in 1930 he sold out his principal business, the Jenkins Television Corporation. A failing heart kept him more and more at home until his death in 1934. With his passing went one of the ten men in the United States having over three hundred patents in their own name. He was a man of great vision, with the courage of his convictions; a man of indomitable will and boundless energy; a man having great love for his fellow men, a fine Christian character respected by all who knew him and loved by those who had the opportunity of being associated with him. Perhaps the greatest monument to him is the continued success of the Society he founded and for which he worked so hard in its early struggle for recognition.

L. C. Porter



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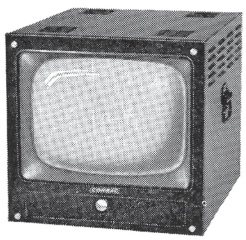

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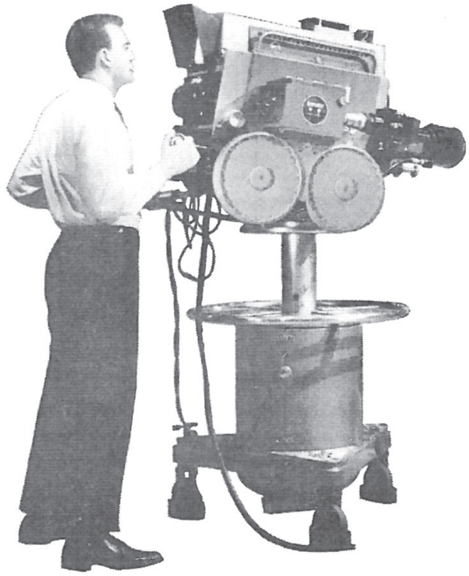

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Published in JSMPTE, 73 (5), May 1964

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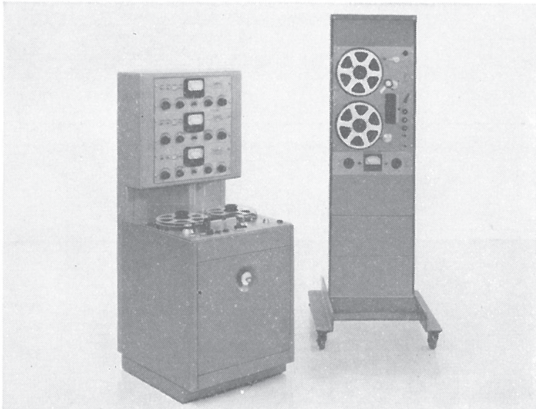

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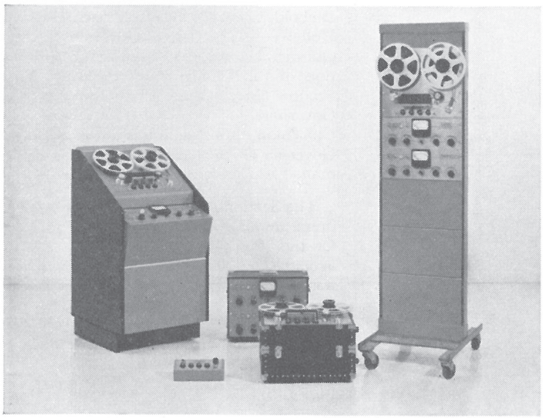

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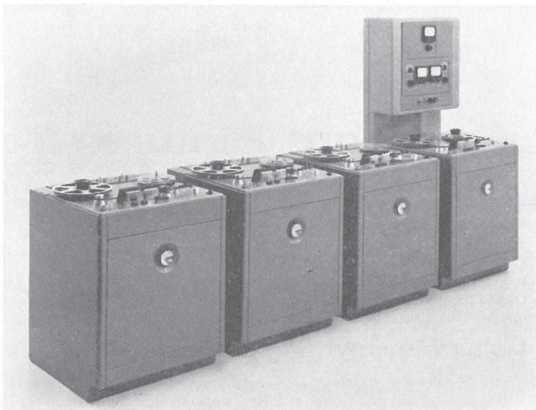

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5. Planning a Motion Picture in Color

Now that we have considered some color fundamentals and the currently important color films and processes, let us proceed to examine the use of color in professional motion pictures.

THE IMPORTANCE OF COLOR

Not many years ago when a producer began to plan the production of a motion picture he automatically thought of it in black-and-white. At any major studio, many vital conferences were held in the "front office" before a picture was made in color. There were good reasons for this. Raw stock, dailies, additional lighting on the sets, laboratory work, print costs — these and other items made a picture cost considerably more in color, and a producer must always be thinking about recouping the huge investment required by a major motion picture.

Today, however, the situation is exactly reversed. Producers have come to accept color in motion pictures as a matter of fact. Now the production of a picture is automatically planned in color, and vital "front office" conferences are held before a picture is made in black-and-white, even though there is still a larger expenditure of money involved in the use of color. The simple fact of the matter is that color has proved to be a tremendous asset to a motion picture — so much so that it has often been considered another "star" in a picture, included in the advertising, in the publicity, and usually on the marquee.

Currently about two-thirds of all the motion-picture entertainment produced annually for theatrical release is in color. The amount of color used in television is much less, of course; but a surprising amount of original photography for television is presently being done on multilayer color camera negative, or color reversal film from which black-and-white prints are made for immediate distribution. The color original is then stored away for future use.

There are those who believe that color will eventually replace black-and-white, both for theatrical and for TV entertainment. And there are those who believe that black-and-white motion pictures will always be with us. There seems to be no one, however, who does not agree that for the most part the motion-picture entertainment of the future will be in color.

COLOR HARMONY

Color harmony may be defined as the systematic arrangement of colors to give a pleasing effect. The subject of color harmony is complex, and to a certain extent a matter of personal taste; nevertheless there are certain fundamental principles which apply.

Published in "Elements of Color," Chapter 5, SMPTE: New York, NY, 1957

(Above) A pleasing arrangement of colors. This is only one of the many good combinations possible. (Below) An extreme example of poor color harmony. Note how the distracting colors of the surroundings draw attention away from the principal subject of the picture.

FIGURE 12 (Courtesy Eastman Kodak Company.)

Most outdoor scenes display good color harmony, probably because our minds have grown to accept the color combinations of nature as pleasing. Indoors, the colors of background, clothing and other elements of a scene can be controlled, and therein lies a danger — the fact that it is easy for us to become obsessed with the wide gamut of colors we have at our disposal. We might well take a cue from nature, and recognize that the most pleasing color pictures are generally those in which only a limited range of colors is used. Likewise, the use of relatively unsaturated colors will frequently add to the naturalness of a color picture.

Examine carefully the pictures shown in Fig. 12. Both are the same in every respect except color, and so provide a valid comparison of color schemes without variations in other factors such as subject, pose and lighting. The top picture is a pleasing arrangement of colors, while the bottom picture is an extreme example of poor color harmony. These pictures also show how a warm colored background tends to appear nearer than a cool colored one, thereby decreasing the apparent depth of the scene.

The effect of a given color scheme depends not only upon the colors themselves, but also upon their comparative areas and their distribution throughout the scene — that is, their juxtaposition. In general, large areas of harsh, brilliant color are seldom pleasing, and are best avoided unless included to serve some unusual purpose. More dramatic effects can be obtained by surrounding a subject with complementary color, whereas small touches of related colors will soften the severity of bolder contrasts. Textures of colored surfaces are also important because they can lead to different color rendition under various lighting arrangements.

OVERALL COLOR PLANNING

A color motion picture as a whole, as well as its succession of sequences, must be conceived not only in color harmony but also in the proper color key. A western, for example, plays well if we merely add generous quantities of red to the natural coloring of the outdoors. Warm, neutral colors contribute to the homely reality of an historical classic. A musical or a pageant calls for a broad gamut of saturated, emphatic colors. A comedy is usually conceived in an effect of bright backgrounds with sharp color accents. And so on. Moreover, within a picture it becomes desirable to use different effects in different sequences, so that the story changes in locale and mood are attended by appropriate color changes.

The overall color planning of a motion picture may originate at any of several sources. The producer or the director may have a flair for thinking in color terms, and thus be able to outline the color effects from the start. In other cases, the art director and the color coordinator, and sometimes a special designer, may be given this important creative work to do. Frequently it is the combined thinking of a number of people, under the art director's guidance, which sets up the color program. This program is then crystallized in the form of color sketches of sets, locations and wardrobe for general approval and guidance.

There are many factors which strongly influence the overall planning of a color motion picture. The feminine star, for example, whose appearance is of paramount concern, must be given undisputed priority as to the color of make-up, hair and costumes which will best compliment her complexion and her figure. If her complexion limits the colors she can wear successfully, this in turn restricts the background colors which will compliment her complexion and her costumes to best advantage.

Fixed colors, such as sky, foliage, skin tones or exterior locations which have predominant background colors will be encountered. These fixed colors become determining factors in selecting colors for wardrobe, sets and properties.

No rigid decisions about color compositions can be made until all considerations such as those above have been weighed. Specialized artistic contributions come from all departments and are integrated into a master color plan. This plan is then detailed and carried out by departments, the objective being to have color "act" with the story, never being a separate entity to compete with or to detract from the dramatic content of the picture.

ART DIRECTION

The great artists have consistently used color to enhance their compositions, to focus attention, and to accentuate rhythm. Motion pictures (and live TV as well) can combine all of these functions of color with an additional, dynamic quality — that of *color in motion.*

In a motion picture the composition is never static. People move, lips move, the camera moves, the point of view moves. And color moves — not only within a scene, but, through "cutting," there is color motion in the juxtaposition and succession of scenes. The interesting speck of color in a long shot can, in one cut, become the screen-filling color in the following close shot. This degree of versatility, which makes possible the telling effects achieved when color is used with skill, is the very reason why color, if uncontrolled, can work to the detriment of a picture. As we have noted, color in a motion picture must help tell the story. If it does not do this we invariably find it in competition with the story.

Generally speaking, the specific problem with respect to the use of color in a motion picture set is to use fewer hues and to use colors of lower saturation, especially for background colors. We are familiar with the manner in which a clutter of detail in the background of a black-and-white picture will cause our eyes to wander away from important foreground action. A background which is a clutter of color will do the same. And if a background is a clutter of *color and detail,* it becomes an even stronger visual magnet. By using fewer and less saturated colors as well as by simplifying background detail, any action of the actors becomes more definite and emphatic, and color plays its proper role as one of the prime factors of story-telling. Surprisingly enough, perhaps, the use of unsaturated colors does not result in a drab or grayed version of reality, but appears as reality itself. Here, again, we must consider the difference between what the color film can see, and what the human eye can see. What we see on the screen when we reduce the number and the degree of saturation of the colors on a set is what we believe we see in everyday life.

This psychological factor can be one of great importance in creating an atmosphere of reality or verisimilitude on the screen. With the filming of an historical or a "period" picture, for example, research is done not only on architecture and decoration, but also on the colors in use during the particular period and in the specific country. Yet the use of the actual colors of the period or the country are very rarely employed. Because of psychological factors governing the response of a modern viewing audience, far better results are achieved by the use of a *desaturated tonality of the times* — that is, a less saturated range or "palette" of color and pattern, but adequately punctuated with authentic identifying colors so that the end result tends to be identified as historically accurate, yet believable. If, during a particular historical period, a great artist or a great school of art existed, a limited palette will sometimes be developed from these paintings and used as the general color theme of the picture. One recent motion picture was done with the paintings of Rembrandt as a basis, modified of course to suit the psychological responses of a modern viewing audience.

Modern and documentary pictures, a good part of which are often filmed in the studio, present a different color problem. To be believable, and in most cases to tie in with actual scenes filmed on locations, *identifying colors* are necessary to give realism. Actual color "stills" are usually studied for attention-attracting or identifying colors, and the use of these identifying colors will then easily create an atmosphere of authenticity and bridge the cuts from real to studio settings. In street scenes the identifying color might be the particular hue of a building or a sign. For interiors, the identifying color is one that relates the interior to the actual exterior shot on location. And if the interior set is a copy of a well-known locale, then the general tonality of the actual room must of course be used.

Particular attention must be given to the color of foliage, especially when natural exteriors are intercut with exteriors filmed on a stage. There are many hues of green foliage, ranging from yellow greens to very blue greens. If the hue of the natural foliage is not faithfully reproduced on the stage, the difference will disturb the viewing audience. We may not realize exactly what is disturbing us as we watch the picture, but the disturbance will be there, distracting our attention from the story, at least momentarily. This is just another example of color working against us if we do not take the trouble to make it work for us.

Musicals and fantasy pictures are open to unlimited opportunities in the use of creative color. Here we are not held down by reality, past or present, and our imaginations can soar. Musicals and fantasies are usually designed to provide the eye with visual pleasure in the way that music pleases the ear. Many times the central color theme is indicated by the story, by the music, or even by lyrics or verses involved. During the past few years much use has been made of the modern master painters for ideas — Picasso, Toulouse-Lautrec, Braque, Utrillo, Modigliani, Rousseau and others. Of course, a picture of this type necessitates a tight control of color by all departments, in order that the desired moods and effects do not get out of hand.

The mood to be employed in the filming of a motion picture is often of importance in planning the color. A picture with many low-key or night exterior scenes usually requires that dark colors be increased in brightness, and sometimes in saturation, to keep them from reproducing as black or near-black. Conversely, a picture with many high-key scenes will require that light colors be decreased in brightness, and sometimes increased in saturation, to keep pastel shades from "washing out" to white or near-white. These adjustments are necessary because no color film (nor even the fastest black-and-white film) can be made to cover a brightness range even approximating that of the human eye.

Our vision, with its remarkable ability to operate over a tremendous range of operating levels, can perceive color and detail both in dark-colored areas at low levels of illumination, and in light-colored areas at high levels of illumination. Film, lacking the adaptive mechanisms of the eye, simply cannot "see" over this wide range of light levels. For this same reason, it has become general color motion-picture practice to use an "off-white" rather than a true white, and a "navy" or a "charcoal" rather than a true black. These colors photograph white and black, respectively, and yet retain modeling and detail.

COSTUME DESIGN AND WARDROBE

As we have already seen, color from the point of view of the costume designer and the wardrobe supervisor is never an isolated problem. Color problems related to costumes are part of the master color plan which is worked out with the Producer, the Director, the Art Director, the Director of Photography and the Color Coordinator — before any preliminary work is started or any discussions are held with stars or players.

In designing costumes and selecting wardrobe, as we would expect, the same color principles apply as we found applying to art direction. Color must be subordinate to the story, and help to tell it. The colors in costumes cannot be permitted to become "eye-catchers" unless such an effect is deliberately desired, and so helps rather than hinders the story.

We have seen that sets and locations establish locale, mood, time and circumstance of the background. Costumes and wardrobe do the same, but have the added function of punctuating the actor against the background. Consequently the color of the costumes usually is slightly complementary to the background, or slightly more saturated, and so helps us to center our attention on the actors and follow the story. In most cases, two specific situations occur: many characters work against a particular background; and one or more characters wear the same costumes throughout several scenes, thereby working the same costumes against several backgrounds. Particular attention is required, therefore, to insure proper separation between wardrobe and backgrounds throughout the picture.

We saw how identifying colors are used to relate sets to actual locales, both exterior and interior. Costumes can also function in this way. For example, the particular colors of a hotel doorman's costume might serve as a color connecting link between interior and exterior scenes. Too, just as the colors used in historical sets are "modernized," so are the colors of historical costumes subtly changed, so that the end result can be identified as historically accurate, yet believable.

As we have seen, skin tones are of prime importance in a color picture. Specific attention is given, therefore, not only to the relationship between skin tones and background, but also between skin tones and costumes. For example, if make-up color is changed to denote the different races of people, other colors should be altered accordingly. As make-up becomes darker, the costumes should employ deeper and more saturated hues. Whites (off-whites) next to skin tones should be dropped somewhat in value, and any large, light areas are also best decreased in value. If a dark make-up is used, an actor wearing a "white" blouse or shirt will appear considerably darker than when wearing a shirt or blouse of lower value — say, a medium gray. If we ignore this fact we will find that either the complexion color or the costume color seems to change from scene to scene, depending upon how the scene is printed.

Color "normalcy" is generally the goal when wardrobe is selected for a color motion picture. By color normalcy we mean that we do not try to *force* color into a picture just because we happen to be working with color. For example, if an actress in a given

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story situation would likely appear in a gray dress, she is not put into cerise just because it is more colorful. This principle holds even if the color key of the picture is light and gay. Naturally, as stated earlier, color normalcy does not apply to musical or fantasy pictures, where color is unrestricted by realism.

Experience has shown that there is a great deal of validity to the psychology of color, at least as far as color costumes are concerned, and an actress is never forced to wear a certain color if it can be avoided. Years ago an actress would have been considered temperamental if she balked at wearing certain colors; now we realize that color preferences and dislikes are quite normal, and to respect them often helps an actress to portray a role better.

Another color "don't" is to "give away" the dramatic content of a scene which is just beginning to be played. For example, we often avoid black and somber colors for sad scenes if we do not want the audience to know in advance that the scene will be sad. Gay colors for gay scenes are often avoided for the same reason. This is just one more way of controlling color so that it helps to tell the story as effectively as possible.

COLOR COORDINATION

The fact that color in a motion picture is selected piecemeal, by many people and over a period of many days, explains why a color coordinator is desirable to maintain order—the order of good color composition. A color coordinator has two main functions: he insures that the subject matter to be photographed will appear to have the right colors under final viewing conditions; and he takes up artistic slack in carrying out the color master plan for a motion picture.

Color coordinators were first introduced to the motion-picture industry by the Technicolor Corporation. At that time, Technicolor was the only commercially successful color process in the professional motion-picture field, and what few pictures were made in color were in Technicolor. Consequently, the industry's color problems became Technicolor's problems, and not the least of these was the problem of color control, which could not be restricted to the laboratory, but had to be extended to the studios and incorporated into the planning and production of a picture. So Technicolor set up a "color consulting" department. Its members worked closely with the producing companies and with the Technicolor laboratory. They worked to secure quality color pictures on the screen, and to avoid costly errors, particularly in the preparation stages of a motion picture.

Of necessity, a color consultant had to see all the material that was being prepared — sets, costumes, backings, furnishings, all the items that appear in the picture. Consequently he knew as much about the color details as anyone connected with the production. It followed, then, that it was expedient for the producing company to have him as a "color coordinator" among the various departments. This was a logical step, for a color consultant had a background of experience in the artistic use of color, plus a knowledge of the laboratory methods of processing color film.

The studios producing black-and-white pictures had no comparable department. Black-and-white pictures posed no problems concerning hue or saturation; there were only brightness values to consider, and the ease with which these brightness values could be coordinated left the separate departments within a studio quite independent.

It may well be that the presence of an outsider, with no intramural attachments, succeeded in initiating the habit of color coordination in the smoothest way possible. The Director of Photography, the Art Director, the Costume Designer and the Make-up Artist all welcome the Color Coordinator as an appreciative collaborator to control the interplay of color among complexions, costumes and backgrounds, so that the special artistry of each will not be negated in the final color reproduction by false notes creeping in as a result of a lack of complete execution of the color master plan.

The Director of Photography, of course, is the final artist who composes the set-ups. His choice of lens, angle of view and lighting technique gives him a high degree of flexibility for artistic presentation. However, while the Director of Photography is a party to formulating the color master plan for a picture, he is seldom able to concern himself with color details, most of which are worked out long before the date of photography by numerous specialized artists and craftsmen who prepare the sets, costumes, furnishings, properties and backings to be used.

In one sense, then, the Color Coordinator is the righthand man of the Director of Photography during the preparation period — foreseeing the compositions which will be needed; insuring colors and textures that will provide balance in each set-up; adjusting backgrounds to make-up, so that dynamic portraits can be rendered and special depth portrayed; and determining contrasts of light and dark colors which the Director of Photography can keep under control without the costly and time-consuming necessity for individual lighting on different areas.

The Color Coordinator is certainly a righthand man for the Art Director. He is equipped with large files of color samples for quick reference, and he retains swatches of wardrobe so that color selections for the sets can be made to exact references. He brings to the Art Director the information needed to make decisions, and he helps spark creative thinking, just as he does for wardrobe, make-up, set decorating, scenic and other departments.

The final requirements for every choice of color are imposed by the color reproducing medium — the color film and process to be used, and whether the final prints are to be made for theatrical or for television presentation. There are some color distortions in all color reproducing media, and the magnitude of these distortions, if ignored, is often great enough to spoil a good color design, the impression of realism, or the appearance of a star. If the artistic intentions of a picture's color master plan are to survive, therefore, these distortions should be compensated for at the time each item of color is selected. The Color Coordinator, being laboratory trained, can visualize color in final viewing terms. He takes the responsibility of applying compensations which he knows will deliver to the ultimate viewing audience the colors which were intended.

The growing practice of having the Color Coordinator sit in with the laboratory group when they "time" the prints, and also with the producing group when the prints are viewed, completes the circle of control. Benefits accrue both ways from this — the producer, director, cinematographer and editor have a direct agent to secure from the laboratory the results they want; the laboratory has all the information needed to deliver those results promptly and economically.

MAKE-UP

Make-up is essentially a "production" problem — that is, except for prepro

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A usual, incorrectly applied make-up.

Same model, all cosmetics removed.

Correct application of proper foundation color.

Application of shadow color to minimize width of jaw and side of nostril. A painted cleft in the chin helps to elongate the face. No blending at edges yet, to clearly illustrate the line of application.

Profile view of shadow color application.

Correct application of highlight color under the eyes to erase circles, at corners of nose to erase lines, and on either side of the cleft in the chin to further emphasize length of face. Edges of shadows have been blended, but not the highlight application.

FIGURE 13

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Profile view of highlight color application.

Correct application of cheek rouge. Edges of highlight color have been blended, and rouge is applied diagonally to cheek bones, just above the line of shadow application.

Initial application of eye shadow color.

One eye completely made up, with eye shadow blended. Correct contour and density of brows with eyebrow pencil. Correct application of mascara to eye-lashes. Compare with the model's left eye, which has not been made up.

Completed make-up. Powder has been applied, lips properly shaped with correct hue and value of lip rouge. Hair changed to compliment the facial contours.

Profile view of completed make-up.

(Make-up by William Tuttle; Color Photography by Clarence S. Bull; Courtesy Metro-Goldwyn-Mayer Pictures.)

duction tests, it must be dealt with primarily during photography. But as we have seen, the make-up for a color picture must be included in the color master plan. Make-up must be considered in advance with respect to the stars and featured players to be photographed, for, since the object of color make-up is to enhance the natural complexion tones and contours of both men and women, the make-ups for different actors must be different.

Make-up must also be considered with respect to the particular color films and processes to be used, because make-ups for the same actor will differ with color processes. Even the color balance and intensity of illumination used for photography must be considered, for these factors can directly affect the colors of the make-up. And finally, as we have seen, the make-up colors must be integrated and coordinated with the other color ingredients, especially the costumes and the sets.

Color make-up problems differ from those involving costumes and sets in several respects. The variety of pigments that can be used in cosmetics is limited to those approved by the Pure Food and Drug Act. And, make-up normally cannot cover the surface of the skin the way paint covers a wall. Foundation make-up can never be applied so heavily as to completely conceal the texture of the normal skin. A heavy application results in a mask-like appearance, whereas an important aspect of make-up for color cinematography is the production of a "natural" complexion tone for both men and women.

Special make-up foundation colors are made for each color process, but merely using the correct series of colors for a particular film is not enough. Selecting the proper shade (the proper combination of brightness and saturation) for each individual actor or actress is the secret to obtaining the most natural results.

Let us try to define exactly what is meant by a "natural" make-up. Paradoxically, it is *not* an exact reproduction of a person's natural skin tones. Actual color measurements made on the faces of both men and women show them to be considerably redder than we would accept in a color reproduction. On film, we want complexion tones to appear more pink than they are in real life, and it is this overly-pink skin tone which our vision tells us is natural. This has been recognized for many years on the legitimate stage, where spotlight filters aptly named "illusion pink" are used to glamorize the female complexion. If we actually do reproduce a beautiful woman's complexion exactly as it is in real life, we will consider it "too ruddy" or "unnaturally reddish," and so will she.

Not only do complexion tones have to be reproduced more pink than they really are, but, as we have already indicated, they must also be the optimum shade for a particular actor or actress. Variations in shade may be required to bring out the very subtle pastel hues so necessary to a good skin tone, or they may be necessary for corrective purposes. For example, if a woman has an unusually ruddy complexion, a darker shade of the proper color series will be required than if her complexion is more normal. In this instance the darker make-up helps to conceal the ruddy tone of her skin, and at the same time it prevents her skin tone from becoming too light.

As a rule, the most flattering skin tone for a woman is one which gives sufficient contrast between her skin and her eyes, so that the eyes, usually considered the most expressive element of the face, become the most important feature by virtue of color contrast. There are some occasions, however, when, because of the type of character being portrayed, the make-up for an actress (or an actor) must be lighter or darker than the same actor would require for a "straight" type of role.

The fact that corrections of various sorts have to be made on many faces necessitates that a substantial range of shades be available in every make-up color series. Areas that are too prominent can be subdued by using a foundation color about three shades darker than the base make-up color. Or, a foundation color about two shades lighter than the base color is often used to highlight areas of a face that would otherwise recede undesirably, such as dark circles under the eyes, or lines at the corner of the nose. This same technique of highlighting and shadowing is also necessary in producing certain character effects, or in simulating the appearance of greater age, by emphasizing lines and wrinkles in the face with shadows, and by highlighting certain fullnesses such as jowls or cheek bones. These techniques have been used in black-and-white motion pictures for many years. They are more difficult with color, but considerably more dramatic when properly done.

Sometimes actors and actresses are photographed with little or no make-up. This is not because their skin tones will reproduce perfectly on color film without it; it is rather that they are playing "extra" roles, and never get close enough to the camera for make-up to be important. Actresses playing "atmosphere" type parts are usually made up with the customary light foundation colors used by women for ordinary street wear. Men playing similar parts are usually not made up at all. People playing "bit" parts, however, who may be photographed in a close shot with one of the principal players, may have to be made up as carefully as the stars.

It is always necessary to consider carefully the foundation make-up with respect to the color balance between men and women. If a woman's make-up is very light and a man's is very dark, the variance in complexion tones will be so obvious on film that it will appear unnatural and disconcerting. Selection of foundation colors which are closer together in value will produce a better balance and give a more pleasing picture. Even though this may be somewhat of a compromise for each of the actors in question, it will usually result in a more natural appearance for both when they are photographed together.

The technique of applying make-up is fully as important as the proper selection of colors, if the perfect effect we are seeking is to be achieved. As we saw earlier, make-up should never be applied too heavily. Highlights and shadows to correct facial proportions must be blended very delicately, so that each color fades naturally into the foundation color. Cheek rouge should be a pastel, blended to a soft blush tone. Eyebrows should be penciled with tiny hair-like strokes to simulate real hairs, never drawn in a solid, continuous line. Make-up should always be applied to the neck, shoulders and arms, if exposed, so as to achieve a continuity of color tone from a woman's hairline to the neckline of her dress. Lip rouge is best applied with a lip brush, so that a perfectly sharp line is achieved. Figure 13 shows several steps in the production of a good make-up.

In producing red lips, we are confronted with a situation which is somewhat unique. The lips are extremely small in area, and they are always surrounded by an area which is lighter in color — namely, the flesh tones of the face. Too, there is only an extremely small portion of the lips that ever falls in the highlight region of the film, this tiny area being the fullest point of the lower lip. The lip rouge, consequently, must be selected with great care or the lips tend to reproduce dark and opaque. In general, the darker the lip rouge the more degraded and opaque the lip color becomes on film. This has ruined many an otherwise good make-up, causing an actress to appear "hard" and "made-up."

For color, most make-up artists prefer to use an oil base foundation rather than the pancake, or water soluble, type of cosmetic. An oil-base foundation can be applied thinner in most cases, and the degree of oiliness which comes through after powdering gives the skin a very natural sheen which is difficult to obtain with a water-soluble base. Pancake-type make-up is widely used for body make-up, however, in colors to match the oil-base foundation used on the face.

Space does not permit us to list here the various color series of cosmetics designed especially for the various color films and processes. Make-up charts for Ansco Color, Eastman Color, Technicolor, and even live color TV are available from the various cosmetics manufacturers.

Michael Dolan

In this column, we provide interesting historical briefs from the Journal articles of days past. The purpose of this column is primarily entertainment, but we hope it will also stimulate your thinking and reflection on the Society's history, how far we have come in the industry, and (sometimes) how some things never change. This column has been sponsored by Television Broadcast Technology, Inc. since March 2001: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7257346.

100 Years Ago in the Journal

One-hundred years ago at a formulating meeting of the Society in Washington, District of Columbia, on 24 July 1916, Henry D. Hubbard, Secretary of the U.S. National Bureau of Standards, addressed the founding members: "...through your organization may you, in the words of Washington, 'raise a standard to which the wise and the honest can repair.'" On this day, the signed Certificate of Incorporation was notarized. Find that and the Constitution and By-Laws below.

CERTIFICATE OF INCORPORATION

SOCIETY OF MOTION PICTURE ENGINEERS

The undersigned persons, all of legal age and citizens of the United States, desiring to associate themselves for certain purposes stated herein, do now here make, sign and acknowledge this certificate of incorporation.

First. The name by which this corporation shall be known in law is "SOCIETY OF MOTION PICTURE ENGINEERS."

Second. The term for which this incorporation is organized is perpetual.

Third. The particular business and objects of this corporation are for the promotion and advancement of the motion picture art, and for mutual benefit.

Fourth. The number of trustees, directors, managers or governors of this corporation for the first year of its existence shall be seven.

Fifth. The said corporation shall have the power for themselves and their successors to have and use a common seal, and alter and change the same at pleasure, and make by-laws and elect officers and agents, and take, receive, hold and convey real and personal property, and do such other things as may be necessary or desirable for the purposes of this corporation.

In testimony whereof, we have hereunto set our hands on the 24th day of July, A. D. 1916.

C. FRANCIS JENKINS,	Washington, D. C.
DONALD J. BELL,	Chicago, Ill.
PAUL H. CROMELIN,	New York City.
C. A. WILLATT,	Boston, Mass.
FRANCIS B. CANNOCK,	New York City.
W. BURTON WESTCOTT,	Boston, Mass.
PAUL BROCKETT,	Washington, D. C.
E. KENDALL GILLETT,	New York City.
HERBERT MILES,	New York City.
J. P. LYONS,	Cleveland, Ohio.

Personally appeared before me the above subscribers, who severally acknowledged the same to be their act and deed for the purposes therein set forth.

Witness my hand and official seal this 24th day of July, A. D. 1916.

(Signed) RALPH S. SHERLINE,
Notary Public.

(Seal.) My commissio expires January 4, 1920.

Certificate of Incorporation, issued 24 July 1916.

CONSTITUTION AND BY-LAWS

Name.

1. The name of this association shall be SOCIETY OF MOTION PICTURE ENGINEERS.

Objects.

2. Its objects shall be: Advancement in the theory and practice of motion picture engineering and the allied arts and sciences, the standardization of the mechanisms and practices employed therein, and the maintenance of a high professional standing among its members.

Membership.

3. The membership of the Society shall consist of Pioneer Members, Honorary Members, Active Members, and Associate Members. A Pioneer Member is defined as one who was in the art as a principal fifteen years or more antedating the time of the organization of this Society; an Honorary Member as one who has been actively engaged in designing, developing or manufacturing materials, mechanisms or processes used in this or allied arts for more than ten years; an Active Member as one who is actually engaged in designing, developing or manufacturing materials, mechanisms or processes used in this or allied arts; and an Associate Member as one who, though not eligible to membership in the active class, is interested directly in the art.

Eligibility.

4. Any person of good character may be a member in any or all classes to which he is eligible.

5. Prospective members shall be proposed in writing by at least two members in good standing, and may be elected only by the unanimous vote of the Board of Governors. Valid autographed ballots may be forwarded by absent members of the Board of Governors.

Constitution and By-Laws [From *Transactions of the SMPE*, October 1916].

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Applications.

6. All applications for membership or transfers in class shall be made on blank forms provided for the purpose, and shall be accompanied by the required fee.

7. The entrance fee shall be twenty-five dollars ($25.00). The annual dues for Active Members shall be ten dollars ($10.00), payable in advance on July 1st of each year.

The annual dues for Associate Members shall be five dollars ($5.00), payable in advance on July 1st of each year.

The dues for Pioneer Members shall be $250, and its payment exempts the member from all future dues.

The dues for Honorary Members shall be $100, and its payment exempts the member from all future dues.

Officers.

8. The officers of the Society shall be a President, two Vice-Presidents, a Secretary, a Treasurer, and a Board of seven Governors, who shall be elected to their respective offices at the October annual meetings by a majority of autographed ballots of the members, and counted by a committee of tellers appointed by the President. All officers shall hold office for one year or until their successors are chosen, except the Board of Governors, as hereinafter provided, and the Vice-Presidents; one of whom latter-named shall be elected for two years and one for one year, and then one for two years, each year thereafter.

Governors.

9. The Board of Governors shall consist of the President, the Secretary, and the Treasurer, *ex officio,* and four active members; two of which last-named shall be elected for a two-year term and two for one year, and then two for two years, each year thereafter.

Duties.

10. The duties of the several officers are those usually appertaining to each such office, together with such additional duties as may be prescribed by the Board of Governors.

The Treasurer shall be bonded in an amount to be determined by the Board of Governors.

Meetings.

11. The regular meetings of the Society shall be held in such places and at such hours as the members may have designated at the preceding meeting. A quorum shall consist of twenty-five or more voting members. Special meetings may be called by the Board of Governors when necessity therefor arises. Active Members only shall be entitled to vote. The Board of Governors shall meet quarterly at such time and place as they may select. Special meetings may be called by the President when occasion requires, or upon the request of any three members of the Board of Governors, not including the President.

Publications.

12. All matters of general interest deemed worthy of permanent record shall be published in serial volumes as soon as possible after each regularly called Members' meeting. A copy shall be mailed each member in good standing to his last address of record. Extra copies shall be printed for general distribution, and may be obtained of the Secretary on the payment of a fee fixed by the Board of Governors.

Emblem.

13. The emblem of the Society shall be a facsimilie of a six-hole film-reel, with the letter S in the upper center opening, and the letters M, P and E in the lower three openings, respectively. The Society's emblem may be worn by members only.

Delinquents.

14. Members who are in arrears of dues for thirty days after notice of such delinquency, mailed to their last address of record, shall have their names posted at the Society's headquarters, and notices of such action mailed them; and thirty days after such posting the member shall be dropped from the rolls if such non-payment has continued.

Suspension.

15. Any member may be suspended or expelled for cause by a four-seventh vote of the Board of Governors; *provided,* he shall be given due notice and a copy in writing of the charges preferred against him and shall be afforded opportunity to be heard ten days prior to such action.

Amendments.

16. These by-laws may be amended, altered or added to at any regularly called Members' meeting on a two-thirds vote by ballot of the members present at that meeting.

SMPTE
Sustaining Membership Levels

Diamond Level – $16,000

As a Diamond Level Sustaining Member you'll receive:

- 15 complimentary individual SMPTE memberships*
- 30 complimentary registrations to SMPTE Educational Webcasts
- Free online institutional subscription to the SMPTE Motion Picture and Television Standards and Practices for one site**
- Three complimentary full registrations for the annual SMPTE Technical Conference & Exhibition
- 15 employees of Diamond Member company will receive a 10% discount off the non-member registration rate
- Banner ad on SMPTE website for three months
- Your company name and logo with a hotlink on the SMPTE website
- A button ad in four issues of the *SMPTE Monthly*
- Technology Spotlight in *SMPTE Monthly*
- Two full-page color ads in the *SMPTE Motion Imaging Journal* (one in the widely distributed SMPTE Progress Report and one of your choice)
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- Discount on booth space for the SMPTE Annual Technical Conference & Exhibition

Platinum Level – $10,500

As a Platinum Level Sustaining Member you'll receive:

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- Discount on an online institutional subcription to the SMPTE Motion Picture and Television Standards and Practices and the entire digital library
- 25 complimentary registrations to SMPTE Educational Webcasts
- Two complimentary full registrations for the annual SMPTE Technical Conference & Exhibition
- 12 employees of Platinum Member company will receive a 10% discount off the non-member registration rate
- Your company name and logo with a hotlink on the SMPTE website
- A full-page color ad in the *SMPTE Motion Imaging Journal* (run of schedule)
- Your company name recognized in the *SMPTE Motion Imaging Journal*
- A button ad in four issues of the *SMPTE Monthly*
- Discount on booth space for the SMPTE Annual Technical Conference & Exhibition

Gold Level – $8,000

As a Gold Level Sustaining Member you'll receive:

- Ten complimentary individual SMPTE memberships*
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- 20 complimentary registrations to SMPTE Educational Webcasts
- One complimentary full registration for the annual SMPTE Technical Conference & Exhibition
- Your company name and logo with a hotlink on the SMPTE website
- A full-page color ad in the *SMPTE Motion Imaging Journal* (any month with the exception of the SMPTE Progress Report & subject to run of schedule)
- Your company name recognized in the *SMPTE Motion Imaging Journal*
- A button ad in three issues of the *SMPTE Monthly*
- Discount on booth space for the SMPTE Annual Technical Conference & Exhibition

Silver Level – $5,500

As a Silver Level Sustaining Member you'll receive:

- Five complimentary individual SMPTE memberships*
- 15 complimentary registrations to SMPTE Educational Webcasts
- Discount on an online institutional subcription to the SMPTE Motion Picture and Television Standards and Practices
- One complimentary full registration for the annual SMPTE Technical Conference & Exhibition
- Your company name and logo with a hotlink on the SMPTE website
- Your company name recognized in the *SMPTE Motion Imaging Journal*
- A button ad in two issues of the *SMPTE Monthly*
- One half-page ad in the *SMPTE Motion Imaging Journal* (any month with the exception of the SMPTE Progress Report & subject to run of schedule)
- Discount on booth space for the SMPTE Annual Technical Conference & Exhibition

Bronze Level – $2,800

As a Bronze Level Sustaining Member you'll receive:

- Three complimentary individual SMPTE memberships*
- Discount on an online institutional subcription to the SMPTE Motion Picture and Television Standards and Practices
- Ten complimentary registrations to SMPTE Educational Webcasts
- Your company name and logo with a hotlink on the SMPTE website
- Your company name recognized in the *SMPTE Motion Imaging Journal*
- A button ad in the *SMPTE Monthly*
- Discount on booth space for the SMPTE Annual Technical Conference & Exhibition

Supporting Level – $1,100

As a Supporting Level Sustaining Member you'll receive:

- One complimentary individual SMPTE membership*
- Five complimentary registrations to SMPTE Educational Webcasts
- Your company name and logo with a hotlink on the SMPTE website
- Your company name recognized in the *SMPTE Motion Imaging Journal*
- A button ad in the *SMPTE Monthly*
- Discount on booth space for the SMPTE Annual Technical Conference & Exhibition

**Complimentary individual SMPTE memberships each include the opportunity to participate on engineering committees and work on standards development.*

***Complimentary subscription is available to a single site within the organization. Additional sites may be added for additional fee.*

All Dues are Listed in US Dollars.

To learn more about all the benefits of becoming a SMPTE member, visit **WWW.SMPTE.ORG/JOIN**

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- ☐ Complimentary individual membership(s)-based on level of participation
- ☐ Significant savings on a number of SMPTE activities
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- ☐ Valuable benefits package at each level

Plus, your membership helps support SMPTE's industry education activities such as Education (*SMPTE Motion Imaging Journal*, section meetings, conferences and the SMPTE Professional Development Academy) as well as SMPTE Standards, Recommended Practices, and Engineering Guidelines – the foundation of much of our industry.

There are several levels of membership, designed to suit your company's level of involvement and budget.

Company Information

Company ____________________

Company Website ____________________

Address ____________________

City ____________________ State __________ Zip __________

Country ____________________

Primary Contact

Primary Contact ____________________

Title ____________________

Email ____________________

Phone ____________________ Fax ____________________

Company description for website and complimentary individuals can be added to your online profile once your Sustaining Membership has been processed.

Choose Your Level:

- ☐ Diamond Level–$16,000
- ☐ Gold Level–$8,000
- ☐ Bronze Level–$2,800
- ☐ Platinum Level–$10,500
- ☐ Silver Level–$5,500
- ☐ Supporting Level–$1,100

Payment

Level of Membership ____________________

Amount Enclosed $ ____________________

☐ Check # ____________________

☐ American Express ☐ Discover ☐ MasterCard ☐ Visa

Card Number ____________________

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Signature ____________________

Name as it appears on card ____________________

1916 – 2016

Return with Payment to:

Society of Motion Picture and Television Engineers
3 Barker Ave. Fl 5 White Plains, NY 10601
T: +1 914 761 1100
F: +1 914 761 3115
www.smpte.org

SMPTE
Membership Application

I wish to:

- ☐ Join
- ☐ Renew

the Society of Motion Picture and Television Engineers.

Membership Type

- ☐ Active/Fellow *Professional (1 Year)* $145
- ☐ Active/Fellow *Professional (3 Years)* $420
- ☐ Active/Fellow *Professional with Standards Community (1 Year)* $395
- ☐ Active/Fellow *Professional with Standards Community (3 Years)* $1,170
- ☐ *Executive (1 Year)* $255
- ☐ *Executive with Standards Community (1 Year)* $505
- ☐ Associate* $45
- ☐ Student $10
- ☐ Life Member/Life Fellow *with Journal Subscription* $35

**Current Active/Fellow members cannot downgrade to Associate level. This level is only available to new members and graduating Student members.*

Note: For those memberships receiving the *Motion Imaging Journal,* $35 of annual dues is allocated to your subcription and is non-deductible. A complete list of member benefits is available at **www.smpte.org**.

I hereby make application for SMPTE membership and agree to be governed by the Society's constitution and bylaws.

Signature

Date

Return with Payment to:

Society of Motion Picture and Television Engineers
3 Barker Ave. Fl 5
White Plains, NY 10601
T: +1 914 761 1100
F: +1 914 761 3115
www.smpte.org

All Dues are Listed in US Dollars.

Personal Information

☐ Mr. ☐ Ms. ☐ Mrs. ☐ Dr.

Name First ____________ MI ______ Last ____________

Title ____________

Date of Birth *(required for determining life membership eligibility)* ____________

Primary Email ____________ Secondary Email ____________

Work Phone ____________ Home Phone ____________

Fax ____________ Cell Phone ____________

Recruiter Name *(if applicable)* ____________

Company Information THIS ADDRESS WILL BE INCLUDED IN THE MEMBERSHIP DIRECTORY

Company ____________

Address ____________

City ____________ State ______ Zip ______ Country ______

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☐ Use my mailing address for billing ☐ Use my company address for billing

Company ____________

Address ____________

City ____________ State ______ Zip ______ Country ______

Mailing Address

☐ Use my billing address for mailing ☐ Use my company address for mailing

Company ____________

Address ____________

City ____________ State ______ Zip ______ Country ______

☐ *SMPTE makes its print mailing (NOT e-mail) list available to qualified, relevant business organizations. If you want to be excluded from receiving these offers, please check here.*

Student Members

Students must transfer to Associate or Active Membership upon graduation. Maximum number of years as student members is six. Student members must fax a copy of their current student ID to +1 914 761 3115 or e-mail membership@lists.smpte.org.

Name of School ____________

Faculty Advisor Name ____________ Faculty Advisor Phone ____________

Payment

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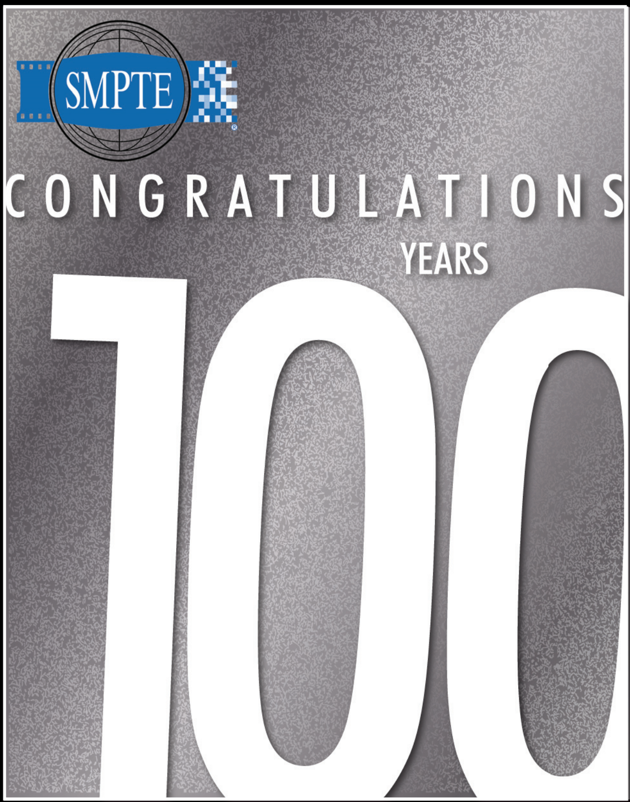

Evertz would like to congratulate the

Society of Motion Picture & Television Engineers

on **100 years** of continued excellence and advancement in moving-imagery education and engineering.

Evertz is also proud to announce its **50th year** in business! We would like to take this opportunity to thank our customers for their continued support over the years which has enabled us to achieve this amazing milestone.

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